The value of forest fragments in maintaining ecosystems for food security in Sub-Saharan Africa

By

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Dedicated in loving memory of my father inlaw,

Haruna Aaron Peter Garba (Hapgee)

A beautiful soul

1949 - 2019

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Abstract

Historically, forest fragments in Afrotropical montane regions have supported a rich diversity of bird species. On the Mambilla Plateau in South East Nigeria, forest fragments have a long history of association with small subsistence farmlands, and it is likely that birds provided ecosystem services to farmers through pest control and possibly pollination. However, more recently, increased human populations have dramatically reduced fragment sizes, or totally cleared them. Anthropogenic fire, grazing and farming have been responsible for most of the more recent forest destruction. This must impact bird populations and the ecosystem services they provide. Understanding the distribution of bird species and their role in providing ecosystem services to subsistence farmers in this forest-farmland mosaic is critical for both farmers and conservation managers. In this study, based on the Mambilla Plateau, I documented in detail the bird community composition and identified the potential roles of birds in providing pest control services to subsistence farmlands. I explored how distance of farms from fragments affected pest control services. Firstly, I surveyed bird community composition in both farmlands and forest fragments, and classified all birds recorded based on two main ecological traits: habitat preference and trophic functional group (based on their feeding guild). Secondly, I investigated the pest control services birds may provide to maize (*Zea mays*) on farms at varying distances from native forest fragments. I explored how excluding birds influenced maize crop yield by comparing the crop productivity in two caged treatments i) birds excluded, ii) birds and insects excluded) versus open (control) plots on maize farms. Thirdly, I tested whether, and if so, to what extent, plasticine pest mimics on groundnut (*Arachis hypogea*) and Bambara nut (*Vigna subterranea*) crops were being attacked by insectivorous birds, and whether attack rates depended on the proximity of farmlands to forest fragments.

I found significant bird biodiversity within this forest-agricultural landscape. While as expected, bird diversity was higher in the forest fragments, the farmlands also supported high bird diversity, although a significant proportion of the farmland species depend on forest fragments for a part of their life cycle. My study did not demonstrate any significant relationship between bird pest control and maize crop productivity (exclosure experiments showed that insectivorous bird abundance was not an important predictor of crop productivity). I also found that crop yield was higher further from forest fragments, and insectivorous birds were more abundant farther away from the forest. However, I did show that it is likely that natural pest control occurs, and that it affects yield substantially, because I

found a significant decrease in yield and increase in insect damage by excluding birds. This suggest that something must be controlling pests on maize (perhaps the key biocontrol insectivores in my study area are not birds, but bats). I also found a strong positive correlation between the abundance of insectivorous birds and mean number of missing mimics and/or bird attack marks on mimics. The positive effect of insect-eating bird abundance on prey mimics became less strong the farther they were from a forest fragment. Together, these findings suggest that pest predation may be a key ecosystem function provided by insectivorous birds on Nigerian subsistence farmlands, and farmlands that are closer to forest fragments may experience a higher rate of pest control than those further away.

Of note is that I had contradicting results regarding the role of birds in pest control from my maize exclosure experiment (Chapter 3) compared with the plasticine mimic experiment (Chapter 4). This suggests that birds, while providing important ecosystem services in some crops, may not necessarily be as important in others. This research highlights the need for further investigations into the role of birds, but also other taxa in biological pest control in rural West Africa.

Chapter 1: The value of forest fragments in maintaining ecosystem for food security in Sub-Saharan Africa

1.1 Introduction

Food security is first on the list of the eight Sustainable Development Goals (Bremner, 2012) and the challenge is perhaps greatest in Sub-Saharan Africa where one in four people are undernourished (FAO & WFP, 2015). A rapidly growing human population is increasing the demand for food across Africa, leading to unprecedented rates of land clearance (Hulme, 2007; Brink & Eva, 2009). Much cleared land is forest, which results in loss of biodiversity and ecosystem services, many of which are vital to agriculture (Gilbert, 2012; Laurance et al., 2014). For example, services such as water supply, erosion control, pollination, seed dispersal, pest control, shades/windbreaks and even climate regulation are being threatened by deforestation (Bregman et al., 2014; Chetana & Ganesh, 2012; Harvey, 2000; Hinsley & Bellamy, 2000; Sreekar et al.,2013; Tilman et al., 2001).

In the Afrotropical montane region, land clearance from subsistence farming is considered the leading cause of habitat and biodiversity loss (Malhi et al., 2014; Richard, 2014; Rudel et al., 2009). This may influence species functional diversity of an ecological community (Sekercioglu, 2012), with negative effects on ecosystem services (Engelen et al., 2017). Out of this challenge has risen the 'land sharing' versus 'land sparing' debate e.g. Phalan et al. (2011), in an attempt to minimize future biodiversity loss. Land sparing is the use of high yielding crops under intensive agriculture, while at the same time leaving areas of natural vegetation untouched (Fischer et al., 2014; Phalan et al, 2011; Tscharntke et al., 2012). There is ample evidence that under certain circumstances land-sparing is most effective at maintaining biodiversity (Hulme et al., 2013). In contrast, land sharing is the practice of growing lower-yielding crops within areas of natural vegetation, theoretically requiring more land but harbours more biodiversity to be maintained within the agricultural landscape (e.g. Hulme, 2007; Rosenzweig & Michael, 2003). For example, evidence from Mesoamerica and Nicaragua showed agricultural landscapes harbour a wide range of species of conservation concern within forest fragments (DeClerck et al., 2010; Harvey, 2000; Martin et al., 2012). Chetana & Ganesh (2012) have also shown the potential value of shade trees in tea plantations for seed dispersal and found that the density of shade trees has a strong influence on seed arrival. Thus, the effective conservation of forest fragments in agricultural landscape could be important.

In sub-Saharan Africa, the lack of technology and dependence on subsistence farming greatly limits the opportunity for land sparing (Crozier et al., 2018). Land sharing must, therefore, be practised in such a way as to maximize agricultural production while at the same time minimizing biodiversity loss. It is therefore important to assess the capacity of subsistence agriculture to sustain biodiversity e.g. (Mulwa et al., 2012), and identify species with different ecological roles within these landscapes e.g. bird species (Lewis et al., 2013; Sekercioglu et al., 2016). Previous studies have traditionally concentrated on forests or agroforests (Buechley et al., 2015; Perfecto et al., 2004; Tscharntke et al., 2008) due to their high levels of biodiversity, species of conservation concern (Hulme, 2007), and species ecological function (Bael et al., 2008; Maas et al., 2013; Maas et al., 2016). Little research attention has been given to biodiversity conservation in tropical subsistence farmlands, even though it has become apparent that subsistence farmlands are spreading in the tropics. This could mean that the survival of some forest animal species may depend on their use of these farmlands. It may therefore be important to incorporate small-holder agricultural lands into conservation policies. Moreover, conservation could be more effective to the farmers if they can relate it to their local environment, which is likely to be their farms (Hulme, 2007).

Despite the increasing land clearance for crop production in Sub-Saharan Africa, maintaining food security remains a challenge. A potential reason for this may be significantly related to high crop yield losses resulting from insect pests (Zakari et al., 2014), threatening subsistence farmers and their income (Zhang et al., 2018). For example, maize (*Zea mays*), groundnuts (*Arachis hypogea*) and cassava (*Manihot esculenta*) are important staple foods, particularly for locals in Africa (Ndjeunga et al., 2003; Tefera, 2012). However, insect pests such as the lepidopteran stem borer (*Busseola fusca*), the fall armyworm (*Spodoptera frugiperda*), and the cassava mealybug, (*Phenacoccus manihoti*), have led to a decline in the production of these crops, accounting for up to 75% of yield losses (Kipkoech et al., 2006; Moolman et al., 2014; Mutamiswa et al., 2017). Although subsistence farmers are aware of the usage of chemicals to control insect pests on crop plants, most farmers are constrained by availability and cost of insecticides (Banjo et al., 2003; Zhang et al., 2018). Therefore any study that will improve our understanding of the relationship between biodiversity and the delivery of natural pest control services to farmlands is crucial, particularly for the development of sustainable agriculture (Birkhofer et al., 2018). For example, bird species display a diverse range of ecological functions (Şekercioğlu, 2006), providing regulatory ecosystem services (Assessment, 2005), through their foraging behaviours (Wenny et al., 2011). They control populations of pests (Classen et al., 2014; Mitani et al., 2001; Naylor & Ehrlich, 1997), pollinate crop plants (Nabhan & Buchmann, 1997; Whelan et al., 2015; Whelan, et al.,, 2008) and disperse seeds (Nathan & Muller-Landau, 2000; Şekercioğlu, 2006). Other studies have established their significance as important mobile links that transfer energy within and among ecosystems (Şekercioğlu, 2006), thus contributing to ecosystem function and resilience (Lundberg & Moberg, 2003; Wenny et al., 2011). Although mammals have comparable roles, birds have twice as many taxa, ten times more flying species and are more resilient to extirpation than mammals (Holbrook et al., 2002), suggesting that their potential role in ecosystem services may be larger than other taxa.

1.2 Birds as ecosystem service providers

1.2.1 Pest control services

Recently, there has been a growing interest in the regulation of natural pests in tropical agroforests, and several studies have shown that in a wide range of agroecosystems birds are effective controllers of invertebrate pests; e.g. in large scale farming operations and in plantations (Classen et al., 2014; Karp et al., 2013; Maas et al., 2015; Tscharntke et al., 2008). In these systems, birds directly reduce infestation rates of invertebrates and indirectly increase crop productivity (Kellermann et al., 2008; Mols & Visser, 2002), acting as biocontrol agents and reducing the need for pesticides. The beneficial role of birds in consuming arthropods, and their influence on regulating insect outbreaks is well documented by United States biological survey reports, summarized by Whelan et al., (2008). For example, the 1958 extermination campaign in China against the Eurasian Tree Sparrow (*Passer montanus*) significantly contributed to insect pest outbreaks rather than increasing rice yield, demonstrating indirectly that the sparrows' control of insects benefitted the crop (Suyin, 1959). Although some bird species (e.g. granivorous species) are often considered as pests feeding on cereals (de Mey et al., 2012), many granivores also forage on invertebrates in their breeding seasons (Wenny et al., 2011; Whelan et al., 2008). Moreover, the European goldfinch (*Carduelis carduelis*) destroyed ten times more seeds of the aggressive pasture weed *Carduus nutans* than an introduced biocontrol agent, the Thistle weevil (*Rhinocyllus conicus*; Kelly & McCallum, 1995). Similarly, some frugivorous and omnivorous species may switch to other food resources (e.g. insect pests), to overcome periods of low resource availability (Lehouck et al., 2009; Mulwa et al., 2013). Other evidence has shown that raptors are important top predators, especially when indirect effects are considered (Kay et al , 1994; Mitani et al., 2001; Roemer et al., 2002). They reduced the populations of rodents in Holot Mashabim Nature Reserve, Israel, indirectly limiting their impact by establishing a landscape of fear (Abramsky et al., 2002; Brown & Kotler, 2004). Kay et al. (1994) reported that perches placed around soybean fields in Australia increased the number of diurnal raptors visiting the fields, which resulted in decreased population growth rate and maximum field population density in the house mouse (*Mus musculus*). Thus, managing farmland for insect pest control by birds offers an alternative to chemical use and may support the argument for land sharing as mentioned above. To what extent bird species contribute to pest control in tropical subsistence farmlands remains largely unknown, particularly in Nigeria where insect pests have a major impact on crop productivity (Banjo et al., 2003; Zhang et al., 2018).

1.2.2 Environmental Clean-up

Bird scavengers provide sanitary services, such as carcass disposal (Houston, 1979). Vultures are the only known obligate vertebrate scavengers (Ruxton & Houston, 2004) and in many ecosystems, they are (or were) the main meat-eaters owing to their efficiency in finding and consuming dead animals (Şekercioğlu, 2006). Although efficient as scavengers, vultures are vulnerable to poisoning, persecution, power line collisions, habitat loss and human disturbance (Houston, 1979; Prakash et al., 2003; Thiollay, 2006; Safford et al., 2019). Their decline in India appears to have led to increases in rotting carcasses, especially around human habitations (Prakash et al., 2003).

1.2.3 Plant reproduction

Bird resource consumption also facilitates the transportation of plant genetic materials via seed dispersal and pollination of crops (Classen et al., 2014; Lundberg & Moberg, 2003), promoting successful reproduction in thousands of crops and plants (Whelan et al., 2015). For example, a frugivorous bird swallowing fruits and defecating viable seeds away from the parent plant and a nectarivorous bird pollinating flowers while foraging promotes genetic diversity (Şekercioğlu, 2006).

Nearly 33% of bird species disperse seeds, primarily through fruit consumption, but also through scatter-hoarding of nuts and conifer seed crops (Vander Wall, 2010). For example, birds disperse the seeds of many woody plant species with direct value to humans for timber, medicine, food, or other uses; yet the dependence of these plants on birds for dispersal and the anthropogenic influence on the seed-dispersal pathways are in many cases poorly understood (Wenny et al., 2011). Seed dispersal reduces the density-dependent mortality of seeds and seedling by enabling escape from seed predators, herbivores, pathogens and competitors (Beckman et al., 2012; Janzen, 1970; Matthesius et al., 2011; Wenny et al., 2011).

More than 900 bird species also pollinate crop plants (Şekercioğlu, 2006; Whelan et al., 2015; Whelan et al., 2008). To meet their higher energy needs, many birds visit numerous flowers regularly, which increases gene flow among plants (Duffey, 2000; Nabhan & Buchmann, 1997; Schuchmann, 1999). Such birds often provide higher quality pollination than do insects, particularly of self-incompatible flowers with patchy distributions (Duffey, 2000).

Given the potential importance of birds within an ecosystem, there is a substantial but mostly unmet need for research on bird composition, their trophic functional groups, and their ecological functions in subsistence farmlands that are at varying distances from native forest fragments. Investigating the potential role of insectivorous bird species in providing ecosystem services, particularly for subsistence farmers in Africa, is an urgent priority because as mentioned above, subsistence farmers are faced with the challenge of high crop yield losses resulting from insect pests (Oerke, 2006; Zhang et al., 2018).

1.3 Afrotropical montane forest and the fate of birds

Grasslands and forests are characteristic of montane regions (Meadows & Linder, 1993), however, remaining forests are often restricted to relatively small patches in areas close to streams and/or on steep slopes protected from fire (Adie et al.,, 2017; Linder, 2014). These forest patches are known to influence connectivity (linkages of habitats) across agricultural landscapes (de Mey et al., 2012). As elsewhere then, the movement of species and genes across this landscape will either be facilitated or obstructed by size and distance between the fragments (Daily et al., 2001; de Mey et al., 2012; Lens et al., 2002). Consequently, the persistence of bird species in fragmented landscapes strongly relies on the connectivity of the landscapes (Aben et al., 2012). Yet, humans have continually increased fragmentation and reduced the size, or totally cleared natural fragments in Afrotropical montane regions. This is alarming in biodiversity terms because habitat loss increases bird extinction as shown elsewhere in the tropics (Şekercioğlu et al., 2012), and tropical montane bird species are more vulnerable to this extinction risk due to increasing habitat loss and climate change (Wormworth et al., 2011). Given that a shift or decline in bird species is likely to affect any of the ecosystem services birds may provide to the subsistence farmlands, conserving these forest fragments must be important, especially because a significant proportion of bird species depend on forest for at least part of their life cycle (e.g breeding; Fuller et al., 2004). However, it is unclear how bird species are affected by subsistence farmlands embedded by forest patches, certainly in West Africa (Deikumah et al., 2017).

On the Mambilla Plateau, SE Nigeria, the focus of this study, previous bird species' studies have been limited to single-species studies e.g. Turacos (Babalola et al., 2012), Sunbirds (Nsor, 2014) and short term bird surveys producing limited checklists and inventories e.g. (Disley, 2003). These do not produce a comprehensive checklist and inventory of overall bird species on the Mambilla plateau. Therefore, we still lack the basic distribution and habitat association data for all bird species on Mambilla Plateau. Yet we need quantitative data to identify conservation problems (Manu et al., 2010). Therefore, assessing the current and future distributions of Afromontane bird communities, their trophic functional groups, preferred habitats and what environmental variables may influence their functional diversity is significant in tropical conservation (Bovo et al., 2018; Buechley et al., 2015; Mulwa et al., 2012; Tobias et al., 2013).

1.4 Bird community composition and trophic functional groups

The number and relative abundance of species in a community is termed taxonomic or species diversity. This term takes into account (i) species richness - a count of the different species represented in an ecosystem, with phenotypic and behavioral traits, which determine where they can exist and how they interact with individuals from other species (McGill et al., 2006) and (ii) species evenness i.e. how similar in abundance each species is (Wilsey & Polley, 2004). However, it is high trait diversity (e.g. trophic functional groups), a consequence of high species diversity, which maintains stability in ecosystem functioning (Laliberte et al., 2010; Tilman & Kareiva, 2018). Hence, trait diversity may be the key to understanding the ecosystem services provided by birds rather than species diversity. In particular, functional diversity (FD) - a term used to describe the diversity of functional roles that species fulfils in communities and ecosystems (Petchey & Gaston, 2006) - has been invoked as an even better predictor of ecosystem services. This is because functional diversity is directly related to species ecological differences rather than to an evolutionarily based taxonomic classification such as diversity, that may not relate to the capacity of the organism in question to provide a particular service (Dıaz & Cabido, 2001; Tilman & Kareiva, 2018).

Put simply, the capacity of a bird species to contribute to various ecosystem services is determined by its functional diversity. For example, what it eats, and how it procures its food (Flynn et al., 2009; Spehn et al., 2005). Nevertheless, little quantitative data from natural or managed systems have linked functional diversity to ecosystem services in tropical agricultural systems (Classen et al., 2014). But if assessed appropriately, functional diversity can clarify the causes of any underlying observed relationships between species richness and ecosystem functioning, especially if the functional classification includes morphological, physiological, phenological and/or behavioural traits (Dıaz & Cabido, 2001) which are directly tied to the ecological function of interest (Philpott et al., 2009). For example, if farmland or native forest fragment support a relatively high diversity and/or richness of the insectivorous trophic functional group, it may indicate greater capacity for birds to contribute to biological control e.g. insect pest control. In this study, I classified all birds recorded into two main ecological traits: habitat preference and trophic functional groups (based on their feeding guild), to investigate the capacity of bird species to contribute to pest control services.

1.5 Further research: challenges and what needs to be done

To summarise, there has been growing interest and discussion about biodiversity conservation and in the role of birds, their trophic functional groups and natural vegetation in providing ecosystem services to agricultural landscapes (Buechley et al., 2015; Engelen et al., 2017; Luck et al., 2012) as a strategy for sustainability. But research on biodiversity loss in Sub Saharan Africa has so far tended to focus on the rapid and extreme loss of diversity through land clearance for tree crops and/or plantations such as oil palm and rubber (Usieta et al., 2013). However, in the tropics a vast amount of land clearance is from subsistence farming which is gradually reducing biodiversity in already degraded and fragmented landscapes. In many African countries, such as Nigeria, this pressure is particularly intense.

Nigeria has the highest human population growth in Africa and is ranked 7th among the top ten most populated countries in the world (WPR, 2019). This means there is a desperate need to increase its food production, of which 80% comes from subsistence farming based on shifting cultivation and the use of simple tools (Lye, 2002). Given these pressures in Africa and the consequent need for continued land clearing for agriculture in a land-sharing framework, this necessitates research that will explore the potential of birds and retained natural vegetation such as native forest fragments in providing ecosystem services in Nigerian farmlands. Here, we therefore use field surveys to provide detailed knowledge of bird communities, biocontrol services provided by birds, and the value of retaining forest fragments to subsistence farmers for their crop plants. This should then contribute to practical and efficient management decisions for both farmers and conservation managers in Africa.

1.6 Thesis structure

This thesis is organised into four major parts, followed by a synthesis of my major findings in a final chapter. Each chapter is written as a stand-alone article which addresses a specific objective or tests specific hypotheses.

In this thesis, I describe the community composition of bird species and investigate the pest control services birds provide to subsistence farmlands that are at varying distances from native forest fragments on the Mambilla Plateau, South Eastern Nigeria. I provide the first comprehensive information from a detailed study on birds on the plateau and their agricultural effects.

1. In Chapter 1, I highlight problems of food security and crop pest severity in Sub-Saharan Africa, I review the literature on birds as ecosystem service providers, and the fate of bird species in Afrotropical montane forest.
2. In chapter 2, I explore in detail the bird community composition on Mambilla forest-agricultural landscape, I compile a two- year data set of bird species in both farmland and forest fragments, and I classify all birds recorded based on two main ecological traits: habitat preference and trophic functional group based on their feeding guild (Bregman et al., 2014). I also investigate the relationship of bird community composition with habitat variables and how the proximity of forest fragments to farmland influences bird composition.
3. In Chapter 3, I investigate the pest control services provided by birds to maize (*Zea mays*) on farms at varying distances from native forest fragments on the Mambilla Plateau. I explore how excluding birds influenced maize crop yield by comparing crop yield in caged (two treatments- i) birds excluded, ii) birds and insects excluded) versus open control plots on maize farms. I also explore to what extent the proximity of farms to forest fragments affected pest control.
4. In Chapter 4, I use plasticine mimics of caterpillars, insect larvae and beetles on experimentally grown crops (groundnuts and bambara nuts) to test whether, and if so, to what extent, pests were being attacked by insectivorous birds, and whether attack rates depend on the proximity of farmlands to forest fragments.
5. In Chapter 5, I provide a synthesis of my major findings, I summarize these findings and identify areas for future research.

1.7 Study area

The Mambilla Plateau in Taraba State Nigeria (7.16°N, 11.66°E) is located in the Cameroon highlands forest ecoregion that is well known for its rich flora and fauna (Figure 1.1), which are among the most diverse in Africa (Arroyo-Lambaer et al., 2018; Olson & Dinerstein, 1998). The plateau, with an average elevation of ∼1650 m asl is characterised by gently undulating hills covered in overgrazed *Sporobilis* grassland (Adewoye et al., 2015), with a loose patchwork of subsistence farms mostly associated with villages and fragments of forest along the sides of streams. Annual food crops grown in the farms include maize (*Zea mays*), ginger (*Zingiber officinalis*), groundnuts (*Arachis hypogea*), kidney beans (*Phaseolus vulgaris*), potatoes (*Solanum tuberosum*), sweet potato (*Ipomoea batatas*) and yam (*Dioscorea bulbifera*). There is a distinct wet and dry season with a mean annual rainfall of 1600 mm (Ezealor, 2002). The minimum average monthly temperature is between 15.5-18.5 ^{0}C and the maximum ranges from 27.5-30.5 ^{0}C (Matthesius et al., 2011). My study area was in farmlands and forest fragments across the Mambilla plateau, I had four study sites on the plateau; Yelwa village, Gembu village and Nguroji village as well as Ngel-Nyaki forest; one of the most floristically diverse montane forests in Nigeria (Chapman & Chapman, 2001), and consequently host to a high diversity of animal species (Chapman et al., 2004). Ngel-Nyaki forest is an important bird area (IBA), as well as being an Endemic Bird Area (EBA) of the Cameroon Mountain range (Ezealor, 2002; Osinubi, 2012). It was identified for the conservation of the Sudan-Guinea Savanna, Guinea-Congo Forest and Afrotropical Highland biomes (Fishpool & Evans, 2001).

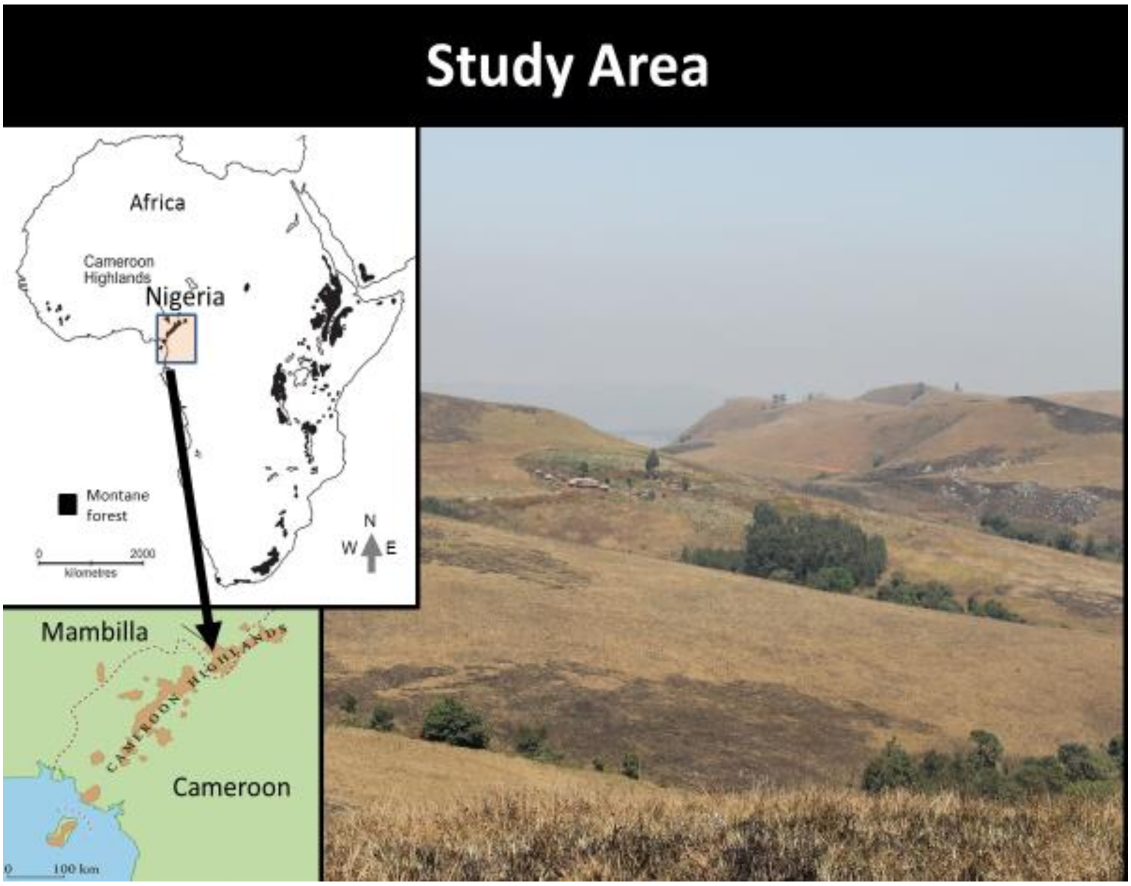

Figure 1: 1. Map of study area showing the forest-farmland landscape of Mambilla Plateau, Nigeria.

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Chapter 2: Bird community composition in the Mambilla forest-agricultural landscape of South East of Nigeria.

Abstract

Forest-agricultural mosaics are common ecosystems across Nigeria. In montane habitats, where the grassland matrix dominates, forest fragments have historically supported a rich diversity of bird species. However, with increasing human population, the forest fragments are becoming smaller or lost altogether; forest habitat is being transformed into farmland. Despite the high probability that bird species and associated ecosystem services are being lost through habitat destruction, bird diversity remains relatively undescribed on the Mambilla Plateau, southeast Nigeria. Here, I assess bird community structure across farmland and forest fragments on the Mambilla Plateau with the aim of providing comprehensive information, to help monitor future rates of change of bird species composition, and to determine a baseline for a study of birds as providers of ecosystem services. I used the point count method to monitor bird species across 32 farmlands and 22 forest fragments. Species were classified based on their habitat preferences and trophic functional guilds, and species composition was explored in relation to habitat type and environmental variables. I recorded a total of 29,451 individual birds comprising 202 species from 59 families. My results show that both farmlands and forest fragments in this area support a high diversity of bird species, with diversity and richness being significantly higher in the forest fragments than farmlands. The proximity of farmland to forest fragment, number of trees, and trees in fruit, were important predictors of bird community structure. Insectivorous bird species were a key trophic functional group in farmlands, suggesting that these species may play a role in pest control. Finally, my results demonstrate the dependence of the bird community on the forest fragments and show that subsistence farmlands may contribute little to supporting forest specialist birds in this region. This study emphasises the importance of forest fragments in conserving biodiversity for the provision of ecosystem services.

2.1 Introduction

Globally, the fragmentation of forest is a dominant human impact, with major implications for ecosystem conservation (Bregmanet al., 2014). Every year, thousands of new fragments are created in the tropics (Sodhiet al., 2011), resulting in millions of hectares of fragmented forests (Taubert et al., 2018). Rural areas with high human populations that rely on subsistence farming are especially prone to forest fragmentation and loss (Donald, 2004;

Wright, 2005). Previous studies have shown that a vast amount of land clearance for subsistence farming is reducing the tropical biodiversity in already degraded and fragmented landscapes (Gibson et al., 2011; Laube et al., 2008; Laurance et al., 2018; Laurance & Peres, 2006). According to a range of forecasts, these processes are likely to increase as the growing demand for food increases pressure on land over the next century (Godfray et al., 2010; Mclaughlin, 2011).

In Afromontane areas however, the situation is slightly different. Here, palynological evidence suggests that the grassland matrix has dominated since the Pleistocene (Lézine et al., 2019). Thus pre-human occupation, Afromontane forests were likely always restricted to relatively small patches close to streams or on steep slopes protected from fire (Adie et al., 2017; Meadows & Linder, 1993). However, humans have likely increased fragmentation and reduced forest fragment size, or totally cleared natural fragments since the occupation of such areas. On the Mambilla Plateau, anthropogenic fire, grazing, and farming, have been responsible for most of the more recent forest destruction (Richard, 2014). As elsewhere then, faced with the challenge of preventing biodiversity loss and maintaining ecosystem function in increasingly fragmented landscapes (Bregman et al., 2014), it is essential to assess biodiversity composition and identify species with different ecological roles within these landscapes (Lewis et al., 2013).

Birds offer a suitable system for understanding species composition and community structure within an ecosystem (Whelan et al., 2015). This is because they are conspicuous and well known compared to other vertebrate groups, occupy a variety of niches and are highly specialized; they perform key ecological functions e.g. pollination and pest control (as reviewed in Chapter 1 of this thesis; Bregman et al., 2014; Van Bael, Brawn, & Robinson, 2003; Whelan et al., 2015). They also provide the most comprehensive dataset of inter-specific variation in functional traits (Vander Wall, 2010).

2.1.1 Agricultural landscapes as habitat for birds

The conservation value of tropical agricultural landscapes is being increasingly recognized (Greenberg et al., 2008; Perfecto & Vandermeer, 2008), and this is important because agriculture makes up over 38% of global land cover (WBG, 2016). There are, therefore, a growing number of studies of bird composition and community structure in tropical agroforests e.g. coffee and cocoa plantations, and the value of agroforests as bird habitat (Buechley et al., 2015; Perfecto & Vandermeer, 2008; Perfecto et al., 2004; Tscharntke et al., 2008). Most of these studies have shown that agroforests provide habitats for a variety of bird species normally associated with forest habitats. Hence agricultural lands are an important component for biodiversity conservation (Buechley et al., 2015; Perfecto & Vandermeer, 2002; Sekercioglu, 2012; Thiollay, 1995). However, these studies have disproportionately focused on agroforestry (a farming technique that combines a mixture of trees, crops and shrubs that results in an agroforest), with little or no data from subsistence farmlands on the benefits of these farmlands as habitats for birds. Therefore, there is a lack of information on the general patterns of bird species composition in other tropical agricultural landscapes, particularly in Nigeria. The global synthesis of these studies is important for estimating any changes in bird communities and for improving tropical bird conservation (Sekercioglu, 2012).

Many factors influence bird assemblages in tropical forest-agricultural landscapes, e.g. habitat variables; number of trees, percentage canopy cover, tree height, trees in fruits and proximity to other habitat types (e.g. distance to nearest forest; Greenberg et al., 1997; Harvey et al., 2006; MacArthur & MacArthur, 1961; Van Bael et al., 2007). For example, agroforest with high trees, particularly when native tree species are present, harbour relatively high bird diversity, which is valuable for biodiversity conservation (Gove et al., 2008; Van Bael et al., 2007). However, to what extent this holds for Nigerian subsistence farmlands is largely unknown, thus more studies are required from a wider range of agricultural lands to know which retained habitat variables aid bird conservation.

2.1.2 Bird trophic functional groups

Recent studies in tropical forests have reported a decrease in the functional integrity (functional groups) of bird communities, associated with human disturbace and forest fragmentation (Banks-Leite et al., 2012; Coelho et al., 2016; De Coster et al., 2015; Şekercioḡlu et al., 2002). However, in tropical agricultural landscapes, most studies focus only on bird composition and community structure, with little attention to foraging guilds and/or conservation status of bird communities. Classifying birds into trophic functional groups based on their foraging guild may aid in the understanding of their functional roles (Ghazoul & Hellier, 2000). Evaluating foraging guilds may also increase understanding of the conservation status of different guilds. This is because the different functional groups may respond differently to disturbance (e.g. land clearing for subsistence farming and forest fragmentation; Latja et al., 2016). For example, insectivorous birds are particularly sensitive to habitat fragmentation (Tobias et al., 2013; Yong et al., 2011), and a decline in these birds is thought to result in increased herbivory from insects in farmlands (Skoczylas et al., 2007;

Whelan et al., 2015). On the other hand, granivorous species prefer disturbed and open habitats (Buechley et al., 2015). Naidoo (2004) reported that frugivorous birds may be found in close proximity to forest areas. This is important for forest regeneration as well as dispersal of seeds of forest tree species into agricultural land (Chapman & Chapman, 1999), because large frugivores are also sensitive to forest fragmentation (Terborgh et al., 2008), which can limit seed dispersal and the potential for forest regeneration (Bovo et al., 2018). Clearly, understanding the distribution patterns of birds feeding guilds needs further investigation in the tropics, particularly in Africa, before concluding on the overall ecological integrity of tropical birds and tropical forest-agricultural landscapes. Hence, it is essential to evaluate and identify the foraging guild structure within these landscapes, to be able to advise farmers on the conservation importance of bird species utilising their farms, e.g. (Komar, 2006), as well as the need to conserve the remnant forest fragments.

With increasing land clearance for crop production in Nigeria, it is also vital to evaluate the impact of habitat loss and fragmentation on biodiversity generally. Studies elsewhere in the world have shown that habitat loss and fragmentation pose a significant threat on species composition, community structure and ecological functions of biodiversity (Scolozzi & Geneletti, 2012; Sekercioglu et al., 2007), reducing vital biological processes (Sigel et al., 2010). However, whether particular species are consistently more likely to disappear after fragmentation remains unclear (Sekercioglu et al., 2007).

The mountains of south-eastern Nigeria are a western extension of the Cameroon mountains (Manu et al., 2010), and are classified as an endemic bird area (EBA; Fishpool and Evans, 2001). Bird composition includes species that are classified by International Union for Conservation of Nature (IUCN) as globally endangered (A1), range-restricted (A2) and biome-restricted (A3) species (Ezealor, 2002), for which conservation action is required. However, previous bird studies on the Mambilla plateau have been limited to single species e.g. Turacos (Babalola et al., 2012), Boubous (Osinubi, 2012) and Sunbirds (Nsor, 2014). One or two studies have produced a species checklist, e.g. (Disley, 2003). Compared with the rest of Africa e.g. (Deikumah et al., 2017; Engelen et al., 2017; Mulwa et al., 2012), relatively little is known about whether land clearance from subsistence farming is reducing the number of bird species in this area. Therefore, there is a clear need for further study to monitor the population trend of bird species, as well as identify conservation problems.

In this study, I compile a two-year data-set of bird species, their habitat preferences and their trophic functional groups, so that future studies can assess changes in bird community patterns as human populations and development increases.

2.1.3 Aim and objectives

My first objective was to describe the composition structure of the bird community within the Mambilla forest agricultural landscape and to list all bird species associated with farmlands and forest fragments as either ‘farmland’, ‘forest fragment’, or ‘generalist’ species (i.e. those which depend on both habitats). Secondly, I sought to classify birds into trophic functional groups (hereafter referred to as TFG) based on diet, and to identify groups potentially active in pest control (See Chapters 3 and 4). Lastly, I test how habitat variables and proximity to forest fragments affect the bird community structure using a linear mixed-effect model. Due to a lack of previous reports on bird composition, bird community structure and bird trophic function groups on the Mambilla Plateau, this chapter is principally descriptive and will serve as a baseline for future studies, as well as provide the background and context for later chapters in this thesis.

I describe;

1. Bird species diversity and species richness across farmlands and forest fragments
2. Bird community structure using non-metric multidimensional scaling (NMDS) ordination plots in terms of bird diversity and richness data from both farmlands and forest fragments and bird trophic functional group (McCune et al., 2002). The above approach aims to characterize the community composition of birds in forest fragments versus species in subsistence farmlands, and assess whether farmlands can enhance, complement, or are simply different from aspects of, forest biodiversity in agricultural areas and vice-versa.
3. The relationships between bird community structure and selected habitat variables, and how the proximity of forest fragments to farmland influences bird community composition.

2.2 Materials and methods

2.2.1. Study area

My study site was on the Mambilla plateau in Taraba State (7.16°N, 11.66°E) SE Nigeria. The entire plateau has an area of 3100 km² and is characterised by distinct wet and dry seasons with a mean annual rainfall of 1600 mm (Ezealor, 2002). The minimum average monthly temperature is between 15.5 ^{0}C - 18.5 ^{0}C and the maximum ranges from 27.5 ^{0}C -

30.5 ^{0}C (Matthesius et al., 2011). With an average elevation of ~1650 m asl, the Plateau is characterised by gently undulating hills covered in overgrazed *Sporobilis* grassland, with a loose patchwork of small subsistence farms mostly associated with villages, and fragments of forest scattered around the plateau. Annual food crops grown in the farms include maize (*Zea mays*), ginger (*Aframomum melegueta*), groundnuts (*Arachis hypogea*), kidney beans (*Phaseolus vulgaris*), Potatoes (*Solanum tuberosum*) and yam (*Dioscorea rotundata*). A detailed description and map of the study area is shown in the preceding chapter, while the locations of my surveyed sites are illustrated on the map below. The sites were farmlands and forest fragments in Yelwa village, Gembu village and Nguroji village as well as Ngel-Nyaki forest.

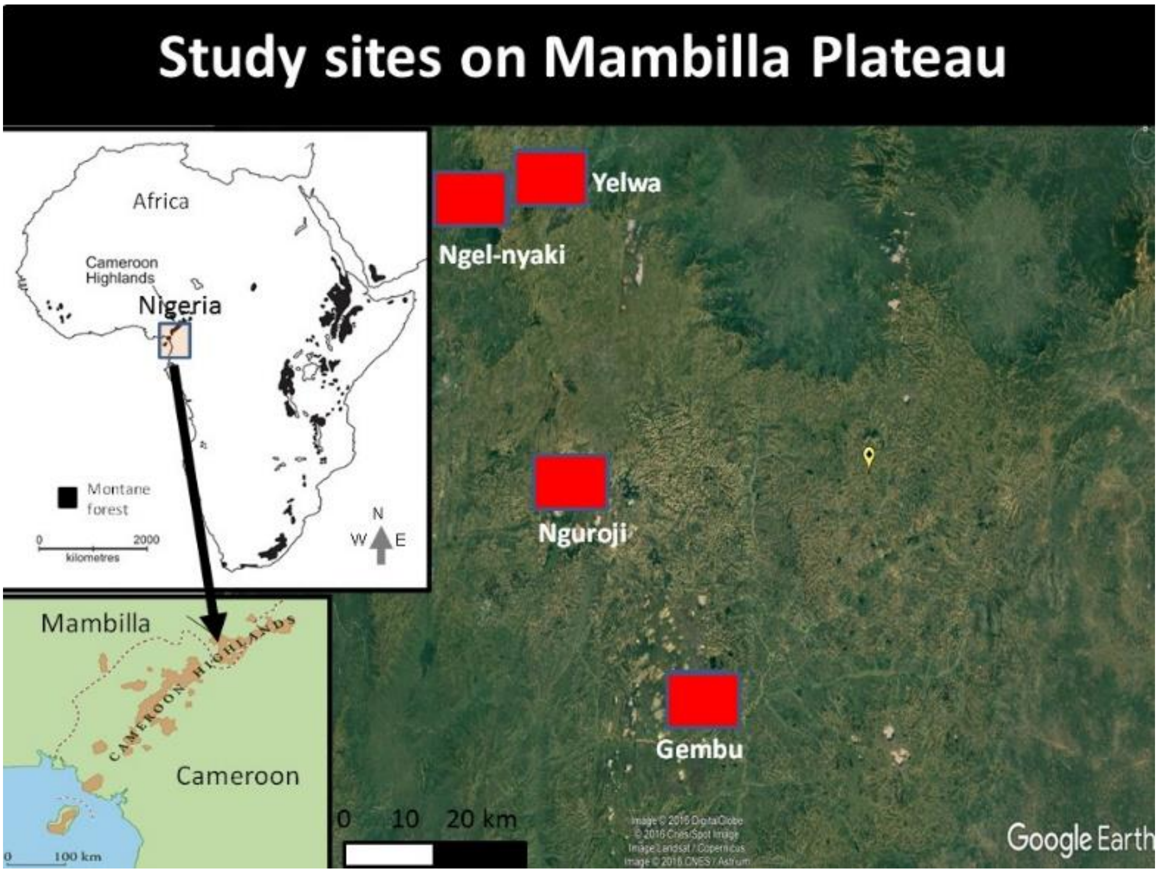


Figure 2. 1: Map of study area showing the location of study sites. Red squares show the position of study sites.

2.2.2 Selection of farmlands and forest fragments

Farmlands (cropped potions of the landscape develop by man) and forest fragments were selected close to Yelwa village, Gembu village and Nguroji village, as well as Ngel-Nyaki forest reserve, to ensure a representative sample of farms close to, and far away from forest fragments. No maps of sufficient detail were available of the area. The selection of study sites (Figure 2.1) was based on the availability of both farmlands and forest fragments in the area. I concentrated on the staple crop, maize (*Zea mays*) in all farmlands, because it was difficult to find farmers with mixed crops who were willing to partake in the study.

2.2.3 Bird identification

Within each farmland and forest fragment, I sampled birds using the point-transect method (Buckland et al., 2001; Burgess et al., 2000) between 6:00 and 11:00 am daily from September 2016 to December 2018. Five transects, each 500m long and spaced at 100m intervals were laid in each farm and fragment (making five points on each of the transect). At each point, I spent 10 minutes on focal observation for birds, and recorded the number of individual bird species within a 25 m radius (O'Connell Jr et al., 1999). All bird species were identified using a guide to the birds of western africa (Borrow & Demey, 2001), and expert help (*pers communication* with Ulf Ottoson).

2.2.4 Birds habitat preference and bird trophic functional groups (TFG)

I classified all birds recorded based on two main ecological traits: habitat preference and trophic functional group (feeding guild; Bregman et al., 2014). I assigned each species to habitat categories according to whether they were detected in: (i) farmland (ii) forest fragments or (iii) in both farmland and forest fragments (generalist species). I used the field guidebook Birds of Western Africa (Borrow & Demey, 2001) to confirm if these birds were observed in their primary habitats. Each bird species was further assigned to one of nine trophic functional groups based on diet: insectivores, granivores, frugivores, nectarivores, piscivores, carrion eaters, omnivores, carnivores and generalists (Appendix 2.4) as described from the literature (Borrow & Demey, 2001; Wattel, 1993). Dietary groups represent the primary diet, with species categorised as omnivores if no primary diet was apparent as suggested by Bregman et al. (2014).

2.2.5 Measurement of farmland and fragment habitat variables

For each point on each transect described above (647 points in total), the following habitat variables were measured within a 20 x 20 m quadrat: number of trees (defined as plants that are >=2m tall); tree height; percentage of tree canopy cover; number of shrubs (i.e. plants that are < 2m tall); percentage of trees in fruit; percentage of trees in flower. I also measured the distance of each point transect in farmland from the nearest forest fragments using a GPS (Garmin eTrex Summit). The distance to forest fragments ranged between 101 to 1001 m.

2.2.6 Data analyses

I analysed all data using R statistical software. Model selection for all analyses was carried out using the information theoretic approach based on Akaike's Information Criterion (AIC; Burnham & Anderson, 2003). Once with diversity as dependent variable and once with species richness as dependent variable. Residuals were checked for violation of model assumptions in all cases. In all cases, a statistical significance level of $p < 0.05$ was used to reject the null hypothesis.

1. I calculated the means and standard errors of bird species attributes and habitat variables of the farmlands and forest fragments. I used a Kruskall-Wallis one-way ANOVA to check for variation in detectability of representative species in both habitats. The bird species chosen for this test were selected based on their total abundance (only species with a total abundance of ≥ 200 individuals recorded were used; Appendix 2.2).
2. I calculated Shannon- Wiener diversity index, *H*, for birds in both habitats as well as for each point transect (131) across both habitats; farmland and fragments. I used generalized linear models with bird diversity and bird species richness as dependent variables to determine if diversity index was dependent on habitat type, habitat variables and distance from forest fragment.
3. I modelled separately, bird diversity and species richness as a function of habitat variables and distance to forest using general linear mixed effects models; I included site as a random effect to account for any spatial autocorrelation, with habitat variables and distance as fixed effects.
4. I used the Non-Metric Multidimensional Scaling (NMDS) ordination to organize sampling points by similarity in species composition. I used the bird diversity, richness and trophic functional group data from the two habitats; farmland and forest fragment and classified the birds' community into a 2-dimensional axes plot (NMDS 1 and NMDS 2). NMDS functions in an interactive manner by minimizing the difference ('stress') between distance in the original matrix and distance in the reduced ordination space. NMDS has been used in tropical bird community analyses (Luck & Daily, 2003; Naidoo, 2004), and is the ordination method of choice for most community ecology applications (McCune et al., 2002).

5. I then used each axis (which represents the community composition) of the NMDS to explore how each was correlated with the habitat variables using general linear models assuming a normal error structure in order to fully describe the biological meaning (i.e. which habitat variable correlates with bird composition and TFG) of the two NMDS axes derived.

2.2.7 Species effort curves

Species accumulation curves illustrate how the number of species in an area surveyed increases with the effort put into observations (Figure 2.2). The curve illustrates that new species were added more quickly at the beginning of observations, but as section lengthened, the number of new species added decreased. The curves approached an asymptote suggesting that almost all species were recorded in both farmlands and forest fragments. I recorded 132 species in the first field season (September 2016 - November 2017), and 70 additional new species were added during the second field season (December 2017- December 2018) as shown in (Figure 2.2), giving an overall total of 202 species. The red arrows show the increase in species number caused by adding data from the second field season which was during the rainy season, and so included species which were not vocal during the dry season.

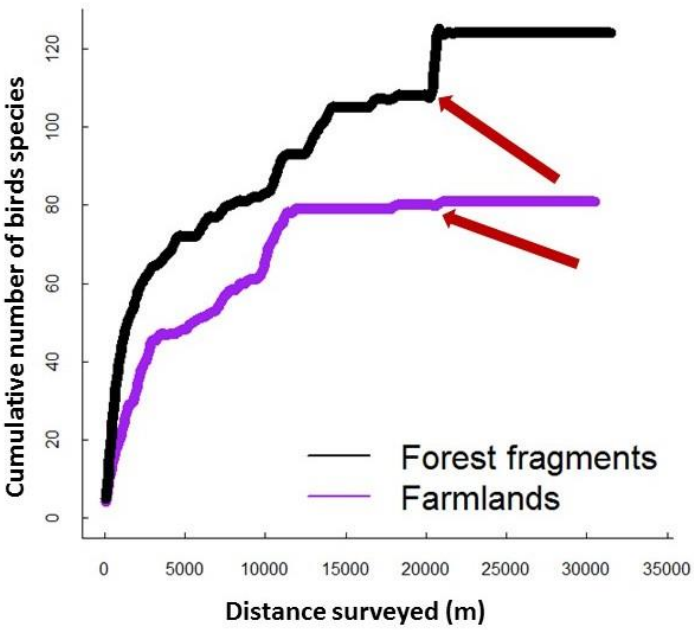


Figure 2. 2: Species-effort curves showing bird species accumulation in the two habitats, farmland and forest.

2.2.8 Test for bias due to detectability

The Kruskall-Wallis one-way ANOVA showed that all species have similar detectability across the two habitats (Appendix 2.2), except for three species; common bulbul (Pycnonotus barbatus) double-spurred francolin (*Ptemistis bicalcaratus*) and banded martin (*Neophedina cincta*). Suggesting that patterns of detectability are the same regardless of any differences in absolute abundance across the two habitats.

2.3 Results

Overall, I surveyed 32 farmlands and 22 forest fragments, sampling 131 transects with 647 points: Yelwa village 270 points, Nguroji village 217 points, Gembu village 40 points, Ngel-Nyaki forest 120 points. A total number of 29,451 individual birds comprising of 202 species from 59 families were recorded (Appendix 2. 4); farmlands: 130 species, forest fragments: 194 species, both farmland and forest fragments: 122 species, farmland only: 10 species and fragments only: 70 species (Appendix 2. 1). I classified these birds into their preferred habitats (see Appendix 2.1 for habitat preferences), and into their trophic functional groups (TFG) based on their primary feeding guild (Table 2.4; Appendix 2.4). Eight of the species recorded are listed by the International Union for Conservation of Nature (IUCN) as requiring conservation action. These include: the hooded vulture (*Necrosyrtes monachus*), and white-backed vulture (*Gyps africanus*), which are critically endangered (CE), yellow-footed honeyguide (*Melignomon eisentrauti*), Cameroon mountain greenbul (*Arizelocichla montana*) and bangwa warbler (*Bradypterus (lopezi) bangwaensis*) listed asnear threatened (NT); woolly-necked stock (*Ciconia episcopus*), Bannerman's weaver (*Ploceus bannermani*), and broad-tailed grassbird (*Schoenicola platyurus*), which are listed as vulnerable (VU).

A comparison of the mean species diversity, richness and habitat variables across habitats showed that farmland had lower bird species diversity and richness than the forest fragments. Similarly, means of measures of habitat variables were lower in farmlands compared to the forest (Table 2.1).

Table 2. 1: The mean (± SE) of bird species attributes and habitat variables per 20 x 20 m quadrat in the farmland and forest fragments.

Parameters	Farmlands (32 farmlands)	Forest fragments (22 forest fragments)
Species richness	48.09 ± 0.17	70.15 ± 0.11
H Diversity index	3.42 ± 0.004	3.74 ± 0.002
Number of trees	8.03 ± 0.24	34.44 ± 0.26
Number of shrubs	3.75 ±0.11	11.91 ± 0.12
Height of trees (m)	0.91 ± 0.25	2.67 ± 0.02
Proportion of trees in fruits	1.31 ± 0.69	7.53 ± 0.13
Proportion of flowering plant	2.72 ± 0.11	15.65 ± 0.14
Percentage of canopy cover	6.56 ± 0.19	23.45 ± 0.21

2.3.1 Bird species diversity and habitat variables

The Shannon-Wiener diversity index, H for farmland was 3.42 and for forest fragments 3.74 (Table 2.2). Distance of farmland from forest fragment was a predictor of species diversity, showing a positive relationship with mean bird diversity (Table 2.2). The proportion of trees in fruit was also a positive predictor of bird species diversity, but was not statistically singinificant.

Table 2. 2: Relationship between species diversity and habitat variables between farmlands and forest fragments.

Variables	Estimate	SE	T-value	P-value
(Intercept)	3.57	0.071	50.18	**<0.001**
Distance to forest	0.000029	0.000010	2.85	**0.006**
Proportion of trees in fruits	0.00017	0.00023	-0.76	0.447

Note: Best model: Bird species diversity = distance + trees in fruits, random=~1|site, method="ML"). The second-best model had a higher AIC value by 1.422. P values in bold represent statistically significant values

2.3.2 Bird species richness and habitat variables

There was a significant difference in the species richness between farmlands and forest fragments (Table 2.3). Height of trees, number of trees, and proportion of flowering plants were predictors of species richness when controlling for site (Table 2.3). Distance, the proportion of trees in fruit, and percentage canopy cover, each showed a significant negative relationship with mean bird species richness (Table 2.3)

Table 2. 3: Relationship between species richness and habitat variables across both farmlands and forest fragments.

Variables	**Estimate**	**SE**	**T-value**	**P-value**
(Intercept)	46.64	2.84	16.3	**<0.001**
Forest fragments	18.65	3.5	5.3	**<0.001**
Distance to forest	-0.0015	0.001	-3.1	**0.002**
Proportion of trees in fruits	-0.025	0.01	-2.2	**0.029**
Proportion of flowering plant	0.027	0.01	2.6	**0.010**
Percentage of canopy cover	-0.037	0.01	-2.9	**0.003**
Height of trees (m)	0.51	0.07	7.1	**<0.001**
Number of shrubs	-0.001	0.01	-0.1	0.93
Number of trees	0.17	0.011	15.4	**<0.001**

***Note*:** The full model: Bird species richness = habitat types + distance to forest + proportion of flowering plant + percentage of canopy cover + height of tress + number of shrubs + number of trees + trees in fruits, random=~1|site, method="ML"). Farmland was set as the intercept. P values in bold represent statistically significant values

2.3.3 Bird community structure

(i) Bird species composition

Non-metric multidimensional scaling (NMDS) resulted in a 2-axis optimal solution (NMDS 1 and NMDS 2), with a stress value of 0.02, indicating a good fit (Buttigieg and Ramette, 2014). The NMDS ordination plot had 131 point transects; each point on the plot representing one point transect from either farmland or forest fragment. Point transects that are closer to each other on the ordination plot have a more similar bird composition than transects which are far away from each other on the plot (Figure 2.3). The distribution of point transects according to the two habitats (farmland and forest fragment) in the ordination plot, indicates that bird community structure can be summarized in terms of dissimilarities and overlap in bird assemblages along 2-axes scores with positive and negative values. The positive scores of NMDS1 and NMDS 2 can be thought of as a gradient of forest fragments species indicative of true forest communities, while the negative scores are indicative of grassland species (Figure 2.3). Forest species like the tropical boubou (*Laniariusae thiopicus)* were recorded at point transects that clustered to the right of the NMDS 1, NMDS2 axis; grassland species like the yellow bishop (*Euplectes capensis)* and yellow-throated long-claw *(Macronyx croceus)* were recorded at point transects that cluster to the left of NMDS 1, NMDS 2 axis.

(ii) Bird trophic functional groups

The NMDS ordination plot revealed that bird species clustered according to their trophic functional groups. I recorded nine trophic functional groups in this study as shown in Table 2.4. Forest species; carnivorous, omnivorous, carrion eaters, piscivorous, frugivorous and nectarivorous species were mostly observed in the forest fragments. Interestingly, I recorded several frugivorous species in the farmlands as well (Table 2.4). More grassland species, mostly granivorous and generalists, were recorded in the forest fragments than in farmlands. Insectivorous species were more abundant in both farmlands and forest fragments; comprising about 35% of all recorded in farmlands and about 50% recorded in forest fragments. The insectivores showed an overlap; dispersed across the farmlands and the forest fragments (i.e. insectivorous species depend on both habitats; Figure 2.3). The overlap between some of the point transects in the farmlands with some point transects in the forest fragments could be attributed to the presence of insectivorous, frugivorous, nectivorous and granivorous species observed at these points (Figure 2.3).

Table 2. 4: Trophic functional group of bird species

Trophic functional group	Farmland	Forest fragments	Farmland only	Forest fragment only	Total
Insectivores	61	99	4	42	103
Granivores	12	29	2	17	29
Nectarivores	3	8	1	5	8
Frugivores	20	29	0	9	29
Carrion eaters	1	12	0	11	12
Omnivores	3	3	0	0	3
Generalists	3	4	0	1	4
Carnivores	3	10	1	7	10
Piscivores	4	3	2	0	4

Note: Farmland; species that occur in farmlands, Forest fragments; species that occur in forest fragments, Farmland only; species that occur only in farmlands, and forest fragments only; species that occur only in forest fragments.

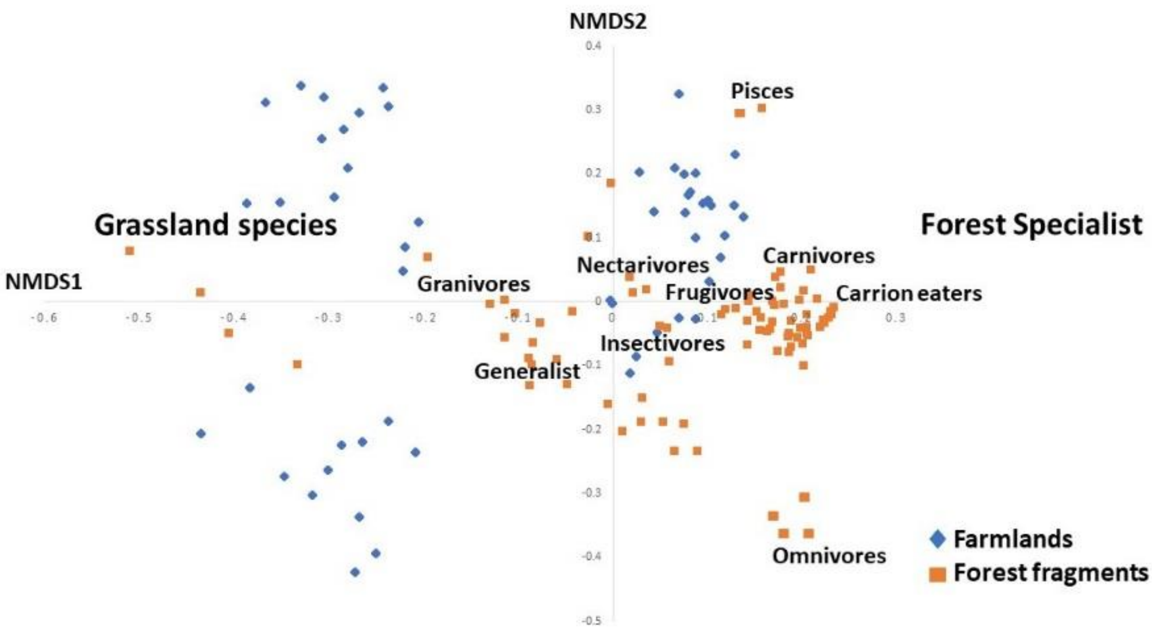
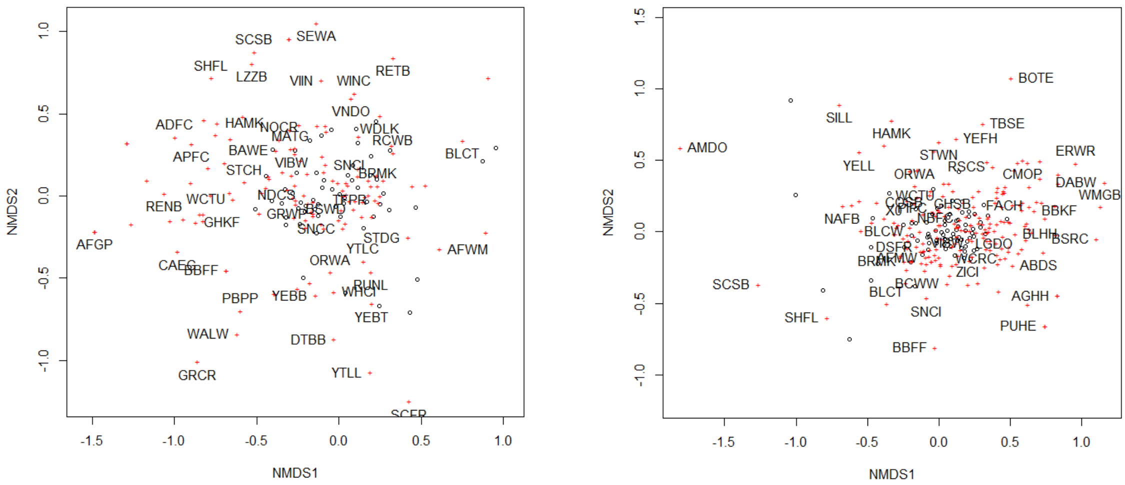


Figure 2. 3: Non-metric multidimensional scaling (NMDS) of bird community structure showing the distribution of bird composition and trophic functional groups on an ordination plot. All the surveyed points are plotted according to their position in a 2-dimensional view of habitat, with axes derived from the NMDS analysis.

A species ordination plot shows the different species that occurred commonly in the different habitat types and in particular, the preponderance of insectivorous species that were recorded in both farmlands and forest fragments (Figure 2.4). For example, singing cisticola (SNCI), African moustached grass-warbler (AFMW), African shrike-flycatcher (SHFL), black-crowned tchagra (BLCT), oriole warbler (ORWA). Species occurring close together on the ordination plots were species that were recorded at the same point transect (Figure 2.4).



(a) **(b)**

Figure 2. 4: Ordination plots of some of the most common bird in both farmlands and forest fragments. (a) bird species in farmlands, and (b) bird species in forest fragments (see legend for species codes in Appendix 2. 3).

(iii) Relating bird community structure to habitat variables

Bird species composition showed a significant dissimilarity along NMDS1 ($F_{7,123}$ = 8.40, P < 0.0001; Figure 2.3), with the distance of point transects in farmland from forest fragments influencing the community structure, as seen in its negative relationship with NMDS1 (Table 2.5). Similarly, bird species communities showed significant dissimilarity along NMDS2 ($F_{7,123}$ = 3.96, P < 0.001; Figure 2.3 and Table 2.5) with the proportion of trees in fruit positively influencing the bird community structure while the height of trees had a negative effect on bird community structure.

Table 2. 5: The relationship between the NMDS axes scores and each habitat variable and distance from forest fragment.

	NMDS1			NMDS2		
Variables	**Est. ± S.E.**	**t**	**p**	**Est. ± S.E.**	**t**	**p**
Intercept	-4.46 ± 1.76	-2.5	**0.001**	4.05 ± 1.45	2.8	**<0.001**
Distance to forest	-9.84 ±4.5	-2.2	**0.003**	-4.036 ±3.67	-1.1	0.27
Proportion of flowering plants	-6.89± 1.34	0.5	0.61	-1.49 ± 1.10	-1.4	0.18
Percentage of canopy cover	-3.35±1.70	-0.2	0.84	1.56 ± 1.39	1.1	0.27
Height of tress (m)	1.38 ± 9.63	1.4	0.16	-1.99 ± 7.94	-2.5	**0.013**
Number of shrubs	2.64 ± 1.49	1.8	0.078	9.89±1.23	0.8	0.42
Number of trees	1.93± 1.45	1.3	0.19	-7.21 ± 1.22	-0.6	0.56
Proportion of trees in fruits	8.23 ± 1.28	0.6	0.52	1.95 ± 1.052	1.8	0.066

Note: Model structure: MDS = distance to forest + proportion of flowering plant + percentage of canopy cover + trees height + shrubs density + trees density + proportion of plants in fruits. N=131. Adjusted R squared; NMDS1 = 0.29 and NMDS2 = 0.14. P values in bold indicate a statistically significant difference.

2.4 Discussion

The data presented in this chapter provides an overview of the bird communities of the Mambilla Plateau forest-agricultural landscape, including their trophic functional groups and habitat preferences. Previous bird studies on the Mambilla plateau have been either short term surveys (e.g. Disley, 2003; Hall and Leventis, unpublished), or species-specific surveys, e.g. (Babalola et al., 2012; Osinubi, 2012). Even combined, the data generated from these studies provide only a small amount of information about bird species communities in this Afrotropical montane region. My study, therefore, presents some of the first quantitative information from an extensive study of birds on the Mambilla plateau. I show that overall, the subsistence farmlands and forest fragments of this area support a high diversity of bird species, but that there are significant differences in the relative abundance of some bird species in the farmlands as compared with forest fragments, which may indicate the importance of forest fragments for particular groups of birds.

An interesting observation from my survey is the fact that most of the birds recorded on farmlands were foraging. Although the identity of particular food items eaten by the birds was often difficult to confirm, some of the birds were feeding on insects. I observed the common bulbul (*Pyconotus barbatus*) feeding on ground-dwelling insects (black ants), and the little bee-eaters (*Merops pusillus*) and the Cisticolas (in large numbers) feeding on insects in the farmlands. The yellow-fronted canary (*Crithagra mozambica*) was observed mostly at the edge of farmlands, foraging from tall grasses. Because most of the important ecosystem services that birds provide result from their foraging behaviour (Wenny et al., 2011), it is likely that the bird species recorded in the farmlands contribute to important ecosystem services (e.g. insect pests control) as suggested elsewhere in East African farmlands (Ndang'ang'a, Njoroge, & Vickery, 2013). Importantly, from opportunistic discussion with some of the farmers, the farmland birds are not considered to be agricultural pests because they do not cause significant damage to maize or other crops.

2.4.1 Bird diversity and richness

I recorded higher bird diversity and species richness in the forest fragments than in the farmlands. My findings corroborate those of several similar studies elsewhere that have compared bird community composition between agricultural and forested areas (Daily et al., 2001; Estrada et al., 1997). For example, Daily et al., (2001) reported more bird species in forest fragments than in agricultural areas in Costa Rica and attributed this to land use intensification. Such an effect is likely linked with the fact that forest fragments provide more resources (e.g. food, cover, nesting and breeding sites) for birds than do farmlands (Maas et al., 2016). Moreover, several reports from studies in forestry and agro-ecosystems show a significant correlation between habitat variables (e.g. plant species richness) and bird species richness (Şekercioḡlu et al., 2002; Waltert et al., 2005).

A reason for the low bird species richness in farmlands compared to the forest maybe that most subsistence farmlands are annually cultivated, thus requiring yearly tilling of the soil, which may reduce secondary succession and make the habitat more homogenous and unable to support a wide range of species. I noted that bird species richness increased with higher tree density and proportion of flowering plants, and decreased with increasing distance of farmlands from forest fragments, suggesting that these habitat variables may be important factors associated with higher bird species richness. The observed pattern is consistent with the “habitat heterogeneity hypothesis” which predicts that high structural vegetation provides habitat for birds, and thus support high species diversity (MacArthur & MacArthur, 1961; Tews et al., 2004).

A previous study in an Afrotropical montane region in western Kenya showed that the conversion of structurally heterogeneous subsistence farmlands to monocultures results in a decline in bird diversity by 30% (Mulwa et al., 2012). Other studies in the tropics have shown that farmlands only support a few forest specialists in the absence of nearby forest (Greenberg et al., 2000; Waltert et al., 2005). These findings emphasize the importance of the Afrotropical montane ecosystem, and particularly forest fragments, in conserving biodiversity. I, therefore stress the necessity of a continuous monitoring scheme for the conservation of birds, as well as maintaining the forest patches on the Mambilla plateau.

Contrary to the findings of my study, previous studies carried out in montane regions of East Africa reported higher density and species richness of birds in farmlands compared to forest habitats (Engelen et al., 2017; Gove et al., 2013; Mulwa et al., 2012). In these studies, it was suggested that the complex mosaic structure of the subsistence farmlands (high structural diversity; farmlands which comprised forest galleries, windbreaks, marshy streams, and different crops), contributed significantly to its high bird diversity. Conversely, subsistence farmlands in West Africa are mostly homogenous and may therefore be less able to support a wide range of species. As such, differences in structural diversity, particularly in tropical farmlands, may have a strong influence on bird diversity (Laube et al., 2008; Sekercioglu et al., 2007). This discrepancy suggests that the distribution of bird diversity in tropical forest-farmland mosaics is highly context-dependent.

Importantly, the studies referenced above all demonstrate that generally, habitat variables and/or vegetation structural diversity correlates somewhat with bird diversity and richness, both in farmland and forest habitats. Therefore, growing tall trees within tropical farmlands and retaining forest remnants in agricultural land may enhance biodiversity (Daily et al., 2001; Hughes et al., 2002); a phenomenon observed in the Amazonian rain forest fragments e.g. (Laurance et al., 2018; Wolfe et al., 2015). Laurance et al. (2018) showed that the regrowth of secondary forest in the Amazon lessens the effects of fragmentation for some species. Similarly, secondary forest regeneration resulted in the recolonization of some species of insectivorous birds that had formerly disappeared from fragments (Stouffer et al., 2011), and the rate of local extinction of birds has also declined (Stouffer et al., 2009).

In my study, bird diversity was also high in farmland where the diversity index (H) was 3.42. One explanation is that some of the forest species were also foraging in farmland (see Appendix 2.2). Therefore, farmlands (regardless of their lower diversity when compared with the forest fragments) also attract bird species that contribute to the overall diversity of bird species on the Mambilla forest-agricultural landscape. My results confirm the findings of Sekercioglu (2012), who showed that about 30% of bird species mostly use farmlands, especially in forest-agricultural landscapes. Similarly, Estrada et al., (1997), reported that 80% of the 226 species recorded during a survey at Los Tuxtlas, Mexico, were found in agricultural habitats. These authors attributed this to the additive effect of bird species recorded in several distinct habitats that together made up the agricultural landscape. Thus, it may be important to incorporate small-holder agricultural lands into conservation policies.

2.4.2 Bird community structure and bird trophic functional groups

The NMDS ordination plot shows some clear distinctions in bird species composition between forest and farmland. For example, red shouldered cuckoo shrike (*Campephaga phoenicea*), western piping hornbill (*Bycanister fistulator*) and western mountain greenbul (*Arizelocichla tephrolaema*), were never recorded outside of the forest and may be forest specialists. Others such as green crombec (*Sylvietta virens*) and chubb's cisticola (*Cisticola chubbi*), were only recorded from farmland, but they may need the forest to complete their life history stages. Several species however spent time in both forest farmland and many of these depend on forest for nesting, illustrating the importance of forest fragments for these species. These results show that the overall bird community of the Mambilla plateau together use both habitat types, and that the subsistence farmlands may be minimally important for forest specialist birds (particularly forest-dependent species) in this region. Although the farms provide important habitat for many species (as shown by its species richness), the habitat is different from the forest (e.g. more homogenous) and does not provide suitable habitats for all forest species (Pearman, 2002; Sekercioglu, 2012). Moreover, the presence of forest-dependent species in farmlands, e.g. white-crested turaco (*Tauraco leucolophus*) (endemic to this region) and tropical boubou (*Laniarius aethiopicus*), may not indicate the actual suitability of the farmlands to sustain these species without surrounding forest (Naidoo, 2004).

Frugivores were more common in the forest fragments than in farmlands. Nevertheless, 20 species out of the 29 frugivorous bird species were also recorded in farmlands. This is significant and may be of economic importance to the maize crops, because some frugivorous species may switch to other food resources (e.g. insect pests), to overcome periods of low resource availability (Lehouck et al., 2009; Mulwa et al., 2013).

Most of the carrion eaters and carnivores were absent from the farmlands, signifying that farmlands have a limited capacity to compensate for forest loss for these groups (Laube et al., 2008). Therefore, given the high and increasing rate of forest clearance for farming on the Mambilla plateau, these species could be driven to extinction, which further highlights the importance of conserving the forest fragments. This is consistent with the results of other studies from Costa Rica (Daily et al., 2001), Cameroon (Waltert et al., 2005), and Kenya (Mulwa et al., 2012), all of which conclude that up to 75% of species may be lost if forest is converted to agricultural lands in the tropics.

The proportion of nectarivores in the farmland was less than half of that in forest fragment as reported elsewhere in the tropics, e.g. (Sekercioglu, 2012; Whelan et al., 2015), suggesting either a decline in potential pollinators, or that crops in the farmlands do not have as much quantity and or quality of nectar as forest plants. Therefore, integrating trees in farmlands may attract nectarivores and other bird species, which may partially make up for the decline or lower numbers of pollinators among farmlands birds (Sekercioglu, 2012).

Insectivorous birds were dispersed across both farmlands and forest fragments. A possible explanation for my finding may be that the lack of pesticides used in these subsistence Mambilla farmlands may contribute to a high density of invertebrate pests, which then attract insectivorous bird species. If true, this finding is important because it suggests that the insectivorous bird species may potentially reduce insect pests in the farmlands. Thus, the need for further research on the importance of these birds for insect pest control (explored in Chapters 3 and 4 of this thesis).

I expected to record a higher number of granivores in the farmlands than in forest fragments as shown in previous studies in tropical agroforests, e.g. (Sekercioglu, 2012; Waltert et al., 2005) because granivores typically prefer open and disturbed habitats (Buechley et al., 2015). However, contrary to those findings, I recorded a higher number of granivorous species in the forest fragments than in farmlands. Examples include the black-crowned waxbill (*Estrilda nonnula*), the bronze manikin (*Spermestes cucullata*) and the red-collared widowbird (*Euplectes ardens*) which may be significant because many granivores are regarded as agricultural pests.

Several previous studies in temperate and tropical agricultural landscapes have linked bird community composition in farmlands with proximity to forests (Clough et al., 2009; Maas et al., 2013; Naidoo, 2004). I explored this relationship and found that the distance of farmlands from forest fragments influenced bird community composition. The analysis also showed that the proportion of fruiting trees positively influenced bird community composition. Therefore, retaining trees in farmlands as well as conserving forest fragments on the Mambilla plateau, may help preserve bird species, which could in turn, benefit crop production as reported in (Johnson et al., 2010; Maas et al., 2009). The susceptibility of insectivorous birds in particular, to habitat fragmentation, may cause a different set of problems to farmers in the tropics (Tobias et al., 2013) because studies have shown that they regulate insect pest in farmlands (Bael et al., 2008; Mooney et al., 2010).

2.4.3 Conclusion

The novelty of my study lies in it being the first extensive bird community study in the Mambilla montane region. In this study, I have described the bird community composition and the distribution of bird trophic functional groups in a forest-subsistence agricultural landscape. With increasing human population pressure and associated loss of fragments, this is a timely study for biodiversity conservation and an important contribution to the literature on birds of Nigeria. Overall, I found a rich diversity of bird species on the Mambilla plateau. While as expected, diversity was highest in the forest fragments (Sekercioglu, 2012), the farmlands also supported a high diversity of species, although a significant proportion of the farmland species depend on forest fragments for at least part of their life cycle (e.g breeding).

My results point to the importance of retaining forest habitat in tropical forest-agricultural landscapes. Lastly, I identified insectivorous species as a critical trophic functional group in farmlands and suggest that these species may be valuable in pest control. Therefore, there is a need to assess the role of these birds in providing ecosystem services in this region.

2.5 References

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2.6 Appendices

Supplementary Information:

Appendix 2.1: Habitat preference of bird species

Habitats	Family name	Common names	Scientific name
Farmland	Macrosphenidae	Green Crombec	*Sylvietta virens*
Farmland	Accipitridae	African Harrier-hawk	*Polyboroides typus*
Farmland	Alcedinidae	Blue-breasted kingfisher	*Halcyon malimbica*
Farmland	Malaconotidae	Brown-crowned Tchagra	*Tchagra australis*
Farmland	Cisticolidae	Chubb's Cisticola	*Cisticola chubbi*
Farmland	Nectariniidae	Scarlet-chested Sunbird	*Chalcomitra senegalensis*
Farmland	Fringillidae	Streaky-headed Seedeater	*Crithagra gularis*
Farmland	Viduidae	Village Indigobird	*Vidua chalybeata*
Farmland	Apodidae	White-rumped Swift	*Apus caffer*
Farmland	Alcedinidae	Woodland Kingfisher	*Halcyon senegalensis*
Farmland and forest fragments	Monarchidae	African Blue-flycatcher	*Elminia longicauda*
Farmland and forest fragments	Columbidae	African Green-pigeon	*Treron calvus*
Farmland and forest fragments	Macrosphenidae	African Moustached Grass-warbler	*Melocichla mentalis*
Farmland and forest fragments	Monarchidae	African Paradise-flycatcher	*Terpsiphone viridis*
Farmland and forest fragments	Motacillidae	African Pipit	*Anthus cinnamomeus*
Farmland and forest fragments	Hirundinidae	African Plain Martin	*Riparia paludicola*
Farmland and forest fragments	Alcedinidae	African Pygmy-kingfisher	*Ispidina picta*
Farmland and forest fragments	Vangidae	African Shrike-flycatcher	*Megabyas flammulatus*
Farmland and forest fragments	Turdidae	African Thrush	*Turdus pelios*
Farmland and forest fragments	Zosteropidae	African Yellow White-eye	*Zosterops senegalensis*
Farmland and forest fragments	Ploceidae	Baglafecht Weaver	*Ploceus baglafecht*
Farmland and forest fragments	Hirundinidae	Banded Martin	*Neophedina cincta*
Farmland and forest fragments	Ploceidae	Bannerman's Weaver	*Ploceus bannermani*

Farmland and forest fragments	Estrildidae	Bar-breasted Firefinch	*Lagonosticta rufopicta*
Farmland and forest fragments	Rallidae	Black Crake	*Zapornia flavirostra*
Farmland and forest fragments	Hirundinidae	Black Saw-wing	*Psalidoprocne pristoptera*
Farmland and forest fragments	Accipitridae	Black Sparrowhawk	*Accipiter melanoleucus*
Farmland and forest fragments	Estrildidae	Black-bellied Firefinch	*Lagonosticta rara*
Farmland and forest fragments	Ploceidae	Black-billed Weaver	*Ploceus melanogaster*
Farmland and forest fragments	Malaconotidae	Black-crowned Tchagra	*Tchagra senegalus*
Farmland and forest fragments	Estrildidae	Black-crowned Waxbill	*Estrilda nonnula*
Farmland and forest fragments	Ardeidae	Black-headed heron	*Ardea melanocephala*
Farmland and forest fragments	Accipitridae	Black-shouldered kite	*Elanus axillaris*
Farmland and forest fragments	Columbidae	Blue-spotted Wood-dove	*Turtur afer*
Farmland and forest fragments	Estrildidae	Bronze mannikin	*Spermestes cucullata*
Farmland and forest fragments	Estrildidae	Brown Twinspot	*Clytospiza monteiri*
Farmland and forest fragments	Emberizidae	Brown-rumped Bunting	*Emberiza affinis*
Farmland and forest fragments	Platysteiridae	Brown-throated Wattle-eye	*Platysteira cyanea*
Farmland and forest fragments	Ardeidae	Cattle Egret	*Bubulcus ibis*
Farmland and forest fragments	Emberizidae	Cinnamon-breasted Bunting	*Emberiza tahapisi*
Farmland and forest fragments	Muscicapidae	Common (African) Stonechat	*Saxicola torquatus*
Farmland and forest fragments	Pycnonotidae	Common Bulbul	*Pyconotus barbatus*
Farmland and forest fragments	Upupidae	Common Hoopoe	*Upupa epops*
Farmland and forest fragments	Sylviidae	Common Whitethroat	*Sylvia communis*
Farmland and forest fragments	Nectariniidae	Copper Sunbird	*Cinnyris cupreus*
Farmland and forest fragments	Cisticolidae	Croaking cisticola	*Cisticola natalensis*
Farmland and forest fragments	Ploceidae	Dark-backed Weaver	*Ploceus bicolor*
Farmland and forest fragments	Phasianidae	Double-spurred Francolin	*Ptemistis bicalcaratus*
Farmland and forest fragments	Lybiidae	Double-toothed Barbet	*Pogonornis bidentatus*
Farmland and forest fragments	Muscicapidae	European Pied Flycatcher	*Ficedula hypoleuca*
Farmland and forest fragments	Muscicapidae	Familiar Chat	*Oeananthe familiaris*
Farmland and forest fragments	Falconidae	Fox kestrel	*Falco alopex*
Farmland and forest fragments	Sylviidae	Garden Warbler	*Sylvia borin*
Farmland and forest fragments	Musophagidae	Green Turaco	*Tauraco persa*
Farmland and forest fragments	Phoeniculidae	Green Woodhoopoe	*Phoeniculus purpureus*
Farmland and forest fragments	Nectariniidae	Green-headed Sunbird	*Cyanomitra verticalis*
Farmland and forest fragments	Cisticolidae	Grey Apalis	*Apalis cinerea*
Farmland and forest fragments	Picidae	Grey Woodpecker	*Dendropicos goertae*
Farmland and forest fragments	Cisticolidae	Grey-backed (Bleating) Camaroptera	*Camaroptera brachyura*
Farmland and forest fragments	Alcedinidae	Grey-headed Kingfisher	*Halcyon leucocephala*
Farmland and forest fragments	Estrildidae	Grey-headed Nigrita	*Nigrita canicapillus*
Farmland and forest fragments	Threskiornithidae	Hadada Ibis	*Bostrychia hagedash*
Farmland and forest fragments	Scopidae	Hamerkop	*Scopus umbretta*
Farmland and forest fragments	Ploceidae	Hartlaub's Marsh Widowbird	*Euplectes hartlaubi*
Farmland and forest fragments	Accipitridae	Hooded Vulture	*Necrosyrtes monachus*
Farmland and forest fragments	Hirundinidae	Large Rock Martin	*Ptyonoprogne fuligula*
Farmland and forest fragments	Meropidae	Little Bee-eater	*Merops pusillus*
Farmland and forest fragments	Ardeidae	Little Egret	*Egretta garzetta*
Farmland and forest fragments	Accipitridae	Long-crested Eagle	*Lophaetus occipitalis*
Farmland and forest fragments	Malaconotidae	Marsh Tchagra	*Bocagia minuta*

Farmland and forest fragments	Muscicapidae	Northern Black-flycatcher	*Melaenomis edolioides*
Farmland and forest fragments	Macrosphenidae	Northern Crombec	*Sylvietta brachyura*
Farmland and forest fragments	Nectariniidae	Northern Double-collared Sunbird	*Cinnyris reichenowi*
Farmland and forest fragments	Passeridae	Northern Grey-headed Sparrow	*Passer griseus*
Farmland and forest fragments	Malaconotidae	Northern Puffback	*Dryoscopus gambensis*
Farmland and forest fragments	Strigidae	Northern White-faced owl	*Ptilopsis leucotis*
Farmland and forest fragments	Estrildidae	Orange-cheeked Waxbill	*Estrilda melpoda*
Farmland and forest fragments	Nectariniidae	Orange-tufted Sunbird	*Cinnyris bouvieri*
Farmland and forest fragments	Cisticolidae	Oriole Warbler	*Hypergerus atriceps*
Farmland and forest fragments	Cisticolidae	Pectoral-patch Cisticola	*Cisticola brunnescens*
Farmland and forest fragments	Corvidae	Pied Crow	*Corvus albus*
Farmland and forest fragments	Viduidae	Pin-tailed Whydah	*Vidua macroura*
Farmland and forest fragments	Motacillidae	Plain-backed Pipit	*Anthus leucophrys*
Farmland and forest fragments	Columbidae	Red-cheeked Cordon-blue	*Uraeginthus bengalus*
Farmland and forest fragments	Estrildidae	Red-Collared Widowbird	*Euplectes ardens*
Farmland and forest fragments	Columbidae	Red-eyed Dove	*Streptopelia semitorquata*
Farmland and forest fragments	Cisticolidae	Red-faced Cisticola	*Cisticola erythrops*
Farmland and forest fragments	Accipitridae	Red-necked Buzzard	*Buteo auguralis*
Farmland and forest fragments	Pycnonotidae	Red-tailed Bristlebill	*Bleda syndactylus*
Farmland and forest fragments	Alaudidae	Rufous-naped Lark	*Mirafra africana*
Farmland and forest fragments	Phasianidae	Scaly Francolin	*Ptemistis squamatus*
Farmland and forest fragments	Acrocephalidae	Sedge Warbler	*Acrocephalus schoenobaenus*
Farmland and forest fragments	Cuculidae	Senegal Coucal	*Centropus senegalensis*
Farmland and forest fragments	Cisticolidae	Senegal Eremomela	*Eremomela pusilla*
Farmland and forest fragments	Cisticolidae	Short-winged Cisticola	*Cisticola brachypterus*
Farmland and forest fragments	Cisticolidae	Singing Cisticola	*Cisticola cantans*
Farmland and forest fragments	Muscicapidae	Snowy-crowned Robin-chat	*Cossypha niveicapilla*
Farmland and forest fragments	Muscicapidae	Sooty Chat	*Myrmecocichla nigra*
Farmland and forest fragments	Coliidae	Speckled Mousebird	*Colius striatus*
Farmland and forest fragments	Ploceidae	Spectacled Weaver	*Ploceus ocularis*
Farmland and forest fragments	Nectariniidae	Splendid Sunbird	*Cinnyris coccinigastrus*
Farmland and forest fragments	Dicruridae	Square-tailed Drongo	*Dicrurus ludwigii*
Farmland and forest fragments	Columbidae	Tambourine Dove	*Turtur tympanistria*
Farmland and forest fragments	Cisticolidae	Tawny-flanked Prinia	*Prinia subflava*
Farmland and forest fragments	Motacillidae	Tree Pipit	*Anthus trivialis*
Farmland and forest fragments	Malaconotidae	Tropical Boubou	*Laniarius aethiopicus*
Farmland and forest fragments	Nectariniidae	Variable Sunbird	*Cinnyris venustus*
Farmland and forest fragments	Ploceidae	Vieillot's Black Weaver	*Ploceus nigerrimus*
Farmland and forest fragments	Ploceidae	Village Weaver	*Ploceus cucullatus*
Farmland and forest fragments	Columbidae	Vinaceous Dove	*Streptopelia vinacea*
Farmland and forest fragments	Charadriidae	Wattled Lapwing	*Venellus senegallus*
Farmland and forest fragments	Lybiidae	Western Green Tinkerbird	*Pogoniulus coryphaea*
Farmland and forest fragments	Musophagidae	Western Grey Plantain-eater	*Crinifer piscator*
Farmland and forest fragments	Turdidae	Whinchat	*Saxicola rubetra*
Farmland and forest fragments	Cisticolidae	Whistling Cisticola	*Cisticola lateralis*
Farmland and forest fragments	Accipitridae	White-backed Vulture	*Gyps africanus*
Farmland and forest fragments	Cisticolidae	White-chinned Prinia	*Schistolais leucopogon*

Farmland and forest fragments	Musophagidae	White-crested Turaco	*Tauraco leucolophus*
Farmland and forest fragments	Phylloscopidae	Willow Warbler	*Phylloscopus trochilus*
Farmland and forest fragments	Ploceidae	Yellow Bishop	*Euplectes capensis*
Farmland and forest fragments	Buphagidae	Yellow-billed Oxpecker	*Buphagus africanus*
Farmland and forest fragments	Musophagidae	Yellow-billed Turaco	*Tauraco macrorhynchus*
Farmland and forest fragments	Malaconotidae	Yellow-breasted Boubou	*Laniarius atroflavus*
Farmland and forest fragments	Fringillidae	Yellow-fronted Canary	*Crithagra mozambica*
Farmland and forest fragments	Ploceidae	Yellow-mantled Widowbird	*Euplectes macroura*
Farmland and forest fragments	Lybiidae	Yellow-rumped Tinkerbird	*Pogoniulus bilineatus*
Farmland and forest fragments	Pycnonotidae	Yellow-throated Greenbul	*Atimastillas flavicollis*
Farmland and forest fragments	Motacillidae	Yellow-throated Longclaw	*Macronyx croceus*
Farmland and forest fragments	Estrildidae	Yellow-winged Pytilia	*Pytilia hypogrammica*
Farmland and forest fragments	Cisticolidae	Zitting Cisticola	*Cisticola juncidis*
Forest fragments	Ciconiidae	Abdim's Stork	*Ciconia abdimii*
Forest fragments	Coraciidae	Abyssinian Roller	*Coracias abyssinicus*
Forest fragments	Columbidae	Adamawa Turtle-dove	*Streptopelia hypopyrrha*
Forest fragments	Muscicapidae	African Dusky Flycatcher	*Muscicapa adusta*
Forest fragments	Cuculidae	African Emerald Cuckoo	*Chrysococcyx cupreus*
Forest fragments	Oriolidae	African Golden Oriole	*Oriolus auratus*
Forest fragments	Bucerotidae	African Grey Hornbill	*Lophoceros nasutus*
Forest fragments	Sylviidae (Timaliidae)	African Hill-babbler	*Sylvia (Pseudoalcippe) abyssinica*
Forest fragments	Apodidae	African Palm-swift	*Cypsiurus parvus*
Forest fragments	Acrocephalidae	African Reed-warbler	*Acrocephalus (scirpaceus) baeticatus*
Forest fragments	Accipitridae	Ayres's Hawk-eagle	*Hieraaetus ayresii*
Forest fragments	Cisticolidae	Bamenda apalis	*Apalis bamendae*
Forest fragments	Sylviidae (Locustellidae)	Bangwa Warbler	*Bradypterus (lopezi) bangwaensis*
Forest fragments	Meropidae	Black Bee-eater	*Merops gularis*
Forest fragments	unidentified	Unidentified species of harrier	*Circus spp.*
Forest fragments	Phylloscopidae	Black-capped Woodland Warbler	*Phylloscopus herberti*
Forest fragments	Cisticolidae	Black-collared Apalis	*Oreolais pulcher*
Forest fragments	Meropidae	Blue-breasted Bee-eater	*Merops variegatus*
Forest fragments	Muscicapidae	Blue-shouldered Robin-chat	*Cossypha cyanocampter*
Forest fragments	Accipitridae	Booted Eagle	*Hieraaetus pennatus*
Forest fragments	Sylviidae (Locustellidae)	Broad-tailed Grassbird	*Schoenicola platyurus*
Forest fragments	Charadriidae	Brown-chested Lapwing	*Vanellus superciliosus*
Forest fragments	Cisticolidae	Buff-throated Apalis	*Apalis rufogularis*
Forest fragments	Pycnonotidae	Cameroon Mountain Greenbul	*Arizelocichla montana*
Forest fragments	Columbidae	Cameroon Olive-pigeon	*Columba sjostedti*
Forest fragments	Laniidae	Common Fiscal	*Lanius collaris*
Forest fragments	Estrildidae	Common Waxbill	*Estrilda astrild*
Forest fragments	Cuculidae	Diederik Cuckoo	*Chrysococcyx caprius*
Forest fragments	Stenostiridae	Dusky Crested-flycatcher	*Elminia nigromitrata*
Forest fragments	Estrildidae	Dybowski's Twinspot	*Euschistospiza dybowskii*
Forest fragments	Lybiidae	Eastern Yellow-billed Barbet	*Trachylaemus purpuratus*
Forest fragments	Picidae	Eurasian Wryneck	*Jynx torquilla*

Forest fragments	Picidae	Fine-spotted Woodpecker	*Campethera punctuligera*
Forest fragments	Alaudidae	Flappet Lark	*Mirafra rufocinnamomea*
Forest fragments	Scotocercidae	Green Hylia	*Hylia prasina*
Forest fragments	Cisticolidae	Green Longtail	*Urolais epichlorus*
Forest fragments	Muscicapidae	Grey Tit-flycatcher	*Myioparus plumbeus*
Forest fragments	Apodidae	Horus Swift	*Apus horus*
Forest fragments	Falconidae	Lanner Falcon	*Falco biarmicus*
Forest fragments	Columbidae	Laughing Dove	*Spilopelia senegalensis*
Forest fragments	Pycnonotidae	Leaf-love	*Pyrrhurus scandens*
Forest fragments	Indicatoridae	Lesser Honeyguide	*Indicator minor*
Forest fragments	Cuculidae	Levaillant's Cuckoo	*Clamator levaillantii*
Forest fragments	Pycnonotidae	Little Greenbul	*Eurillas virens*
Forest fragments	Accipitridae	Lizard Buzzard	*Kaupifalco monogrammicus*
Forest fragments	Motacillidae	Long-billed Pipit	*Anthus similis*
Forest fragments	Indicatoridae	Lyre-tailed Honeyguide	*Melichneutes robustus*
Forest fragments	Accipitridae	Montagu's Harrier	*Circus pygargus*
Forest fragments	Apodidae	Mottled Spinetail	*Telacanthura ussheri*
Forest fragments	Columbidae	Mourning Collared-dove	*Streptopelia decipiens*
Forest fragments	Laniidae	Naked-faced Barbet	*Gymnobucco calvus*
Forest fragments	Muscicapidae	Northern Wheatear	*Oenanthe oenanthe*
Forest fragments	Nectariniidae	Olive Sunbird	*Cyanomitra olivacea*
Forest fragments	Paridae	Pale-eyed Black Tit	*Melaniparus guineensis*
Forest fragments	Ardeidae	Purple Heron	*Ardea purpurea*
Forest fragments	Coraciidae	Purple Roller	*Coracias naevius*
Forest fragments	Campephagidae	Red-shouldered Cuckooshrike	*Campephaga phoenicea*
Forest fragments	Picidae	Rufous-necked Wryneck	*Jynx ruficollis*
Forest fragments	Lybiidae	Speckled Tinkerbird	*Pogoniulus scolopaceus*
Forest fragments	Caprimulgidae	Standard-winged Nightjar	*Caprimulgus longipennis*
Forest fragments	Alaudidae	Sun lark	*Galerida modesta*
Forest fragments	Pycnonotidae	Swamp Palm Bulbul	*Thescelocichla leucopleura*
Forest fragments	Fringillidae	Thick-billed Seedeater	*Crithagra burtoni*
Forest fragments	Dicruridae	Velvet-mantled Drongo	*Dicrurus modestus*
Forest fragments	Accipitridae	Western Marsh Harrier	*Circus aeruginosus*
Forest fragments	Pycnonotidae	Western Mountain Greenbul	*Arizelocichla tephrolaema*
Forest fragments	Bucerotidae	Western Piping Hornbill	*Bycanister fistulator*
Forest fragments	Motacillidae	Western Yellow Wagtail	*Motacilla flava*
Forest fragments	Muscicapidae	White-crowned Robin-chat	*Cossypha albicapillus*
Forest fragments	Rallidae	White-spotted Flufftail	*Sarothrura pulchra*
Forest fragments	Ciconiidae	Woolly-necked Stock	*Ciconia episcopus*
Forest fragments	Indicatoridae	Yellow-footed Honeyguide	*Melignomon eisentrauti*

Appendix 2.2: Kruskal Wallis rank sum test one Way Anova, showing detectability of some species across the different habitats

species	chi-squared	df	p value
Yellow-fronted Canary	1.40	1	0.234
Village Weaver	1.41	1	0.235
Common (African) Stonechat	0.00038	1	0.984
Common Bulbul	10.29	1	**0.001**
Croaking cisticola	0.059	1	0.808
Doubled spurred Francolin	8.532	1	**0.003**
Grey-backed Camaroptera	0.98	1	0.320
Orange-tufted Sunbird	0.69	1	0.404
Pin-tailed Whydah	2.047	1	0.152
Senegal Coucal	2.54	1	0.111
Tropical Boubou	3.79	1	0.051
Yellow-throated longclaw	3.55	1	0.060
Banded Martin	4.22	1	**0.039**
Black-shouldered kite	0.12	1	0.724
Red eyed Dove	0.91	1	0.340
Yellow-mantled Widowbird	0.17	1	0.680
African Blue-flycatcher	1.61	1	0.205
Northern Grey-headed Sparrow	1.02	1	0.313
Short-winged Cisticola	0.89	1	0.343

P values in bold showing significant difference

Appendix 2.3: Legends for birds' species codes used in figure 4

Code	Common names
ADFC	African Dusky Flycatcher
AFGP	African Green-pigeon
AFMW	African Moustached Grass-warbler
AGHB	African Grey Hornbill
AMDO	Mourning Collared-dove
APFC	African Paradise-flycatcher
BAWE	Bannerman's Weaver
BBFF	Black-bellied Firefinch
BBKF	Blue-breated kingfisher
BCWW	Black-capped Woodland Warbler
BLCT	Black-crowned Tchagra
BLHH	Black-headed heron
BOTE	Booted Eagle
BRMK	Bronze mannikin
BSRC	Blue-shouldered Robin-chat
BSWD	Blue-spotted Wood-dove

CAEG	Cattle Egret
CMOP	Cameroon Olive-pigeon
COSB	Copper Sunbird
DABW	Dark-backed Weaver
DTBB	Doubled-toothed Barbet
ERWR	Eurasian Wryneck
GHKF	Grey-headed Kingfisher
GHSB	Green-headed Sunbird
GRCR	Green Crombec
GRWP	Grey Woodpecker
HAMK	Hamerkop
LGDO	Laughing Dove
LZZB	Lizard Buzzard
MATG	Marsh Tchagra
NBFC	Northern black-flycatcher
NDCS	Northern Doubled-collared Sunbird
ORWA	Oriole Warbler
PBPP	Plain-backed Pipit
PUHE	Purple Heron
RCWB	Red-Collared Widowbird
RENB	Red-necked Buzzard
RETB	Red-tailed Bristlebill
RUNL	Rufous-naped Lark
SCFR	Scaly Francolin
SCSB	Scarlet-chested Sunbird
SHFL	African Shrike-flycatcher
SILL	Leaf-love
SNCC	Senegal Coucal
SNCI	Singing Cisticola
STCH	Sooty Chat
STDG	Square-tailed Drongo
STWN	Standard-winged Nightjar
TBSE	Thick-billed Seedeater
TFPR	Tawny-flanked Prinia
VIBW	Viellot's Black Weaver
VIIN	Village Indigobird
VNDO	Vinaceous Dove
WCTU	White-crested Turaco
WHCI	Whistling Cisticola
WINC	Whinchat
WMGB	Western Mountain Greenbul
YEBT	Yellow-billed Turaco
YEFH	Yellow-footed Honneyguide
YELL	Western Yellow Wagtail
YTLC	Yellow-throated longclaw
YTLL	Yellow-throated Greenbul

ZICI	Zitting Cisticola

Appendix 2.4: Checklist of bird species

Family name	Scientific name	Common names	Conservation status	TFG
Accipitridae	*Polyboroides typus*	African Harrier-hawk	LC	carnivore
Accipitridae	*Accipiter melanoleucus*	Black Sparrowhawk	LC	carnivore
Accipitridae	*Elanus axillaris*	Black-shouldered kite	LC	carnivore
Accipitridae	*Necrosyrtes monachus*	Hooded Vulture	CR	carrion
Accipitridae	*Lophaetus occipitalis*	Long-crested Eagle	LC	carnivores
Accipitridae	*Buteo auguralis*	Red-necked Buzzard	LC	carnivore
Accipitridae	*Gyps africanus*	White-backed Vulture	CR	carrion
Accipitridae	*Hieraaetus ayresii*	Ayres's Hawk-eagle	LC	carnivore
Accipitridae	*Circus spp*	unidentified species of harrier	EN	carnivore
Accipitridae	*Hieraaetus pennatus*	Booted Eagle	LC	carnivore
Accipitridae	*Kaupifalco monogrammicus*	Lizard Buzzard	LC	carnivore
Accipitridae	*Circus pygargus*	Montagu's Harrier	LC	carnivore
Accipitridae	*Circus aeruginosus*	Western Marsh Harrier	LC	carnivore
Acrocephalidae	*Acrocephalus schoenobaenus*	Sedge Warbler	LC	insectivorous
Acrocephalidae	*Acrocephalus (scirpaceus) baeticatus*	African Reed-warbler	DD	insectivorous
Alaudidae	*Mirafra Africana*	Rufous-naped Lark	LC	insectivorous
Alaudidae	*Mirafra rufocinnamomea*	Flappet Lark	LC	insectivorous
Alaudidae	*Galerida modesta*	Sun lark	LC	insectivorous
Alcedinidae	*Halcyon malimbica*	Blue-breasted kingfisher	LC	pisces
Alcedinidae	*Halcyon senegalensis*	Woodland Kingfisher	LC	pisces
Alcedinidae	*Ispidina picta*	African Pygmy-kingfisher	LC	pisces
Alcedinidae	*Halcyon leucocephala*	Grey-headed Kingfisher	LC	pisces
Apodidae	*Apus caffer*	White-rumped Swift	LC	insectivorous
Apodidae	*Cypsiurus parvus*	African Palm-swift	LC	insectivorous
Apodidae	*Apus horus*	Horus Swift	LC	insectivorous
Apodidae	*Telacanthura ussheri*	Mottled Spinetail	LC	insectivorous
Ardeidae	*Ardea melanocephala*	Black-headed heron	LC	carnivore
Ardeidae	*Bubulcus ibis*	Cattle Egret	LC	insectivorous
Ardeidae	*Egretta garzetta*	Little Egret	LC	insectivorous
Ardeidae	*Ardea purpurea*	Purple Heron	LC	carnivore
Bucerotidae	*Lophoceros nasutus*	African Grey Hornbill	LC	frugivores
Bucerotidae	*Bycanister fistulator*	Western Piping Hornbill	LC	frugivores
Buphagidae	*Buphagus africanus*	Yellow-billed Oxpecker	LC	carnivore
Campephagidae	*Campephaga phoenicea*	Red-shouldered Cuckooshrike	LC	insectivorous
Caprimulgidae	*Caprimulgus longipennis*	Standard-winged Nightjar	LC	insectivorous
Charadriidae	*Venellus senegallus*	Wattled Lapwing	LC	insectivorous
Charadriidae	*Vanellus superciliosus*	Brown-chested Lapwing	LC	insectivorous
Ciconiidae	*Ciconia abdimii*	Abdim's Stork	LC	insectivorous
Ciconiidae	*Ciconia episcopus*	Woolly-necked Stock	VU	carnivore
Cisticolidae	*Cisticola chubbi*	Chubb's Cisticola	LC	insectivorous

Cisticolidae	*Cisticola natalensis*	Croaking cisticola	LC	insectivorous
Cisticolidae	*Apalis cinerea*	Grey Apalis	LC	insectivorous
Cisticolidae	*Camaroptera brachyura*	Grey-backed (Bleating) Camaroptera	DD	insectivorous
Cisticolidae	*Hypergerus atriceps*	Oriole Warbler	LC	insectivorous
Cisticolidae	*Cisticola brunnescens*	Pectoral-patch Cisticola	LC	insectivorous
Cisticolidae	*Cisticola erythrops*	Red-faced Cisticola	LC	insectivorous
Cisticolidae	*Eremomela pusilla*	Senegal Eremomela	LC	insectivorous
Cisticolidae	*Cisticola brachypterus*	Short-winged Cisticola	LC	insectivorous
Cisticolidae	*Cisticola cantans*	Singing Cisticola	LC	granivores
Cisticolidae	*Prinia subflava*	Tawny-flanked Prinia	LC	insectivorous
Cisticolidae	*Cisticola lateralis*	Whistling Cisticola	LC	insectivorous
Cisticolidae	*Schistolais leucopogon*	White-chinned Prinia	LC	insectivorous
Cisticolidae	*Cisticola juncidis*	Zitting Cisticola	LC	insectivorous
Cisticolidae	*Apalis bamendae*	Bamenda apalis	LC	insectivorous
Cisticolidae	*Oreolais pulcher*	Black-collared Apalis	LC	insectivorous
Cisticolidae	*Apalis rufogularis*	Buff-throated Apalis	LC	insectivorous
Cisticolidae	*Urolais epichlorus*	Green Longtail	LC	insectivorous
Coliidae	*Colius striatus*	Speckled Mousebird	LC	frugivores
Columbidae	*Treron calvus*	African Green-pigeon	LC	frugivores
Columbidae	*Turtur afer*	Blue-spotted Wood-dove	LC	frugivores
Columbidae	*Uraeginthus bengalus*	Red-cheeked Cordon-blue	LC	frugivores
Columbidae	*Streptopelia semitorquata*	Red-eyed Dove	LC	frugivores
Columbidae	*Turtur tympanistria*	Tambourine Dove	LC	frugivores
Columbidae	*Streptopelia vinacea*	Vinaceous Dove	LC	frugivores
Columbidae	*Streptopelia hypopyrrha*	Adamawa Turtle-dove	LC	frugivores
Columbidae	*Columba sjostedti*	Cameroon Olive-pigeon	LC	frugivores
Columbidae	*Spilopelia senegalensis*	Laughing Dove	LC	frugivores
Columbidae	*Streptopelia decipiens*	Mourning Collared-dove	LC	frugivores
Coraciidae	*Coracias abyssinicus*	Abyssinian Roller	LC	insectivorous
Coraciidae	*Coracias naevius*	Purple Roller	LC	insectivorous
Corvidae	*Corvus albus*	Pied Crow	LC	omnivorous
Cuculidae	*Centropus senegalensis*	Senegal Coucal	LC	insectivorous
Cuculidae	*Chrysococcyx cupreus*	African Emerald Cuckoo	LC	insectivorous
Cuculidae	*Chrysococcyx caprius*	Diederik Cuckoo	LC	insectivorous
Cuculidae	*Clamator levaillantii*	Levaillant's Cuckoo	LC	insectivorous
Dicruridae	*Dicrurus ludwigii*	Square-tailed Drongo	LC	insectivorous
Dicruridae	*Dicrurus modestus*	Velvet-mantled Drongo	LC	insectivorous
Emberizidae	*Emberiza affinis*	Brown-rumped Bunting	LC	insectivorous
Emberizidae	*Emberiza tahapisi*	Cinnamon-breasted Bunting	LC	granivores
Estrildidae	*Lagonosticta rufopicta*	Bar-breasted Firefinch	LC	granivores
Estrildidae	*Lagonosticta rara*	Black-bellied Firefinch	LC	granivores
Estrildidae	*Estrilda nonnula*	Black-crowned Waxbill	LC	granivores
Estrildidae	*Spermestes cucullata*	Bronze mannikin	LC	granivores
Estrildidae	*Clytospiza monteiri*	Brown Twinspot	LC	granivores
Estrildidae	*Nigrita canicapillus*	Grey-headed Nigrita	LC	granivores

Estrildidae	*Estrilda melpoda*	Orange-cheeked Waxbill	LC	granivores
Estrildidae	*Euplectes ardens*	Red-Collared Widowbird	LC	granivores
Estrildidae	*Pytilia hypogrammica*	Yellow-winged Pytilia	LC	granivores
Estrildidae	*Estrilda astrild*	Common Waxbill	LC	granivores
Estrildidae	*Euschistospiza dybowskii*	Dybowski's Twinspot	LC	granivores
Falconidae	*Falco alopex*	Fox kestrel	LC	carnivore
Falconidae	*Falco biarmicus*	Lanner Falcon	LC	carnivores
Fringillidae	*Crithagra gularis*	Streaky-headed Seedeater	LC	granivores
Fringillidae	*Crithagra mozambica*	Yellow-fronted Canary	LC	granivores
Fringillidae	*Crithagra burtoni*	Thick-billed Seedeater	LC	granivores
Hirundinidae	*Riparia paludicola*	African Plain Martin	LC	insectivorous
Hirundinidae	*Neophedina cincta*	Banded Martin	LC	insectivorous
Hirundinidae	*Psalidoprocne pristoptera*	Black Saw-wing	LC	insectivorous
Hirundinidae	*Ptyonoprogne fuligula*	Large Rock Martin	LC	insectivorous
Indicatoridae	*Indicator minor*	Lesser Honeyguide	LC	insectivorous
Indicatoridae	*Melichneutes robustus*	Lyre-tailed Honeyguide	LC	insectivorous
Indicatoridae	*Melignomon eisentrauti*	Yellow-footed Honeyguide	NT	insectivorous
Laniidae	*Lanius collaris*	Common Fiscal	LC	insectivorous
Laniidae	*Gymnobucco calvus*	Naked-faced Barbet	LC	frugivores
Lybiidae	*Pogonornis bidentatus*	Double-toothed Barbet	LC	frugivores
Lybiidae	*Pogoniulus coryphaea*	Western Green Tinkerbird	LC	frugivores
Lybiidae	*Pogoniulus bilineatus*	Yellow-rumped Tinkerbird	LC	frugivores
Lybiidae	*Trachylaemus purpuratus*	Eastern Yellow-billed Barbet	LC	frugivores
Lybiidae	*Pogoniulus scolopaceus*	Speckled Tinkerbird	DD	frugivores
Macrosphenidae	*Sylvietta virens*	Green Crombec	LC	insectivorous
Macrosphenidae	*Melocichla mentalis*	African Moustached Grass-warbler	LC	insectivorous
Macrosphenidae	*Sylvietta brachyura*	Northern Crombec	LC	insectivorous
Malaconotidae	*Tchagra australis*	Brown-crowned Tchagra	LC	insectivorous
Malaconotidae	*Tchagra senegalus*	Black-crowned Tchagra	LC	insectivorous
Malaconotidae	*Bocagia minuta*	Marsh Tchagra	LC	insectivorous
Malaconotidae	*Dryoscopus gambensis*	Northern Puffback	LC	insectivorous
Malaconotidae	*Laniarius aethiopicus*	Tropical Boubou	LC	frugivores
Malaconotidae	*Laniarius atroflavus*	Yellow-breasted Boubou	LC	frugivores
Meropidae	*Merops pusillus*	Little Bee-eater	LC	insectivorous
Meropidae	*Merops gularis*	Black Bee-eater	LC	insectivorous
Meropidae	*Merops variegatus*	Blue-breasted Bee-eater	LC	insectivorous
Monarchidae	*Elminia longicauda*	African Blue-flycatcher	LC	insectivorous
Monarchidae	*Terpsiphone viridis*	African Paradise-flycatcher	LC	insectivorous
Motacillidae	*Anthus cinnamomeus*	African Pipit	LC	insectivorous
Motacillidae	*Anthus leucophrys*	Plain-backed Pipit	LC	insectivorous
Motacillidae	*Anthus trivialis*	Tree Pipit	LC	insectivorous
Motacillidae	*Macronyx croceus*	Yellow-throated Longclaw	LC	insectivorous
Motacillidae	*Anthus similis*	Long-billed Pipit	LC	insectivorous
Motacillidae	*Motacilla flava*	Western Yellow Wagtail	LC	insectivorous
Muscicapidae	*Saxicola torquatus*	Common (African) Stonechat	LC	insectivorous

Muscicapidae	*Ficedula hypoleuca*	European Pied Flycatcher	LC	insectivorous
Muscicapidae	*Oeananthe familiaris*	Familiar Chat	LC	insectivorous
Muscicapidae	*Melaenomis edolioides*	Northern Black-flycatcher	LC	insectivorous
Muscicapidae	*Cossypha niveicapilla*	Snowy-crowned Robin-chat	LC	insectivorous
Muscicapidae	*Myrmecocichla nigra*	Sooty Chat	LC	insectivorous
Muscicapidae	*Muscicapa adusta*	African Dusky Flycatcher	LC	insectivorous
Muscicapidae	*Cossypha cyanocampter*	Blue-shouldered Robin-chat	LC	insectivorous
Muscicapidae	*Myioparus plumbeus*	Grey Tit-flycatcher	LC	insectivorous
Muscicapidae	*Oenanthe oenanthe*	Northern Wheatear	LC	insectivorous
Muscicapidae	*Cossypha albicapillus*	White-crowned Robin-chat	LC	insectivorous
Musophagidae	*Tauraco persa*	Green Turaco	LC	frugivores
Musophagidae	*Crinifer piscator*	Western Grey Plantain-eater	DD	frugivores
Musophagidae	*Tauraco leucolophus*	White-crested Turaco	LC	frugivores
Musophagidae	*Tauraco macrorhynchus*	Yellow-billed Turaco	LC	frugivores
Nectariniidae	*Chalcomitra senegalensis*	Scarlet-chested Sunbird	LC	nectarivores
Nectariniidae	*Cinnyris cupreus*	Copper Sunbird	LC	nectarivores
Nectariniidae	*Cyanomitra verticalis*	Green-headed Sunbird	LC	nectarivores
Nectariniidae	*Cinnyris reichenowi*	Northern Double-collared Sunbird	LC	nectarivores
Nectariniidae	*Cinnyris bouvieri*	Orange-tufted Sunbird	LC	nectarivores
Nectariniidae	*Cinnyris coccinigastrus*	Splendid Sunbird	LC	nectarivores
Nectariniidae	*Cinnyris venustus*	Variable Sunbird	LC	nectarivores
Nectariniidae	*Cyanomitra olivacea*	Olive Sunbird	LC	nectarivores
Oriolidae	*Oriolus auratus*	African Golden Oriole	LC	frugivores
Paridae	*Melaniparus guineensis*	Pale-eyed Black Tit	LC	insectivorous
Passeridae	*Passer griseus*	Northern Grey-headed Sparrow	LC	granivores
Phasianidae	*Ptemistis bicalcaratus*	Double-spurred Francolin	LC	generalist
Phasianidae	*Ptemistis squamatus*	Scaly Francolin	LC	generalist
Phoeniculidae	*Phoeniculus purpureus*	Green Woodhoopoe	LC	insectivorous
Phylloscopidae	*Phylloscopus trochilus*	Willow Warbler	LC	insectivorous
Picidae	*Dendropicos goertae*	Grey Woodpecker	LC	insectivorous
Picidae	*Jynx torquilla*	Eurasian Wryneck	LC	insectivorous
Picidae	*Campethera punctuligera*	Fine-spotted Woodpecker	LC	insectivorous
Picidae	*Jynx ruficollis*	Rufous-necked Wryneck	LC	insectivorous
Platysteiridae	*Platysteira cyanea*	Brown-throated Wattle-eye	LC	insectivorous
Ploceidae	*Ploceus baglafecht*	Baglafecht Weaver	LC	granivores
Ploceidae	*Ploceus bannermani*	Bannerman's Weaver	VU	granivores
Ploceidae	*Ploceus melanogaster*	Black-billed Weaver	LC	granivores
Ploceidae	*Ploceus bicolor*	Dark-backed Weaver	LC	granivores
Ploceidae	*Euplectes hartlaubi*	Hartlaub's Marsh Widowbird	DD	granivores
Ploceidae	*Ploceus ocularis*	Spectacled Weaver	DD	granivores
Ploceidae	*Ploceus nigerrimus*	Vieillot's Black Weaver	LC	granivores
Ploceidae	*Ploceus cucullatus*	Village Weaver	LC	granivores
Ploceidae	*Euplectes capensis*	Yellow Bishop	LC	granivores
Ploceidae	*Euplectes macroura*	Yellow-mantled Widowbird	LC	granivores
Pycnonotidae	*Pyconotus barbatus*	Common Bulbul	LC	generalist

Pycnonotidae	*Bleda syndactylus*	Red-tailed Bristlebill	LC	insectivorous
Pycnonotidae	*Atimastillas flavicollis*	Yellow-throated Greenbul	LC	frugivores
Pycnonotidae	*Arizelocichla montana*	Cameroon Mountain Greenbul	NT	frugivores
Pycnonotidae	*Pyrrhurus scandens*	Leaf-love	LC	insectivorous
Pycnonotidae	*Eurillas virens*	Little Greenbul	LC	generalist
Pycnonotidae	*Thescelocichla leucopleura*	Swamp Palm Bulbul	LC	frugivores
Pycnonotidae	*Arizelocichla tephrolaema*	Western Mountain Greenbul	LC	frugivores
Rallidae	*Zapornia flavirostra*	Black Crake	LC	omnivorous
Rallidae	*Sarothrura pulchra*	White-spotted Flufftail	LC	insectivorous
Scopidae	*Scopus umbretta*	Hamerkop	LC	carnivores
Scotocercidae	*Hylia prasina*	Green Hylia	LC	insectivorous
Stenostiridae	*Elminia nigromitrata*	Dusky Crested-flycatcher	LC	insectivorous
Strigidae	*Ptilopsis leucotis*	Northern White-faced owl	LC	carnivore
Sylviidae	*Sylvia communis*	Common Whitethroat	LC	omnivorous
Sylviidae	*Sylvia borin*	Garden Warbler	LC	insectivorous
Phylloscopidae	*Phylloscopus herberti*	Black-capped Woodland Warbler	LC	insectivorous
Sylviidae (Locustellidae)	*Bradypterus (lopezi) bangwaensis*	Bangwa Warbler	NT	insectivorous
Sylviidae (Locustellidae)	*Schoenicola platyurus*	Broad-tailed Grassbird	VU	insectivorous
Sylviidae (Timaliidae)	*Sylvia (Pseudoalcippe) abyssinica*	African Hill-babbler	LC	insectivorous
Threskiornithidae	*Bostrychia hagedash*	Hadada Ibis	LC	carnivores
Turdidae	*Turdus pelios*	African Thrush	LC	insectivorous
Turdidae	*Saxicola rubetra*	Whinchat	LC	insectivorous
Upupidae	*Upupa epops*	Common Hoopoe	LC	insectivorous
Vangidae	*Megabyas flammulatus*	African Shrike-flycatcher	LC	insectivorous
Viduidae	*Vidua chalybeata*	Village Indigobird	LC	insectivorous
Viduidae	*Vidua macroura*	Pin-tailed Whydah	LC	granivores
Zosteropidae	*Zosterops senegalensis*	African Yellow White-eye	LC	insectivorous

Note: Conservation Status; Least Concern (LC), Vulnerable (VU), Near Threatened (NT), Data Deficient (DD), Critically Endangered (CE), Endangered (EN)

Chapter 3: Evidence for vertebrate control of invertebrate pests of maize on subsistence farms.

Abstract

Birds provide the vital ecosystem service of invertebrate pest control in many agroecosystems, but to what extent this applies to African subsistence farms is unknown. Nor is it known, whether, or to what extent, natural forest fragments associated with subsistence farms act as refugia for potential bird pest control agents. Such information is critical for deciding between land sparing (more intensive farming on less land) and land sharing (wildlife-friendly farming). Here, I investigate the pest control services provided by birds to maize (*Zea mays*) on farms at varying distances from native forest fragments on the Mambilla Plateau in South Eastern Nigeria. I explored how the exclusion of birds influenced maize crop yield by comparing crop yield in caged (two treatments- i) birds excluded, ii) birds and insects excluded) versus open control plots on maize farms. I also explored extent to which the proximity of farms to forest fragments affected pest control. I hypothesised that: i) excluding birds would result in increased insect damage and lower yield, ii) increasing distance of farmlands from forest fragments would result in a reduced abundance of insectivorous bird species and iii) pest reduction would be greater on farms close to forest fragments. I recorded crop yield (both number of cobs and total weight) and crop damage (percentage insect damage to maize leaves and cobs) on 20 maize farms at varying distances from forest fragments. I assessed bird species composition using point counts. My results show that in this system, excluding birds from maize crops had a significant negative effect on crop yield and quality, but the insect and bird exclusion treatment had similar effects, suggesting either that the exclosure itself increased yield, or more likely, that the exclosure was not effective in keeping out insects. However, insectivorous bird abundance was not an important predictor of crop yield quality and quantity. Moreover, there was a negative relationship between the proximity of farms to forest fragments, and both crop yield and the abundance of the insectivorous birds. Possible explanations may be that only one or a few avian insectivore species feeds on the insect fauna of maize, and that these species do not use forests as a favoured habitat. Alternatively, insectivorous bats rather than birds may be more active in pest control. The value of planted eucalyptus plantations as habitat for birds needs investigation. Overall though, my results suggest that in this part of Nigeria, retaining forest fragments may not promote insect pest control by insectivorous birds in maize, but instead

retained forest fragments may reduce yields, although the mechanism for this is unclear. Contrary to expectations, my results suggest that ‘land sparing’ (holding conservation land separate from crop production), might be a better strategy for both farmers and conservation managers in this specific African context.

3.1 Introduction

In Africa, the current human population of 1.25 billion is predicted to double by 2050 (Kaneda & Bietsch, 2016), meaning that more than half of the global population growth between now and 2050 will be in Africa (UN, 2019). While agricultural intensification is the most common approach to achieving global food security for rapidly increasing human populations (Garnett et al., 2013; Ramankutty & Rhemtulla, 2012; Rudel et al., 2009; Tilman, et al., 2011), this is not always achievable in Sub Saharan Africa. Approximately 41% of the population of Sub Saharan Africa still lives in poverty, and maintains rural livelihoods; this is most extreme in rural and farming communities (Davis et al., 2017; Laurance et al., 2014); where farming is often practised without basic agricultural resources such as tractors, irrigation or genetic resources (Globalist, 2017; Nchuchuwe & Adejuwon, 2012).

Subsistence farms (Ofor et al., 2009; Williamson et al., 2008), often dominated by *Zea mays* (maize) are critical to the African economy because maize is a staple crop across Africa (Byerlee & Heisey, 1997), especially in Nigeria (Richard, 2014). However, despite its predominance, subsistence farming is in direct conflict with the Aichi goals of the Convention of Biological Diversity because it leads to forest fragmentation (Bogaert et al., 2008), reduced biodiversity (Green et al., 2005; Laurance, 2007; Norris et al., 2010) and an associated loss of ecosystem services (Whelan et al., 2008). Africa is not alone in facing a food security crisis (Borlaug, 2007) and a major global challenge is combining agriculture with biodiversity conservation (Tanentzap et al., 2015; Tscharntke et al., 2012).

Out of this challenge has risen the “land sparing” versus “land sharing” debate. The idea behind land sparing is to intensify agricultural practices so that yields are sufficiently high to reduce the need for farther conversion of natural habitats for agriculture. In contrast, land sharing is when farmers take more land but use it less intensively, so that crops benefit from ecosystem services such as pollination and pest control services, provided by the natural biodiversity co-existing with crops (Green et al., 2005; Hulme et al., 2013; Phalan et al., 2011; Tscharntke et al., 2012). In Sub Saharan Africa, lack of technology and dependence on subsistence farming limits the opportunity for land sparing (Laurance et al., 2014) and there is an argument for land sharing being the obvious way to maximize agricultural production while minimizing biodiversity loss. The extent to which this holds true for African subsistence farming is largely untested, and more studies are required from a wider range of locations (Godfray, 2011; Hulme et al., 2013). Moreover, little data exists as to the benefits or losses to agriculture of land sharing. More generally, global patterns of biodiversity-related ecosystem services remain understudied (Maas et al., 2013).

Invertebrate pests have a major impact on crop productivity globally (Dhaliwal et al., 2015; Oerke, 2006; Peshin et al., 2009; Pimentel, 2009), and especially so in Africa (De Groote, 2002; De Groote et al., 2004; Moolman et al., 2014; Mutamiswa et al., 2017). In Africa, pests, many of which are herbivorous insects, destroy up to 51% of potential crop yield (Zakari et al., 2014; Zhang et al., 2018). While globally, insecticides have been successful in increasing crop yields (Atreya et al., 2012), their use in Africa is fraught with difficulties (Zhang et al., 2018). Insecticides are commonly applied without regard to safety precautions (Day et al., 2017), with major implications for human health, ecosystem and environment (Pimentel & Burgess, 2014). Their regular use can lead to pest resistance (Williamson et al., 2008), harm insect pollinators and destroy food resources of insect predators such as birds and bats (Maas et al., 2013; Whelan et al., 2015; Whelan et al., 2008).

Several recent studies have shown that in a wide range of agroecosystems, e.g. in large scale farming operations and in plantations, birds are effective controllers of invertebrate pests (Classen et al., 2014; Karp et al., 2013; Maas et al., 2015; Tscharntke et al., 2008). In these systems, birds directly reduce infestation rates of invertebrates and indirectly increase crop productivity (Kellermann et al., 2008; Mols & Visser, 2002), acting as biocontrol agents and reducing the need for pesticides. Managing farmland for insect pest control by birds offers an alternative to insecticide use and supports the argument for land sharing. However, to what extent vertebrates e.g. birds and bats contribute to pest control in tropical subsistence farmlands, particularly in Sub-Saharan Africa, remains largely unknown (Zhang et al., 2018).

This study focuses on Nigeria, where maize is a major component of the population's diet and the staple of subsistence farmers (Richard, 2014). Across Nigeria, subsistence maize farms form a patchwork within a semi-natural environment comprising degraded grassland, scrubland or forest fragments that are at varying distances from the farmlands. Therefore, crop plants may depend on these fragments for pest control services. Besides, many populations of "farmland" birds depend on forest fragments, particularly for breeding (Fuller et al., 2004). For example, insectivorous birds' species were more abundant in both farmlands and forest fragments in Mambilla Plateau (Chapter 2). Thus, the need to focus on the insectivorous species because they are likely to be providing pest control services to the farmlands; evident in their distribution on Non-metric Multidimensional Scaling (NMDS) ordination plot (Chapter 2; figure 2.4) and their primary feeding guild (Borrow & Demey, 2001; Wattel, 1993). However, to what extent birds' effect invertebrate pest control in maize is unknown but is important information in future management of rural landscapes across Africa. Although bats are expected to play an important role in invertebrate pest control, I focus on birds because logistics (inability to collect data at night) dictated that I focused on birds as key predators. Moreover, birds exhibit the most diverse range of ecological functions (Sekercioglu, 2006), providing important ecosystem services (Assessment, 2005).

Therefore, in this chapter, I test the hypotheses that insectivorous birds provide pest control services to maize crops and that maize crops closer to forest fragments will benefit more from these pest control services than crops farther away. I base my thinking on the fact that most of the insectivorous birds in the study use the forest fragments to roost and breed in (Wattel, 1993). I used an experiment, which involved a comparison of maize plant productivity in the i) presence and ii) absence of birds on Mambilla Plateau. My experiments included three treatments- a) open access (subsequently referred to as control) with no exclusion (birds and insects), b) birds exclosure c) birds and insects excluded, to confirm that any effects on crop yield are actually to do with insects. I tried the proper experimental design, excluding insects as well where I would expect same yields as control if birds were reducing insect damage to crops, but this had the same effect of bird exclosure only, suggesting that insects were not properly excluded (see Methods and Appendices). Therefore, I concentrate on the effects of the bird exclosure and control treatments, and make the following predictions;

1. Crop yield quality and quantity will be higher in the control treatments (i.e. in the presence of birds). Birds will suppress the activities of herbivorous insects on maize crops, which will increase crop yield by reducing insect damage to maize cobs and foliage.
2. The proportion of cob damage and leaf damage caused by insect herbivory on crops will be higher in the bird excluded treatment (i.e. in the absence of birds), which in turn will affect crop yield quality and quantity. I expect this because insect pests have access to crops. Therefore, they will quickly infest the cobs and leaves.

3. The increasing distance of farmland from forest fragment will reduce bird abundance and abundance of insectivorous species, and so will influence crop productivity through reduced effects of birds on increasing yield (i.e. I expect a weaker effect of the bird exclusion treatment further away from forest fragments).

Specific objectives were to determine:

1. Whether excluding birds from maize crops leads to a reduction in yield quality and quantity.
2. If there is a relationship between insectivorous bird abundance and maize crop yield quality and quantity.
3. If increasing distance of farmlands from forest fragments results in reduced insectivorous bird abundance.
4. If maize crop yield quality and quantity were affected by increasing distance from the forest fragments

3.2 Materials and methods

3.2.1 Study area

My study area was in farmlands along the north western escarpment of the Mambilla plateau in Taraba State (7.16°N, 11.66°E), SE Nigeria, close to the Nigerian Montane Forest Project (NMFP) field station. There is a distinct wet and dry season with a mean annual rainfall between 1600mm and 2000mm (Ezealor, 2002). The minimum average monthly temperature ranges from 15.5-18.5 ºC and the maximum from 27.5-30.5 ºC (Matthesius et al., 2011). The plateau, with an average elevation of 1,600 m is characterised by gently undulating hills covered in overgrazed *Sporobilis* grassland, with a loose patchwork of small subsistence farms mostly associated with villages (Figure 3.1) and fragments of forest along the sides of streams. Annual food crops grown in the farms include maize, ginger (*Aframomum melegueta*), groundnuts (*Arachis hypogea*), kidney beans (*Phaseolus vulgaris*), potatoes (*Soloanum tuberosum*) and yam (*Dioscorea rotundata*). A year-long bird survey, conducted as part of a wider study associated with this research showed that insectivorous birds are an important component of the bird fauna, comprising over 50% of all avian species in the area (Chapter 2). For my experiment, I selected 20 maize farms situated at varying distances from the forest fragments (Figure 3.1). Farmlands were within each of 200m, 400m, 500m and 650 m from the forest fragment. All farms were free from pesticide use and were at least 200 m apart from each other. The willingness (or otherwise) of farmers to allow work on their land, placed a limit on the number of farms included in the study.

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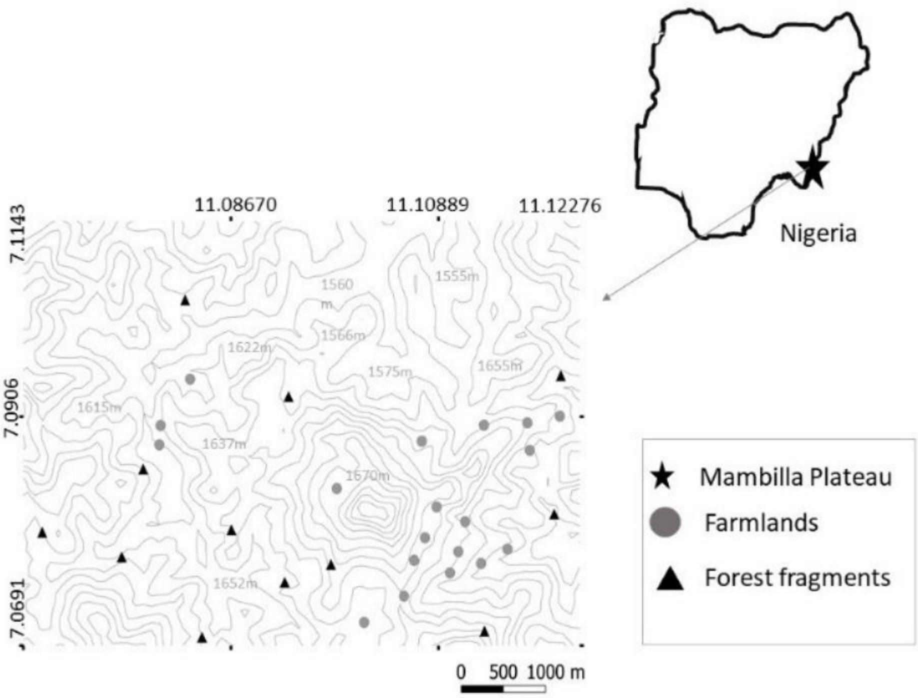

(a)

(b)

Figure 3. 1: The study landscape (A) Map of Nigeria and the location of experimental site on Mambilla Plateau, Nigeria (B) Representative landscape views of forest fragment and maize farmland; yellow arrow pointing at the forest fragment, blue arrow pointing at eucalyptus plantation and a red arrow pointing at maize farmlands. The light areas in the picture denoted by a black circle are open grasslands.

3.2.2 Exclosure experiment set-up

Exclosure experiments were conducted during the wet season April–October 2017, when maize is traditionally cultivated on the Mambilla Plateau. In each of the 20 farms studied, farmers had planted their maize seeds in early April as part of their routine maize planting schedules. Thereafter, I established one 20 x 10 m plot on each farm and subdivided each plot into three 6.7 x 10 m subplots, with a distance of 2.5 m between each subplot. One of the three subplots was designated as a bird exclusion treatment, one as birds and insects-excluded treatment, and one was retained as a control treatment (open access).

The exclosures consisted of two different cage types, each approximately 4x4x4 m (one excluding birds only and the other excluding birds and insects) that were placed in the plots (Figure 3.2). Bird-exclusion cages were built with wooden frames covered with agricultural wire netting with pore size of 0.8mm x 1.2mm that allowed phytophagous insects to enter the cage but excluded birds (Figure 3.2a). Cages for the exclusion of birds and insects were built with cultivation guard net cubes (approx. 4 x 4 x 4 m, mesh size 0.1mm x 0.1mm), which were intended to exclude both insects and birds from maize plants, although insects may not have been excluded – see below (Figure 3.2b). The exclusion cages were placed in the respective subplots as soon as the maize seedlings germinated. Each cage was placed over three maize plants and staked them down. Care was taken to prevent the netting from resting against growing foliage, which would have made leaves accessible to hovering birds and permitted entry of ground-foraging birds. In the control (i. e. open access) three maize plants were also identified as control plants. Although these three plants were not inside a cage, they were of similar proximity to each other as the three plants in the exclusion cages (Figure 3.2).

(a) (b)

Figure 3. 2: Experimental set-up; from left to right (a) birds excluded, (b) birds and insects excluded and control maize plants.

3.2.3 Data collection

For each treatment, I recorded the following parameters: (i) the weight of crop yield, (ii) number of maize cobs with holes from insect herbivory, and (iii) percentage of leaf damage

***Crop yield and cob damage*:** Twenty-one weeks after planting, when the maize cobs were ripe, I harvested them from each of the three plants in each of the three treatments across the 20 farms. First, the number of cobs from each plot in each treatment were counted, and the husks were peeled off. Any holes in the kernels, caused by invertebrate herbivores (hereafter referred to as damaged cobs of maize), were also counted and recorded. The cobs were then dried on a mat exposed to sun and wind, until they reached a constant weight, using a digital Camry mechanical weighing scale (NS 5 - 20 kg, unit of scale was in grams). At the time of harvest, I also assessed damage by phytophagous insects on each plant from each of the treatments.

***Leaf damage*:** Leaf damage was visually estimated as the percentage of leaf area damaged by herbivores, relative to the total leaf area (Morrison & Lindell, 2012). I considered damage as perforated, skeletonized, curled or partly cut leaves (Lemessa et al., 2015; Morrison & Lindell, 2012; Van Bael et al., 2003). To control for possible differences in leaf damage before the experiment began, I checked to see if there was any leaf damage following the sprouting of maize plants but found none.

***Bird identification*:** I sampled birds in each location using point counts (Burgess et al., 2000). Each farm was surveyed once per week between 6:30 am to 10:30 am. I spent 10 minutes on focal observation of birds and recorded bird species within a 50 m radius at each experimental plot. I observed and recorded bird species foraging at either upper strata or lower strata of maize plants using the methodology of Dehling et al. (2014). Observations were made along the crop edge to avoid any form of disturbance.

3.2.4 Data analyses

First, the *means and standard errors* of crop productivity parameters were calculated across the three treatment (Table 3.1), and then general linear mixed effects models (GLMMs) were used to test whether bird abundance had any effect on crop productivity (crop yield, leaf damage and cobs damage) across the three treatments. Unexpectedly, crop yield, cob and leaf damage measures for both exclosure types were very similar suggesting that insects were not excluded completely from the cages that were intended to exclude both birds and insects (see Appendix 3.1: Table 1 and Figure 3.3). Therefore, because this was considered to be a failure of experimental implementation, the models were re-run using the bird exclusion and control treatments only.

To address the objectives of the experiment, I used general linear mixed effects models (GLMMs) to test:

1. Whether bird exclusion from farmlands influenced crop yield – quality and quantity and proportion of phytophagous leaf damage across different plots (replications).
2. If insectivorous birds are responsible for the pest control services as measured by insectivorous bird abundance.

For each of the three parameters; I modelled crop productivity (crop yield, phytophagous leaf damage and cob damage) as a function of abundance of insectivorous birds; I included plots as random effects, with treatment and bird abundance as fixed effects, and included their interaction to test (i) if any change in crop yield depended on abundance of insectivorous birds. (ii) if the reduction leaf damage by treatment depended on abundance of insectivorous birds, and (iii) if reduction in crop damage by treatment depended on abundance of insectivorous birds.

3. I used GLMMs to test if increasing distance of farmlands from forest fragments resulted in decreased insectivorous bird abundance. Abundance was modelled as a function of distance from the nearest fragment; plots were included as random effects, with distance as a fixed effect.
4. GLMMs were also used to test whether the distance of farmlands from forest fragments had any effect on crop yield – quality and quantity. Crop yield, leaf damage and cob damage were modelled as a function of the distance of plots in the farmlands from forest fragments; plots were included as random effects, with treatment and distance as fixed effects, and including their interaction to test if the reduction in crop yield by treatment depended on the distance from the forest fragment.

Model selection was carried out using the information-theoretic approach based on Akaike's Information Criterion (AIC; Burnham & Anderson 2003). Simplification of models was undertaken using deletion of least significant effects from an initial full model. In all cases, a statistical significance level of $p < 0.05$ was chosen to reject the null hypothesis. All main statistical analyses were carried out using the R statistical package version 3.5.6 (R Core Team, 2018).

3.3 Results

In total, I recorded 3,343 birds belonging to 94 different species across the 20 farmlands; over 50% of these were insectivorous birds (see appendix for a checklist).

The exclusion of birds from the maize plots led to markedly reduced crop yield (weight and number of cobs) and cob damage, and increased phytophagous leaf damage (Table 3.1), but the insect and bird exclusion treatment also reduced yield in a similar way (Appendix 3.1: Table 1).

Crop yield increased with bird abundance for both the control and birds-excluded treatment in the same way (Table 3.2, Figure 3.3). This suggests that excluding all birds from maize plant (exclosure treatment) was not an important predictor of crop yield because, if yields increase because of birds, I expect a greater effect (i.e. larger increase in yield) when there are more birds. Therefore, I concentrated on the abundance of insectivorous bird species; which make upthe trophic functional group that is likely to be providing pest control services to the farmlands.

Table 3. 1: The mean (± SE) of three experimental treatments (insect and birds excluded from crops, birds only excluded from crops and crops accessible to birds) across 20 farmlands.

	Replications (40 points)		
Parameters	Insect and birds excluded	Birds excluded	Open access
Crop yield	244.13 ± 35.67	306.33 ± 47.87	773 ± 48.35
Cobs of maize damage	0.025 ± 0.025	0.13 ± 0.064	0.075 ± 0.075
Number of cobs of maize	1.76 ± 0.19	1.93 ± 0.21	2.73 ± 0.16
Percentage of leaf damage	0.550 ± 0.550	2.625 ± 1.35	0.000 ± 0.000

Notes: Control treatment had a higher crop yield and cobs of maize relative to the birds excluded and birds and insects excluded. Mean proportion of leaf damage and cobs damage was highest in cages excluding birds only.

Table 3. 2: The relationship between crop yield and total bird abundance across the two treatments. The model including the interaction between treatment and bird abundance had a higher AIC by 1.5.

Parameters	Estimate	SE	*t*	*p*
(Intercept)	-10.22	139.72	-0.07	0.942
Bird abundance	5.58	2.32	2.40	**0.021**
Open access	466.68	57.21	8.16	**<0.001**

Notes: Birds excluded is set as the intercept. Significant p–values are given in bold. In the second best model with AIC value 1141.95**,** the interaction between treatment and bird abundance was not significant (p=0.489), therefore the interaction was removed from the starting model (Appendix 1: Table 2).

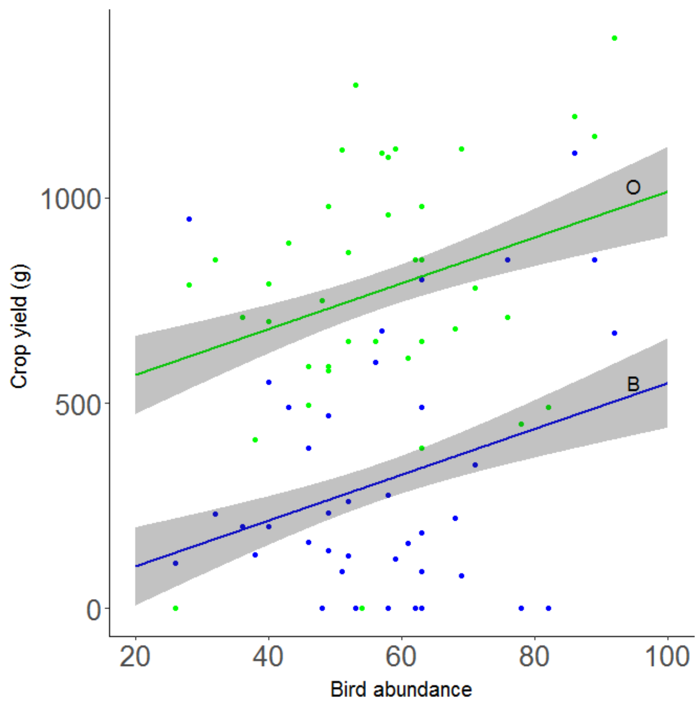

Figure 3. 3: Relationship between crop yield and bird abundance across treatments; O – open access and B – Birds excluded. Statistics are presented in Table 3.2

The best fit model from my GLMM to test the effect of insectivorous abundance on crop yield and whether or not this was influenced by treatment is presented in Table 3.3A. In this model, crop yield was significantly higher in open plots than in bird-excluded ones ($p<0.001$), but there was no significant interaction with insectivorous species abundance (Appendix 3.2: Table 1A). On the other hand, the full model (Figure 3.4 and Appendix 3.2: Table 1A) did indicate a positive non-significant- trend for higher yield in the control treatment plots with higher insectivorous species abundance, but no such pattern was observed in the bird-excluded plots.

The best fit model from my GLMM to test whether, and if so how, insectivorous species abundance affect cob damage is presented in Table 3.3B, and shows that there were no significant differences across treatments or species abundance; suggesting that this was not due to insectivorous bird species abundance (Appendix 3.2: Table 1B). Similarly, the best fit model from the GLMM to test the effect of insectivorous species abundance on phytophagous insect damage to leaves, and whether or not this is influenced by treatment is presented in Table 3.3C. In this case, there was only a suggestion of lower leaf damage in the open vs bird excluded treatments, but there is no indication that this being related to the abundance of insectivorous birds (Appendix 3.2: Table 1C).

The second set of objectives explored the influence of distance from forest fragments on insectivorous species abundance and crop yield. The best fit model predicting the relationship between distance and insectivorous species showed a significant positive effect of distance between forest fragment on insectivorous bird abundance (Table 3.4, Figure 3.5)

Table 3. 3: The relationship between maize crop productivity (crop yield, cobs damage and leaf damage) and insectivorous species abundance across the two treatments.

Variables	Estimate	SE	*t*	*p*
A. Crop yield model (AIC = 1145.62)				
(Intercept)	216.82	146.67	1.48	0.147
Insectivorous species	6.29	9.74	0.65	0.522
Open access	466.68	57.21	8.16	**<0.001**
B. Cob damage model (AIC = 102.02)				
(Intercept)	0.11	0.19	-0.59	0.556
Insectivorous species	0.017	0.012	1.35	0.183
Open access	-0.05	0.1	-0.51	0.613
C. Leaf damage model (AIC = 522.26)				
(Intercept)	3.06	2.6	1.18	0.247
Insectivorous species	-0.03	0.17	-0.18	0.859
Open access	-2.63	1.36	-1.94	**0.06**

Notes: Bird excluded was set as the intercept. Significant p–values are given in bold. Insectivorous species * treatment were not significant for all the three parameters; crop yield (p = 0.145), cobs damage (p = 0.927), and leaf damage (p = 0.860). A list of all full models is in Appendix 2: Table 1.

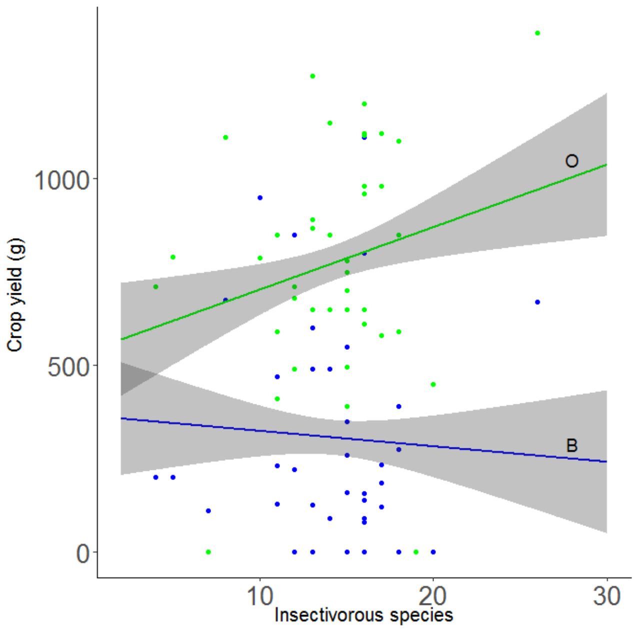

Figure 3. 4: Relationship between crop yield and insectivorous abundance across treatments; O – open access, and B – Birds excluded. Statistics are presented in Appendix 3.2: Table 1A, O showed a higher crop yield with a high abundance of insectivorous species and B showed insectivorous species affects crop yield; crop yield decrease with insectivorous species. Note the interaction is not statistically significant, but the trend is consistent with insectivores affecting yield.

Table 3. 4: The relationship between distance to forest fragment and insectivorous species abundance.

Variables	Estimate	SE	*t*	*p*
(Intercept)	12.90	0.85	15.20	**<0.001**
Distance	0.0053	0.0025	2.084	**0.044**

Significant p–values are given in bold

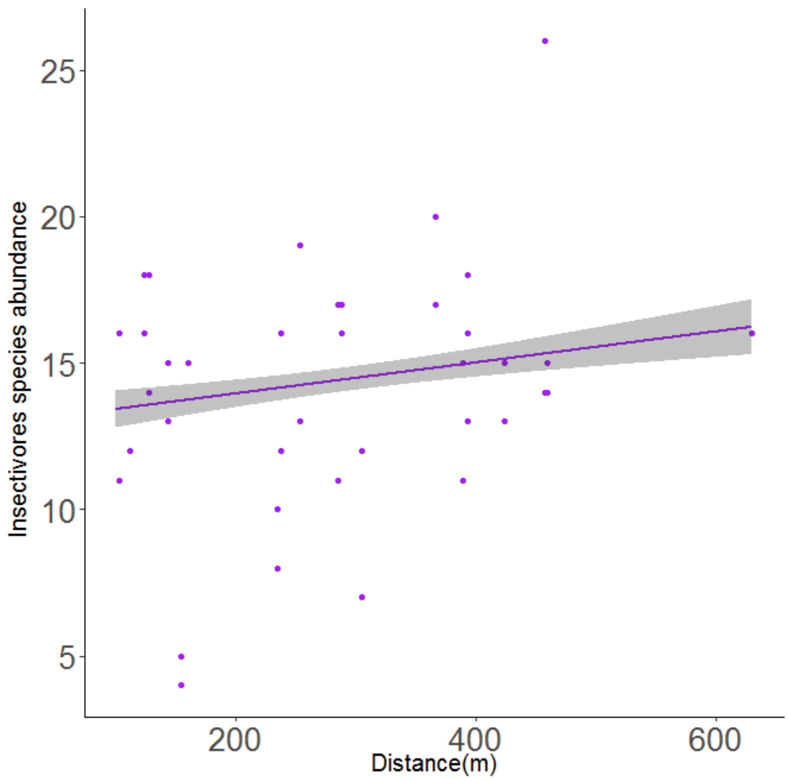

Figure 3. 5: The relationship between distance from forest fragments and insectivore abundance. Statistics are presented in Table 3.4.

Crop yield was also positively correlated with yield when experimental treatment was included in the model, but distance affected yield in a similar way for both treatment and control (Table 3.5A, Figure 3.6). There was no significant interaction between treatments and distance of farmland from forest fragments, so the interaction was removed from the starting model (Appendix 3.3: Table 1A). Neither distance, nor experimental treatment had a significant effect on cob damage, and there was also no difference in the effect of distance dependent on treatment (Table 3.5B, Appendix 3.3: Table 1B). This again suggests that the crop yield effects of excluding birds from maize plants were not due to birds reducing insect damage. Similarly, there was a marginal effect of treatment on leaf damage, but distance had no effect, and there was again no difference in the effect of distance, dependent on treatment (Table 3.5C, Appendix 3.3: Table 1C). Median values for leaf damaged on maize plants in the bird-excluded cages and leaf damaged on maize plants in the control treatment were similar, and the small differences observed were driven by a few relatively high values (Appendix 3.3: Figure 1; denoted as the outliers as shown by the red asterisk in the plot).

Table 3. 5: The relationship between maize crop productivity (crop yield, cobs damage and leaf damage) and distance to forest fragments across the two treatments

Variables	Estimate	SE	*t*	*p*
A. Best crop yield model (AIC = 1140.06)				
(Intercept)	115.01	89.56	1.28	0.207
Open access	466.68	57.21	8.16	**<0.001**
Distance	0.65	0.26	2.49	**0.017**
B. Best cob damage model (AIC = 102.81)				
(Intercept)	0.23	0.13	1.85	0.071
Open access	-0.05	0.1	-0.51	0.615
Distance	-0.0004	0.00035	-1.03	0.31
C. Best leaf damage model (AIC = 521.93)				
(Intercept)	3.47	1.72	2.02	**0.051**
Open access	-2.63	1.35	-1.94	**0.06**
Distance	-0.0029	0.0048	-0.59	0.558

Note: Bird excluded was set as the intercept. Significant p–values are given in bold. Distance * treatment were not significant for all the three parameters; crop yield (p = 0.561), cobs damage (p = 0.404), and leaf damage (p = 0.560). Thus, the interactions were removed from the models. A list of all full models is in Appendix 3.3: Table 1.

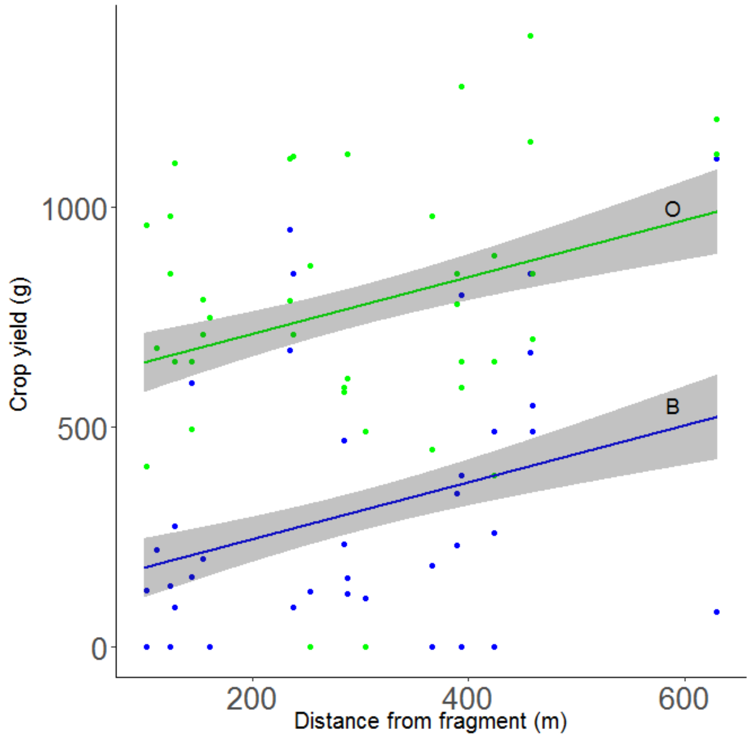

Figure 3. 6: The relationship between crop yield and distance of farmlands from forest fragments for the two treatments; O – open access, B – Birds excluded. Farmlands that are further away from the forest fragments had a higher crop yield. Statistics are presented in Table 3.5

3.4 Discussion

My results demonstrate that excluding insectivores from subsistence maize crops on the Mambilla plateau leads to a reduction in crop yield and crop quality, as compared with maize to which birds have open access. I have therefore, shown that natural pest control does increase crop yield. However, contrary to my expectations, my results do not show that insectivorous birds are solely responsible for this pest control. Moreover, I found no support for my hypothesis predicting a positive relationship between proximity of farms to forest fragments and the abundance of insectivorous birds. On the contrary, my results suggest that crop yield and insectivorous bird abundance both increased with distance away from forest fragments.

An important issue I faced was the apparent failure of the second treatment, bird and insect exclusion (see below). Consequently, I have based my conclusions on just the data from control (open) plots versus bird excluded plots. While this is not ideal (because there is no comparative measure of yield in the absence of insect damage to clearly demonstrate that the change in yield is due to the exclusion of insectivore pest control), the results make an important contribution to the literature by showing that the relationship between retaining forest fragments in a landscape and enhanced insect pest control is not straightforward.

3.4.1 Limitations of the study

Contrary to what was hypothesized, crop yield in the insect and bird exclosure treatment (theoretically eliminating insect crop damage) was lower than in the control treatment, and similar to that of bird exclusion only. This suggests that insects were not effectively excluded from the bird and insect exclosure treatment. In the cages built to exclude both insects and birds, insects may have laid their eggs on the maize plants prior to exclosure, and it is possible that this effect was inadvertently enhanced by the exclusion of larger insects or predatory wasps, crickets and spiders. Insect pests may also have entered the cages from below the cage base, although I was careful to pin them down securely to the ground. Alternatively, or in addition, the exclosure itself may have decreased yield in this treatment because of the negative effect of the mesh on growing conditions (e.g. through shading or microclimate). Another potential effect of the mesh may have been on pollination; maize is mostly wind pollinated and the cage meshing may have slowed wind flow past the maize. However, since the mean crop yield was also lower in the bird-only exclosure treatment compared to the control, the overall mean effects observed across treatments may be due to the exclusion of birds, rather than side effects of the net; which would have affected shading and air flow quite differently because of the difference in the size of the mesh in each treatment.

3.4.2 Crop yield – quantity and quality, and insectivorous bird abundance

Previous studies in a range of forestry and other agroecosystems have shown birds to be effective pest control agents (Bael et al., 2008; Karp et al., 2013; Maas et al., 2015; Martin et al., 2013; Mols & Visser, 2002). Moreover, some of these studies showed a positive relationship between bird abundance and levels of pest control either logarithmic (Maas et al., 2015) or linear (Crawford & Jennings, 1989). Therefore, I expected that excluding birds from maize crops would lead to reduced predation of phytophagous insects, allowing more insect damage to maize and associated loss of yield. However, that was not the case, which is supported by the fact that some previous studies did not find a link between insectivorous birds and pest control, e.g. (Morrison & Lindell, 2012; Tremblay et al., 2001; Williams-Guillén et al., 2008), so that my findings are not unique. The lack of this ecosystem service by birds as shown by my results may be partly due to the ecology of maize and/or Mambilla subsistence farmlands, or my experimental design, or perhaps, a combination of both ecology and design limitations. Because I found only a weak and non significant effect of insectivorous birds reducing leaf damage to maize, it is possible that birds in these subsistence farmlands do not consume sufficient quantities of insects to make a difference. Perhaps this is the case, and birds do not include maize plants as an important source of insects, especially if other crops in the system are more attractive to phytophagous insects.

Yet, it is apparent that there is some agent(s) controlling pests on maize, because I demonstrated a significant decrease in yield and an increase in insect damage when birds were excluded. Perhaps the key biocontrol insectivores in my study area are not birds, but bats. Previous studies elsewhere in the tropics have found that bats can play a significant role as predators of phytophagous insects. For example, Williams-Guillén et al. (2008), reported that bats have a larger impact in reducing arthropod abundance in Mexican coffee plantations than birds. This makes sense, especially because many herbivorous insects are most active at night (Maas et al., 2013; Morrison & Lindell, 2012) when bats are also active. For example, many insect pests of maize are night flying moths e.g. corn earworm moth, cutworms, army worms, cone worms, borers, and grain moths (Ortega, 1987), which presumably makes them more vulnerable to bat predation (Kalka & Kalko, 2006). Kunz et al. (2011), showed that most of these agricultural insect pests have been found in the diets of bats, as identified by their stomach contents and feacal samples. Due to logistical constraints, I was unable to test for bats – this would have involved going out at dawn and dusk to remove and replace cages and the security situation on the plateau did not allow for this. Bats are, however, common in the farmlands of my study area (Chapman *personal communication*).

Another explanation which has been given in previous studies for the lack of evidence for birds as pest control agents, is that entomophagous arthropods such as spiders, scorpions and centipedes (Agamy, 2003; Maas et al., 2016), are excluded alongside birds in exclusion experiments such as this study. However, the wire mesh I used in the bird exclusion experiment had large enough holes to allow such arthopods to move freely across the mesh boundary, and the yield in the treatment with mesh size small enough to exclude these arthropods was similar, which suggests that this was not the case. My finding is consistent with some other studies that showed birds did not control insect herbivory in farmlands and agroforestry e.g. (Lemessa et al., 2015; Maas et al., 2013; Morrison & Lindell, 2012; Williams-Guillén et al., 2008). In most of these studies, it was suggested that exclosure experiments might be biased because of the small areas of habitats enclosed, especially if the targeted species (i.e. the phytophagous insects in my study) are highly mobile and move freely (Greenberg et al., 2000; Tremblay et al., 2001). This can prevent a large build-up of insects in the exclosure cages, such that the effect of pest control on crop plants is not easily detected (Van Bael et al., 2003). Kunz et al. (2011), for example, suggested that exclosure experiments are likely to underestimate vertebrates' effects in insect pest control, because many insectivorous species capture insects in flight, further away from exclosures.

Alternatively, a significant proportion of insect pests of maize may not attack leaves, or at least do not make holes that significantly reduce leaf surface area. For example, *Busseola fusca* the stem borer (De Groote, 2002; Ofor et al., 2009) does relatively little damage to leaves but attacks maize stems (Tremblay et al., 2001). Similarly, aphids are phloem-feeding insects (Morrison & Lindell, 2012) and while they can severely damage plants, leading to reduced yield, they do not necessarily reduce leaf surface area by creating holes (Goggin, 2007; Zangerl et al., 2002). Indeed, Zangerl et al. (2002), showed that measuring holes in leaves of plants (as in my experiment), may underestimate the definite harm caused by chewing insects on plant productivity. This is because even with a tiny hole, the area of leaf adjacent to holes left by phytophagous insects can suffer severe reduced photosynthetic ability, sometimes more than the area with observable damage (Morrison & Lindell, 2012), which negatively affects crop productivity and which may increase mortality in seedlings and samplings (Eichhorn et al., 2010; Mäntylä et al., 2011). Thus, it is possible that in this study, birds had greater effect on insect pests than was apparent because crop damage due to insects potentially extends beyond insect herbivory on leaves (Morrison & Lindell, 2012). For example, in the case of the stem borer, birds may catch the moths and therefore reduce the number of larvae in the stems.

The general discrepancy in results from exclosure experiments in tropical agricultural systems as to whether or not birds significantly reduce leaf damage (through limiting herbivory) suggests that conclusions from any single study are not necessarily transferable among different regions and land use systems within the tropics (Maas et al., 2016): Table 3.6. Clearly my study is extremely important, because it is the only one carried out in West Africa. I therefore strongly recommend further studies on the economic importance of birds as well as other insect pest predators within the Nigerian agricultural landscape where land clearing present serious threats to ecosystem processes and biodiversity.

Table 3. 6: Summary of selected articles in tropical agricultural systems that quantified whether or not birds significantly reduced leaf damage using exclosure experiments

Measured effect	Author(s)	Habitat	Geographical location
Birds did not control for insect herbivory	Williams-Guillén et al., 2008	Coffee agroforest	Mexico
	Morrison and Lindell, 2012	Island	Costa Rica
	Mass et al., 2013	Cacao plantation	Indonesia
Birds reduced leaf damage through limiting insects herbivory	Greenberg et al., 2000	Coffee plantation	Guatemala
	Kalka et al., 2008	Tropical lowland forest	Panama
	Morrison and Lindell, 2012	Plantation	Costa Rica
Excluding birds only had a weak impact on leaf damage	Lemessa et al., 2015	Home-gardens	Ethiopia

3.4.3 Insectivorous birds, crop yield and distance to forest fragments

While I found a substantial effect of distance of farmland from forest fragment on both insectivorous bird abundance and crop yield, it was in the opposite direction to what was expected. Rather than forest fragments attracting insectivorous birds and therefore, indirectly improving pest control, I found the opposite. Insectivorous birds were more abundant, and crop yields higher, farther away from forest fragments. While I had based my hypothesis on the findings of several previous studies, including Maas et al., (2015) in a cocoa plantation in Central Sulawesi, Indonesia (Table 7), other studies had not found this positive relationship between forests, birds and crop yield. For example, Clough et al. (2009), working in cacao plantations in Indonesian forest found the diversity of insectivorous birds did not depend strongly on the distance to forest, and estimates for the effect of distance to the forest were substantially lower and more uncertain for insectivores than for forest specialists.

Table 3. 7: Summary of selected articles that assessed bird abundance in farmlands and or plantation in relation to forest proximity.

Measured effect	Author(s)	Habitat	Geographical location
Bird species abundance significantly decreases with increasing Distance to primary forest	Anand et al. (2008)	Coffee plantations, tropical moist deciduous forest, open habitats such as grasslands	India
	Laube et al. (2008)	Farmlands and Forest	Kenya
	Mass et al. (2015)	Cacao plantation and forest	Indonesia
Insectivorous birds did not depend strongly on the distance to forest	Clough et al. (2009)	Cocoa agroforestry, sub-montane rainforest	Indonesia

One possible explanation for the contradictory findings between this and other studies (Table 3.7) may be the different environments. Previous studies that have shown a decrease in bird abundance with increasing distance to primary forest in tropical agroforest landscapes, mostly in cocoa plantations, where fruits have evolved to be mammal dispersed. The authors recorded many forest specialists (particularly frugivores and nectarivores), which are unlikely to be able to subsist in cocoa plantations without the immediate proximity of natural forest e.g. (Clough et al., 2009). In complete contrast, my experiment was conducted on subsistence maize farms in a dry and predominantly grassland habitat. Here, insectivorous bird species comprised >50% of all birds recorded, and they likely have different habitat requirements to the forest specialists. I suggest that in the future, more experiments should be conducted on mixed farmlands, as well as different crop plants, which may have a higher diversity of insect pests (that may attract more birds). Alternatively, there is a possibility that only one or a few avian insectivore species feed on maize insect fauna, and that these species do not use forests as a favoured habitat. Another possibility is simply that rather than actually being more abundant, the insectivores were more detectable in farmlands away from the forest.

The increase in maize yield found with increasing distance from forest fragments in this study, could be driven by factors unrelated to insectivorous bird abundance. Such factors might include for example, age of farm, soil quality, habitat characteristics and abundance of insectivorous bats (see above). Other potential factors which may contribute to an explanation of my results include the fact that farmlands closer to forest fragments may have suffered disturbance from Tantalus monkeys (*Chlorocebus tantalus*), a common pest in maize farms on the Mambilla Plateau, which could affect crop yield (*pers-comm with* farmers). There are many potential confounding variables not considered in this study, and the relationships operating in this context - distribution patterns of insectivorous birds and bats, their effects on trophic cascades in tropical ecosystems and their landscape drivers in tropical forests and agroforestry systems – are complicated (Maas et al., 2016). Therefore, further studies that will assess the influence of landscape habitat characteristics and different land use patterns on ecosystem functioning in Nigeria are recommended.

In this study, I only explored the relationship between maize crops and distance to natural forest fragments. However, it may be that other habitats are more important for insectivorous birds in this system. So, for example, measuring the distance of maize crop from uncultivated grassland or eucalyptus plantations in this study, could have provided additional insights. Kavanagh et al. (2007) showed that eucalyptus plantations provided habitat for bird species, including many declining species in agricultural landscapes in south-eastern Australia. Currently, we do not know how important these habitats are for insectivorous birds (or bats) on the Mambilla Plateau even though such knowledge could inform the protection and conservation of bird species. Therefore, these areas of potential habitat for birds need investigation because they may hold a great abundance of alternative resources for bird species, confounding any relationship between crop yield and proximity to retained natural forest fragments.

3.4.4 Conclusion

My study was the first application of exclosure experiments in Nigerian subsistence farmlands to investigate potential ecosystem services by birds to crops. While I was unable to demonstrate any significant pest control by birds in the studied maize crop, (results showed that insectivorous bird abundance was not an important predictor of crop yield, cob damage or leaf damage), I demonstrated that natural pest control likely occurs, and that it affects yield substantially. My results point to pest control agents such as grassland or farmland bird species and possibly bats, other than forest-based insectivorous birds being the control agents. My results also suggest that in this area of Nigeria, at least, there may be no economic benefit to maize farmers, of retaining forest fragments near farms in terms of pest control (although other ecosystem services from retaining forest fragments such as watershed protection may provide strong arguments for their retention). Overall, farmers may be better off planting maize away from forest, which then suggests a conservation strategy of land sparing, rather than land sharing. However, there are clearly limitations in the methodology of the study, particularly with respect to the insect and bird exclusion treatment, which, therefore, makes the conclusions far from robust. Nevertheless, the results identify several issues, which in future studies should be addressed for more accurate results, and indicate that the hypothesis that retaining forest fragments in a West African farming landscape provides beneficial pest control ecosystem services is likely to be an over simplification, and is also context dependent.

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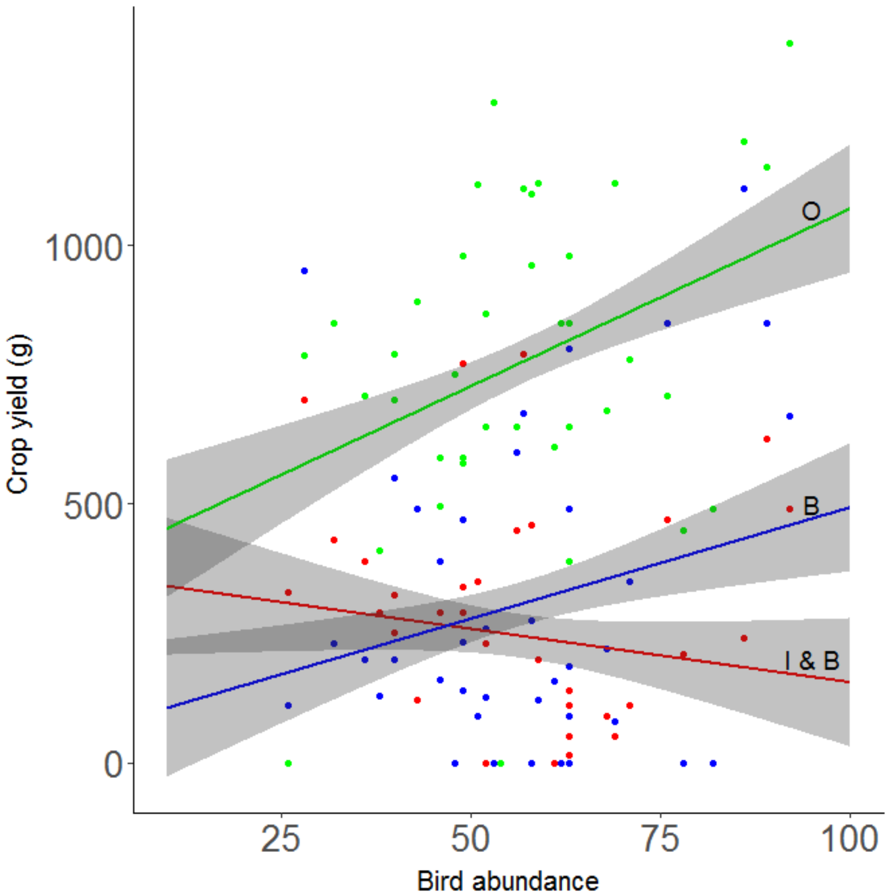
3.6 Appendices

Supplementary Information:

Appendix 3.1: Table 1. The relationship between maize crop productivity (crop yield, cob damage and leaf damage) and bird abundance across the three treatments.

Variables	**Estimate**	**SE**	***t***	***p***
A. Crop yield				
(Intercept)	361.07	162.26	2.23	**0.029**
Abundance	-2.06	2.76	-0.75	0.459
Birds excluded	-298.89	189.57	-1.58	0.119
Open access	22.99	189.57	0.12	0.904
Abundance*Birds excluded	6.37	3.22	1.98	**0.052**
Abundance*Open access	8.92	3.22	2.77	**0.007**
B. Cob damage				
(Intercept)	-0.011	0.22	-0.050	0.960
Abundance	0.00064	0.0038	0.17	0.867
Birds excluded	0.14	0.31	0.45	0.655
Open access	-0.0051	0.31	-0.016	0.987
Abundance*Birds excluded	-0.00070	0.0053	-0.13	0.895
Abundance*Open access	0.00097	0.0053	0.18	0.855
C. Leaf damage				
(Intercept)	-0.25	3.17	-0.078	0.938
Abundance	0.014	0.054	0.26	0.796
Birds excluded	6.91	3.93	1.76	0.083
Open access	0.25	3.93	0.063	0.950
Abundance*Birds excluded	-0.085	0.067	-1.28	0.206
Abundance*Open access	-0.014	0.067	-0.21	0.834

Insect and birds excluded as well as Insect and birds excluded* were set as the intercept. Significant p–values are given in bold.



Appendix 3.1: Figure 1. Relationship between crop yield and bird abundance across treatments; O – open access, B – Birds excluded, and I & B – Insects and Birds excluded. Crop yield increased with the increase in bird abundance for control treatment and birds excluded treatment. While for insects and birds excluded treatment, crop yield decreases with an increase in bird abundance. Statistics are presented in **Appendix 3.1: Table 1.**

Appendix 3.1: **Table 2**: The relationship between crop yield and bird abundance across the two treatments.

Variables	Estimate	SE	*t*	*p*
(Intercept)	62.18	174.59	0.36	0.724
Bird abundance	4.30	2.97	1.45	0.155
Open access	321.88	214.80	1.50	0.142
Bird abundance*Open access	2.55	3.65	0.70	0.489

Birds excluded as well as bird abundance*bird excluded is set as the intercept.

Appendix 3.2: **Table 1**. The relationship between maize crop productivity (crop yield, cobs damage and leaf damage) and insectivorous species abundance across the two treatments.

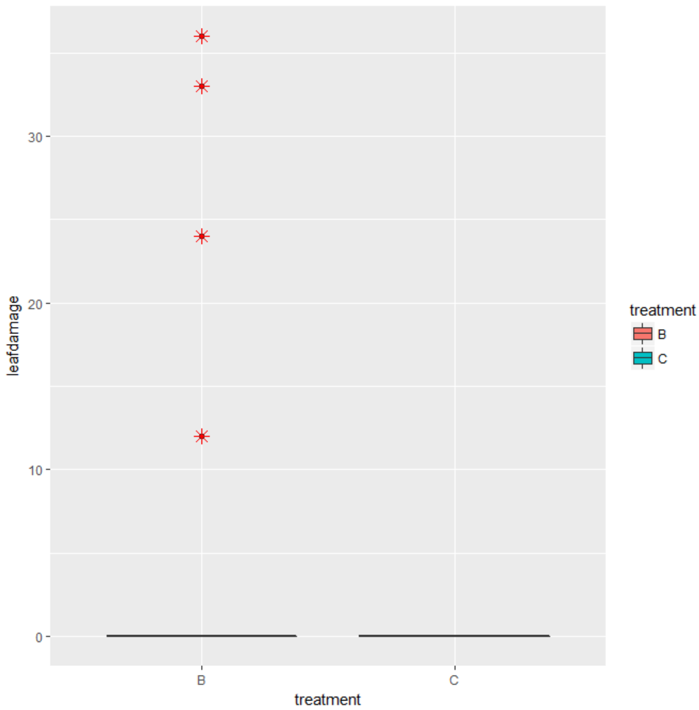
Variables	Estimate	SE	*t*	*p*
A. Crop yield (AIC = 1114.353)				
(Intercept)	365.15	178.062	2.051	**0.047**
Insectivorous species	-4.14	12.052	-0.34	0.733
Open access	170.017	207.27	0.82	0.417
Insectivorous*open access	20.85	14.03	1.49	0.145
B. Cob damage (AIC = 104.01)				
(Intercept)	-0.1	0.26	-0.37	0.714
Insectivorous birds	0.016	0.017	0.89	0.381
Open access	-0.082	0.37	-0.23	0.823
Insectivorous birds*open access	0.0023	0.025	0.092	0.927
C. Leaf damage (AIC = 524.23)				
(Intercept)	3.49	3.57	0.98	0.335
Insectivorous birds	-0.061	0.24	-0.25	0.803
Open access	-3.49	5.049	-0.69	0.494
Insectivorous birds*open access	0.061	0.34	0.18	0.860

Birds excluded is set as the intercept. Significant p–value is given in bold

Appendix 3.3: **Table 1**. The relationship between maize crop productivity (crop yield, cobs damage and leaf damage) and insectivorous species abundance across the two treatments.

Variables	Estimate	SE	*t*	*p*
A. Crop yield (AIC = 1141.70)				
(Intercept)	79.45	108.63	0.73	0.469
Open access	537.8	134.22	4.0067	**<0.001**
Distance	0.77	0.33	2.31	**0.026**
Open access*Distance	-0.24	0.41	-0.59	0.561
B. Cob damage (AIC = 104.06)				
(Intercept)	0.14	0.16	0.88	0.383
Open access	0.13	0.23	0.55	0.587
Distance	-0.000065	0.0005	-0.13	0.898
Open access*Distance	-0.00059	0.0007	-0.84	0.404
C. Leaf damage (AIC = 523.56)				
(Intercept)	4.32	2.25	1.92	0.063
Open access	-4.32	3.18	-1.36	0.183
Distance	-0.0057	0.0069	-0.83	0.411
Open access*Distance	0.0057	0.01	0.59	0.560

Birds excluded as well as distance*bird excluded is set as the intercept. Significant p–values are given in bold



Appendix 3.3: Figure 1. Box plots to illustrate mean leaf damage across the two treatments; B – Birds excluded, and C – control treatment

Appendix 3.4: List of all fitted models

Table 3.2: Crop yield = bird abundance + treatments, random=~1|replication, method="ML".

Table 3.3:

- **A.** Crop yield = insectivorous species abundance + treatments, random=~1|replication, method="ML
- **B.** Cob damage = insectivorous species abundance + treatments, random=~1|replication, method="ML".
- **C.** Leaf damage = insectivorous species abundance + treatment, random=~1|replication, method="ML".

Table 3.4: Insectivorous species abundance = distance, random=~1|replication, method="ML

Table 3.5:

- **A.** Crop yield = Distance + treatments, random=~1|replication, method="ML
- **B.** Cob damage = Distance + treatments, random=~1|replication, method="ML".
- **C.** Leaf damage = Distance + treatment, random=~1|replication, method="ML".

Appendix 3.1: Table 1:

- **A.** Crop yield = bird abundance + treatments + bird abundance * treatment, random=~1|replication, method="ML".
- **B.** Cob damage = bird abundance + treatments + bird abundance * treatment, random=~1|replication, method="ML".
- **C.** Leaf damage = bird abundance + treatments + bird abundance * treatment, random=~1|replication, method="ML".

Appendix 3.1: Table 2: Crop yield = bird abundance + treatments + bird abundance*treatment, random=~1|replication, method="ML".

Appendix 3.2: Table 1

- **A.** Crop yield = insectivorous species abundance + treatments + insectivorous species *treatment, random=~1|replication, method="ML.
- **B.** Cob damage = insectivorous species abundance + treatments + insectivorous species *treatment, random=~1|replication, method="ML".
- **C.** Leaf damage = insectivorous species abundance + insectivorous species*treatment, random=~1|replication, method="ML".

Appendix 3.3: Table 1

- **A.** Crop yield = distance + treatments + distance *treatment, random=~1|replication, method="ML.
- **B.** Cob damage = distance + treatments + distance *treatment, random=~1|replication, method="ML.
- **C.** Leaf damage = distance + treatments + distance *treatment, random=~1|replication, method="ML.

Appendix 3.5: Cricket; large arthropod in maize farmlands.

Appendix 3.6: Checklist of bird species recorded at experimental plots

Scientific name	Common names	Family name	TFG
Sylvietta virens	Green Crombec	Macrosphenidae	insectivorous
Polyboroides typus	African Harrier-hawk	Accipitridae	carnivore
Halcyon malimbica	Blue-breated kingfisher	Alcedinidae	pisces
Halcyon senegalensis	Woodland Kingfisher	Alcedinidae	pisces
Apus caffer	White-rumped Swift	Apodidae	insectivorous
Cisticola chubbi	Chubb's Cisticola	Cisticolidae	insectivorous
Crithagra gularis	Streaky-headed Seedeater	Fringillidae	granivores
Tchagra australis	Brown-crowned Tchagra	Malaconotidae	insectivorous
Chalcomitra senegalensis	Scarlet-chested Sunbird	Nectariniidae	nectarivores
Vidua chalybeata	Village Indigobird	Viduidae	insectivorous
Hieraaetus ayresii	Ayres's Hawk-eagle	Accipitridae	carnivore
Circus pygagus	Montagu’s Harrier	Accipitridae	carnivore
Hieraaetus pennatus	Booted Eagle	Accipitridae	carnivore
Circus aeruginosus	Western Marsh Harrier	Accipitridae	carnivore
Kaupifalco monogrammicus	Lizard Buzzard	Accipitridae	carnivore
Circus pygargus	Montagu's Harrier	Accipitridae	carnivore
Acrocephalus (scirpaceus) baeticatus	African Reed-warbler	Acrocephalidae	insectivorous
Mirafra rufocinnamomea	Flappet Lark	Alaudidae	insectivorous
Galerida modesta	Sun lark	Alaudidae	insectivorous
Cypsiurus parvus	African Palm-swift	Apodidae	insectivorous
Apus horus	Horus Swift	Apodidae	insectivorous
Telacanthura ussheri	Mottled Spinetail	Apodidae	insectivorous
Ardea purpurea	Purple Heron	Ardeidae	carnivore
Lophoceros nasutus	African Grey Hornbill	Bucerotidae	frugivores

Bycanister fistulator	Western Piping Hornbill	Bucerotidae	frugivores
Campephaga phoenicea	Red-shouldered Cuckooshrike	Campephagidae	insectivorous
Caprimulgus longipennis	Standard-winged Nightjar	Caprimulgidae	insectivorous
Vanellus superciliosus	Brown-chested Lapwing	Charadriidae	insectivorous
Ciconia abdimii	Abdim's Stork	Ciconiidae	insectivorous
Ciconia episcopus	Asian Woollyneck	Ciconiidae	carnivore
Oreolais pulcher	Black-collared Apalis	Cisticolidae	insectivorous
Apalis bamendae	Bamenda apalis	Cisticolidae	insectivorous
Apalis rufogularis	Buff-throated Apalis	Cisticolidae	insectivorous
Urolais epichlorus	Green Longtail	Cisticolidae	insectivorous
Streptopelia hypopyrrha	Adamawa Turtle-dove	Columbidae	frugivores
Streptopelia decipiens	Mourning Collared-dove	Columbidae	frugivores
Columba sjostedti	Cameroon Olive-pigeon	Columbidae	frugivores
Spilopelia senegalensis	Laughing Dove	Columbidae	frugivores
Coracias abyssinicus	Abyssinian Roller	Coraciidae	insectivorous
Coracias naevius	Purple Roller	Coraciidae	insectivorous
Chrysococcyx cupreus	African Emerald Cuckoo	Cuculidae	insectivorous
Chrysococcyx caprius	Diederik Cuckoo	Cuculidae	insectivorous
Clamator levaillantii	Levaillant's Cuckoo	Cuculidae	insectivorous
Dicrurus modestus	Velvet-mantled Drongo	Dicruridae	insectivorous
Estrilda astrild	Common Waxbill	Estrildidae	granivores
Euschistospiza dybowskii	Dybowski'sTwinspot	Estrildidae	granivores
Falco biarmicus	Lanner Falcon	Falconidae	carnivores
Crithagra burtoni	Thick-billed Seedeater	Fringillidae	granivores
Indicator minor	Lesser Honeyguide	Indicatoridae	insectivorous
Melichneutes robustus	Lyre-tailed Honeyguide	Indicatoridae	insectivorous
Melignomon eisentrauti	Yellow-footed Honneyguide	Indicatoridae	insectivorous
Gymnobucco calvus	Naked-faced Barbet	Laniidae	frugivores
Pogoniulus scolopaceus	Speckled Thinkerbird	Lybiidae	frugivores
Trachylaemus purpuratus	Eastern Yellow-billed Barbet	Lybiidae	frugivores
Merops variegatus	Blue-breated Bee-eater	Meropidae	insectivorous
Merops gularis	Black Bee-eater	Meropidae	insectivorous
Anthus similis	Long-billed Pipit	Motacillidae	insectivorous
Motacilla flava	Western Yellow Wagtail	Motacillidae	insectivorous
Muscicapa adusta	African Dusky Flycatcher	Muscicapidae	insectivorous
Cossypha cyanocampter	Blue-shouldered Robin-chat	Muscicapidae	insectivorous
Myioparus plumbeus	Grey Tit-flycatcher	Muscicapidae	insectivorous
Oenanthe oenanthe	Northern Wheatear	Muscicapidae	insectivorous
Cossypha albicapillus	White-crowned Robin-chat	Muscicapidae	insectivorous
Cyanomitra olivacea	Olive Sunbird	Nectariniidae	nectarivores
Oriolus auratus	African Golden Oriole	Oriolidae	frugivores
Melaniparus guineensis	Pale-eyed Black Tit	Paridae	insectivorous
Jynx torquilla	Eurasian Wryneck	Picidae	insectivorous
Campethera punctuligera	Fine-spotted Woodpecker	Picidae	insectivorous
Jynx ruficollis	Rufous-necked Wryneck	Picidae	insectivorous
Arizelocichla montana	Cameroon Mountain Greenbul	Pycnonotidae	frugivores
Eurillas virens	Little Greenbul	Pycnonotidae	generalist
Pyrrhurus scandens	Leaf-love	Pycnonotidae	insectivorous
Thescelocichla leucopleura	Swamp Palm Bulbul	Pycnonotidae	frugivores
Arizelocichla tephrolaema	Western Mountain Greenbul	Pycnonotidae	frugivores
Sarothrura pulchra	White-spotted Flufftail	Rallidae	insectivorous

Hylia prasina	Green Hylia	Scotocercidae	insectivorous
Elminia nigromitrata	Dusky Crested-flycatcher	Stenostiridae	insectivorous
Phylloscopus herberti	Black-capped Woodland Warbler	Phylloscopidae	insectivorous
Bradypterus (lopezi) bangwaensis	Bangwa Warbler	Sylviidae (Locustellidae)	insectivorous
Schoenicola platyurus	Broad-tailed Grassbird	Sylviidae (Locustellidae)	insectivorous
Sylvia (Pseudoalcippe) abyssinica	African Hill-babbler	Sylviidae (Timaliidae)	insectivorous
Lanius collaris	Common Fiscal	Laniidae	insectivorous
Gyps africanus	White-backed Vulture	Accipitridae	carrion
Accipiter melanoleucus	Black Sparrowhawk	Accipitridae	carnivore
Elanus axillaris	Black-shouldered kite	Accipitridae	carnivore
Necrosyrtes monachus	Hooded Vulture	Accipitridae	carrion
Lophaetus occipitalis	Long-crested Eagle	Accipitridae	carnivores
Buteo auguralis	Red-necked Buzzard	Accipitridae	carnivore
Acrocephalus schoenobaenus	Sedge Warbler	Acrocephalidae	insectivorous
Mirafra africana	Rufous-naped Lark	Alaudidae	insectivorous
Ispidina picta	African Pygmy-kingfisher	Alcedinidae	pisces
Halcyon leucocephala	Grey-headed Kingfisher	Alcedinidae	pisces
Ardea melanocephala	Black-headed heron	Ardeidae	carnivore
Bubulcus ibis	Cattle Egret	Ardeidae	insectivorous
Egretta garzetta	Little Egret	Ardeidae	insectivorous
Buphagus africanus	Yellow-billed Oxpecker	Buphagidae	carnivore
Venellus senegallus	Wattled Lapwing	Charadriidae	insectivorous
Cisticola natalensis	Croaking cisticola	Cisticolidae	insectivorous
Camaroptera brachyura	Grey-backed (Bleating) Camaroptera	Cisticolidae	insectivorous
Apalis cinerea	Grey Apalis	Cisticolidae	insectivorous
Hypergerus atriceps	Oriole Warbler	Cisticolidae	insectivorous
Cisticola brunnescens	Pectoral-patch Cisticola	Cisticolidae	insectivorous
Cisticola erythrops	Red-faced Cisticola	Cisticolidae	insectivorous
Eremomela pusilla	Senegal Eremomela	Cisticolidae	insectivorous
Cisticola cantans	Singing Cisticola	Cisticolidae	granivores
Cisticola brachypterus	Short-winged Cisticola	Cisticolidae	insectivorous
Prinia subflava	Tawny-flanked Prinia	Cisticolidae	insectivorous
Cisticola lateralis	Whistling Cisticola	Cisticolidae	insectivorous
Schistolais leucopogon	White-chinned Prinia	Cisticolidae	insectivorous
Cisticola juncidis	Zitting Cisticola	Cisticolidae	insectivorous
Colius striatus	Speckled Mousebird	Coliidae	frugivores
Treron calvus	African Green-pigeon	Columbidae	frugivores
Turtur afer	Blue-spotted Wood-dove	Columbidae	frugivores
Streptopelia semitorquata	Red eyed Dove	Columbidae	frugivores
Turtur tympanistria	Tambourine Dove	Columbidae	frugivores
Streptopelia vinacea	Vinaceous Dove	Columbidae	frugivores
Corvus albus	Pied Crow	Corvidae	omnivorous
Centropus senegalensis	Senegal Coucal	Cuculidae	insectivorous
Dicrurus ludwigii	Square-tailed Drongo	Dicruridae	insectivorous
Emberiza affinis	Brown-rumped Bunting	Emberizidae	insectivorous
Emberiza tahapisi	Cinnamon-breasted Bunting	Emberizidae	granivores
Lagonosticta rufopicta	Bar-breasted Firefinch	Estrildidae	granivores
Lagonosticta rara	Black-bellied Firefinch	Estrildidae	granivores
Estrilda nonnula	Black-crowned Waxbill	Estrildidae	granivores
Spermestes cucullata	Bronze mannikin	Estrildidae	granivores

Clytospiza monteiri	Brown Twinspot	Estrildidae	granivores
Nigrita canicapillus	Grey-headed Nigrita	Estrildidae	granivores
Estrilda melpoda	Orange-cheeked Waxbill	Estrildidae	granivores
Uraeginthus bengalus	Red-cheeked Cordon-blue	Estrildidae	granivores
Pytilia hypogrammica	Yellow-winged Pytilia	Estrildidae	granivores
Falco alopex	Fox kestrel	Falconidae	carnivore
Crithagra mozambica	Yellow-fronted Canary	Fringillidae	granivores
Neophedina cincta	Banded Martin	Hirundinidae	insectivorous
Psalidoprocne pristoptera	Black Saw-wing	Hirundinidae	insectivorous
Riparia paludicola	African Plain Martin	Hirundinidae	insectivorous
Ptyonoprogne fuligula	Large Rock Martin	Hirundinidae	insectivorous
Pogonornis bidentatus	Doubled-toothed Barbet	Lybiidae	frugivores
Pogoniulus coryphaea	Western Green Thinkerbird	Lybiidae	frugivores
Pogoniulus bilineatus	Yellow-rumped Tinkerbird	Lybiidae	frugivores
Melocichla mentalis	African Moustached Grass-warbler	Macrosphenidae	insectivorous
Sylvietta brachyura	Northern Crombec	Macrosphenidae	insectivorous
Tchagra senegalus	Black-crowned Tchagra	Malaconotidae	insectivorous
Bocagia minuta	Marsh Tchagra	Malaconotidae	insectivorous
Dryoscopus gambensis	Northern Puffback	Malaconotidae	insectivorous
Laniarius aethiopicus	Tropical Boubou	Malaconotidae	frugivores
Laniarius atroflavus	Yellow-breasted Boubou	Malaconotidae	frugivores
Merops pusillus	Little Bee-eater	Meropidae	insectivorous
Elminia longicauda	African Blue-flycatcher	Monarchidae	insectivorous
Terpsiphone viridis	African Paradise-flycatcher	Monarchidae	insectivorous
Anthus cinnamomeus	African Pipit	Motacillidae	insectivorous
Anthus leucophrys	Plain-backed Pipit	Motacillidae	insectivorous
Anthus trivialis	Tree Pipit	Motacillidae	insectivorous
Macronyx croceus	Yellow-throated Longclaw	Motacillidae	insectivorous
Saxicola torquatus	Common (African) Stonechat	Muscicapidae	insectivorous
Oeananthe familiaris	Familiar Chat	Muscicapidae	insectivorous
Melaenomis edolioides	Northern Black-flycatcher	Muscicapidae	insectivorous
Ficedula hypoleuca	European Pied Flycatcher	Muscicapidae	insectivorous
Cossypha niveicapilla	Snowy-Crowned Robin-chat	Muscicapidae	insectivorous
Myrmecocichla nigra	Sooty Chat	Muscicapidae	insectivorous
Tauraco persa	Green Turaco	Musophagidae	frugivores
Tauraco leucolophus	White-crested Turaco	Musophagidae	frugivores
Crinifer piscator	Western Grey Plantain-eater	Musophagidae	frugivores
Tauraco macrorhynchus	Yellow-billed Turaco	Musophagidae	frugivores
Cinnyris cupreus	Copper Sunbird	Nectariniidae	nectarivores
Cyanomitra verticalis	Green-headed Sunbird	Nectariniidae	nectarivores
Cinnyris reichenowi	Northern Doubled-collared Sunbird	Nectariniidae	nectarivores
Cinnyris bouvieri	Orange-tufted Sunbird	Nectariniidae	nectarivores
Cinnyris coccinigastrus	Splendid Sunbird	Nectariniidae	nectarivores
Cinnyris venustus	Variable Sunbird	Nectariniidae	nectarivores
Passer griseus	Northern Grey-headed Sparrow	Passeridae	granivores
Ptemistis bicalcaratus	Doubled spurred Francolin	Phasianidae	generalist
Ptemistis squamatus	Scaly Francolin	Phasianidae	generalist
Phoeniculus purpureus	Green Woodhoopoe	Phoeniculidae	insectivorous
Phylloscopus trochilus	Willow Warbler	Phylloscopidae	insectivorous
Dendropicos goertae	Grey Woodpecker	Picidae	insectivorous
Platysteira cyanea	Brown-throated Wattle-eye	Platysteiridae	insectivorous

Ploceus bannermani	Bannerman's Weaver	Ploceidae	granivores
Ploceus melanogaster	Black-billed Weaver	Ploceidae	granivores
Ploceus baglafecht	Baglafecht Weaver	Ploceidae	granivores
Ploceus bicolor	Dark-backed Weaver	Ploceidae	granivores
Euplectes hartlaubi	Hartlaub's Marsh Widowbird	Ploceidae	granivores
Euplectes ardens	Red-Collared Widowbird	Ploceidae	granivores
Ploceus ocularis	Spectacled Weaver	Ploceidae	granivores
Ploceus nigerrimus	Viellot's Black Weaver	Ploceidae	granivores
Ploceus cucullatus	Village Weaver	Ploceidae	granivores
Euplectes capensis	Yellow Bishop	Ploceidae	granivores
Euplectes macroura	Yellow-mantled Widowbird	Ploceidae	granivores
Pyconotus barbatus	Common Bulbul	Pycnonotidae	generalist
Bleda syndactylus	Red-tailed Bristlebill	Pycnonotidae	insectivorous
Atimastillas flavicollis	Yellow-throated Greenbul	Pycnonotidae	frugivores
Zapornia flavirostra	Black Crake	Rallidae	omnivorous
Scopus umbretta	Hamerkop	Scopidae	carnivores
Ptilopsis leucotis	Northern White-faced owl	Strigidae	carnivore
Sylvia communis	Common Whitethroat	Sylviidae	omnivorous
Sylvia borin	Garden Warbler	Sylviidae	insectivorous
Bostrychia hagedash	Hadada Ibis	Threskiornithidae	carnivores
Turdus pelios	African Thrush	Turdidae	insectivorous
Saxicola rubetra	Whinchat	Turdidae	insectivorous
Megabyas flammulatus	African Shrike-flycatcher	Vangidae	insectivorous
Vidua macroura	Pin-tailed Whydah	Viduidae	granivores
Zosterops senegalensis	African Yellow White-eye	Zosteropidae	insectivorous
Upupa epops	Common Hoopoe	Upupidae	insectivorous

Chapter 4: Bird predation on artificial insect models across Mambilla farmlands

Abstract

Bird predation may be important in regulating insect herbivory in subsistence farmlands. However, quantitative estimates of pest predation by birds in subsistence farms and how these might depend on retained natural habitats near farmlands is largely unknown in Africa. I used plasticine mimics of caterpillars, insect larvae and beetles on experimentally grown crops on the Mambilla Plateau, South Eastern Nigeria to test whether, and to what extent, pests were attacked by insectivorous birds. I also investigated whether attack rates depended on the proximity of farmlands to forest fragments. I placed 90 potted plants each of groundnut (*Arachis hypogea*), and Bambara nut (*Vigna subterranea*) across 15 line transects and distributed 540 mimics across the two crop plant species. Mimics were inspected daily for 12 weeks to record (i) the presence of bird beak marks, and (ii) the number of missing mimics. All mimics were collected weekly for beak mark identification, and subsequently replaced, after removing all existing marks. I found a strong positive correlation between the abundance of insectivorous birds and mean number of missing mimics and/or bird attack marks on mimics. The positive effect of insect-eating bird abundance on prey mimics became less strong the farther they were from a forest fragment. I found increased predation rates and abundance of insectivorous birds closer to forest fragments. Bird predation rates were higher on the mimics placed on groundnut plants than on Bambara nut plants, but did not vary with mimic colour. My results suggest that pest predation may be a key ecosystem service provided by insectivorous birds on Nigerian farmlands, and farmlands that are closer to forest fragments may experience a higher rate of pest control by insectivorous birds than those further away.

4.1 Introduction

Food insecurity is a major challenge in Africa (Mwaniki, 2006) and there is a need to strongly increase food production through agricultural practices. About 80% of Africa's population derive their livelihood directly from subsistence agriculture (Carvalho, 2006; FAO, 2015). However, a major challenge faced by African subsistence farmers is loss of productivity through crop damage caused by insect pests (Oerke, 2006; Oliveira et al., 2014; van Lenteren et al., 2018; Wilson & Tisdell, 2001). Many studies have shown that insect pests are major competitors with humans for resources generated by agriculture (Oerke &

Dehne, 2004), either in the field (i.e., during planting or pre-harvest) and during storage (post-harvest; Oerke, 2006). In sub-Saharan Africa, Lepidopteran stem borers (*Busseola fusca*) and the fall armyworm (*Spodoptera frugiperda*) are among the most destructive insect pests of crops, accounting for up to 75% of yield losses (De Groote, 2002; Kfir et al., 2002; Kipkoech et al., 2006; Moolman et al., 2014; Mutamiswa et al., 2017), threatening both food security and farmers' income (Zhang et al., 2018). Similarly, various species of mealybugs are appearing in high proportions on crop plants, vegetables, fruits and ornamentals (Tanwar et al., 2007); the cassava mealybug, (*Phenacoccus manihoti*; Homoptera: Pseudococcidae), has consistently remained the most destructive pest of cassava in Africa (Neuenschwander, 2001). In West Africa, 57.8% of food insecurity is caused by insect pests; for example, Niger's food crisis in 2005 was attributed to a locust invasion that destroyed crop yields (Zakari et al., 2014). About 30% of cocoa yield loss in Nigeria was caused by the brown cocoa mirid (*Sahlbergella singularis*; Anikwe et al., 2010). In western Kenya, 12.9% of crop loss was caused by stemborers (De Groote, 2002), while 13.5% of crops inspected were damaged (De Groote et al., 2004). In several North African countries, the tomato leaf miner, *Tuta absoluta* (Meyrick; Lepidoptera: Gelechiidae) is one of the recent devastating pests attacking tomato crops (Goda et al., 2015). This pest is considered a key agricultural threat to North African tomato production; it feeds on all aerial parts of tomato plants, causing economic losses of up to 80%–100% (Desneux et al., 2010; Goda et al., 2015). For Africa, these represent a significant food insecurity problem.

Globally, pesticides are used in agriculture to secure yields and sometimes to improve the quality of food (Atreya et al., 2012). In fact, the green revolution has no doubt justified the use of pesticides; by the year 2050, agriculture must feed 10 billion people, which means there is a need to increase world food supplies e.g. (Green et al., 2005; Tilman et al., 2002; Tilman et al., 2001), and one way to achieve this is by usage of pesticides (Carvalho, 2006). This has no doubt led to increased world food supplies, but at the same time caused several ecological and environmental problems (Carvalho, 2006; Wilson & Tisdell, 2001). About three billion tons of pesticides are applied each year in the world (Paoletti & Pimentel, 2000), and thus, one would expect a complete eradication of insect pests in crop plants; yet insect pests destroy up to 40% of all crops (Deutsch et al., 2018; Oerke & Dehne, 2004; Oliveira et al., 2014; Paoletti & Pimentel, 2000). This could possibly be because the high and continuous use of insecticides has led to the development of insecticide resistance by insect pests (Haddi, 2012). Therefore, the continuous use of pesticides for insect pest control may eventually have a negative impact on agricultural production and reduce agricultural sustainability. A major concern is that the high usage of chemical pesticides in agriculture is likely to contaminate the ecosystem and environment and may increase the health risk of farmers, consumers and other mammals (Pimentel & Burgess, 2014). Every year worldwide, the use of pesticides causes 26 million non-fatal poisonings, with three million people hospitalised, 220 thousand dead and about 750 thousand developing chronic illnesses (Pimentel & Burgess, 2014). Atreya et al., (2012) showed that in the United States, pesticide poisonings have been estimated to be 300 thousand per year. It is important to note that in agricultural systems of most developing countries, farmers are entrapped in the systems of pest control, using pesticides that result in many unintentional risks (Wilson & Tisdell, 2001). Moreover, while the majority of developed countries use less toxic chemicals, for example, herbicides, the most common chemicals used in developing countries are insecticides, which have led to insecticide resistance in pests (Day et al., 2017) and damage to human health (Hart & Pimentel, 2002; Pimentel & Burgess, 2014). Therefore, the uninhibited use of chemical pesticides has necessitated alternatives, mainly due to human and environmental concerns.

An alternative to the use of chemicals is vertebrate biological control. Vertebrates (e.g., birds as predators of insect pests) may provide an economically and environmentally sound alternative to chemical pest control (Berger & Wirth, 2004; Sekercioglu, 2006; Whelan et al., 2015; Whelan, Wenny, & Marquis, 2008). Many recent studies show that birds provide important pest control services on crop plants in both temperate and tropical agricultural landscapes (Bael et al., 2008; Classen et al., 2014; Howe et al., 2009; Kellermann et al., 2008; Lemessa et al., 2015; Maas et al., 2015). They show not only that bird predation reduces herbivorous insect populations, but that plants respond to this reduction with higher crop yield (Classen et al., 2014; Koh, 2008; Van Bael et al., 2003). For example, in the tropics, caterpillars were effectively reduced by insectivorous birds in different types of agroecosystems (Maas et al., 2013; Mols & Visser, 2002). Maas et al. (2015) found that the damage to cocoa flowers by lepidopteran larvae affected crop yield, and the absence of birds resulted in a 9% reduction of final crop yield. Similarly, Mols and Visser (2002) found that great tits (*Parus major*) reduced lepidopteran larvae densities in an apple plantation; the drop was 2.6% of the original (from 13.8% to 11.2%), thereby increasing yield per tree from 4.7 kg to 7.8 kg. Other studies from Neotropical coffee agro-forestry have conclusively demonstrated high bird predation rates on coffee berry borer beetle (*Hypothenemus hampei*) abundance, resulting in a significant increase in crop yields (Karp et al., 2013; Perfecto et al., 2004). A study by Kellerman et al. (2008) reported that bird predation on the coffee berry borer saved farmers US$310 ha^{-1} in coffee yield loss in one Jamaican plantation. Thus, the benefits of birds in biocontrol are considerable. Nevertheless, bird predation success is likely to be influenced by other factors (Bael et al., 2008), including habitat complexity (Philpott et al., 2009) and surrounding landscape (Clough et al., 2009). For bird species, especially insectivorous birds, the degree of herbivorous insect regulation they provide may depend on the landscape context, such as the proximity of habitat that sustains them, e.g forest (Maas et al., 2016; Tscharntke et al., 2008).

4.1.2 Bird predation success in relation to forest fragments

Forest fragments around farmlands are a key feature repeatedly associated with increased predation rates by birds that feed on insect pests in agricultural landscapes (Karp et al., 2013; Maas et al., 2013). Many studies in the tropics have linked the success of birds as predators of insect herbivores in agro-forestry with native forest proximity (Clough et al., 2009; Daily et al., 2001; Lemessa et al., 2015; Philpott et al., 2009; Puckett et al., 2009; Taylor et al., 1993). Several other studies on predation by birds have shown how bird species use forest fragments as sites for breeding, hibernation and roosting (Fuller et al., 2001), while providing pest control services in the adjacent farmlands (Sekercioglu, 2012). Therefore, conservation of forest fragments is hypothesised to improve farm yield by supporting bird predators of crop pests. For example, in Central Sulawesi, the lemon-bellied white-eye (*Zosterops chloris*) occurs in both coffee plantation and forest habitats. It plays an important role in suppressing insect pests in the coffee plantation, and control is enhanced by the plantation's proximity to forest (Clough et al., 2009).

4.1.3 Nigerian forest–agricultural landscape

The agricultural landscape in south-eastern Nigeria consists of a mosaic of small subsistence farms with annual crops such as maize, groundnuts, and Bambara nuts, with patches of forest at varying distances from the crop fields (Richard, 2014). Caterpillars, beetles and larvae are important insect pests of ground nuts and Bambara nuts, and outbreaks result in the reduction of potential crop yield (Ebregt et al., 2005; Wightman & Wightman, 1994). However, such landscapes should theoretically harbour bird species that could predate on the invertebrate pests. Thus, Nigerian subsistence farmers could potentially benefit from biological pest control by birds, and if forests are important for insectivores, the efficacy of control may be influenced by proximity of farm to forest. Although there have been no studies to test this hypothesis of pest control by birds in Nigerian subsistence farmlands, my initial survey on the bird community structure of the agricultural- forest landscape of the Mambilla Plateau recorded 202 bird species. These included many insectivores, indicating the potential for biological pest control services. Therefore, it was important that I used field experiments to quantify bird predation rates on insect pests in subsistence farmlands that are close to forest fragments. Such experiments could provide key knowledge of biocontrol services by birds as well as the value of proximity to retained forest fragments to subsistence farmers for their crop plants.

4.1.4 Measuring pest predation rate

It is difficult to observe and measure the actual rates of pest control services like bird predation rates on insects. Birds are relatively small, they attack quickly and infrequency, and most predation leaves no trace (Low et al., 2014). However recently, artificial plasticene models of prey, e.g., caterpillars, have been used to assess predation rates from attack marks left in the plasticine (Roels et al., 2018; Roslin et al., 2017; Seifert et al., 2015). This method has been shown to provide reasonably accurate information on predator activities and allows the assessment of relative predation pressure by different predators, including birds, because predators leave recognisable marks on the attack model, at least to a higher taxonomic level (Koh & Menge, 2006; Posa et al., 2007; Tvardikova & Novotny, 2012). Plasticine – a soft modelling material is available in different colours and can be made into different sizes (Howe et al., 2009). It can be modelled to resemble specific prey species (Roels et al., 2018; Roslin et al., 2017). For example, green and brown coloured plasticine is often used to imitate artificial caterpillars because they are perceived by predators to be palatable and undefended (i.e., lacking hairs or striking colours indicative of a defence mechanism to predators; Howe et al., 2015; Low et al., 2014; Seifert et al., 2015; Tvardikova & Novotny, 2012).

4.1.5 Biological pest control research gaps in Nigeria

Internationally, biocontrol services by bird species are one of the recognised ecosystem services in forest–agricultural landscapes. However, our knowledge about this level of biocontrol is lacking in sub-Saharan Africa’s agricultural landscapes, particularly in Nigeria, and it is not known whether forest fragments increase pest control and boost yield at any scale. To date, no study in tropical Nigeria has investigated the importance of forest fragments for bird predation services on crop plants using predation field experiments. There is a need for functional biocontrol studies (directly measured in a standardised field experiment), which will show a causative link between bird predation rates on crop pests and the importance of retaining forest fragments for predation success.

In this chapter, I aimed to fill the gap by investigating: (i) whether pests (using artificial plasticine models) are attacked by insect-eating birds, (ii) whether different prey types (i.e., different prey models) are attacked at different rates, and (iii) whether this predation rate depends on the proximity of farmland to forest fragments. I created mimics from green and brown plasticine to resemble caterpillars and used grey plasticine to resemble beetles and insect larvae. I placed the insect mimics on crop plants of groundnuts and Bambara nuts in farmlands. I used groundnuts and Bambara nuts in this study because they are common food and cash crops grown in the savanna regions of Africa (Berchie et al., 2012; Ebregt et al., 2005; Richard, 2014; Zakari et al., 2014). They are very important for the farmers on the Mambilla Plateau, especially because of their nitrogen-fixing attributes (Richard, 2014). When the farmers grow them with maize or potatoes, they can get by with little or no external sources of fertiliser, which are often unavailable or too expensive. Groundnut is a major source of oil for the people and is also sold to generate income. Bambara nut is a wholesome food and is an ideal option for many during "lean times" because it is quite filling (Hillocks et al., 2012; Oniang'o et al., 2003; Poulter, 1981; Yao et al., 2015). Bambara nut has a high drought tolerance compared with ground nuts, its seed is comparable to cowpea (Effa & Uko, 2017) and is becoming a popular supplement to cowpea in the tropics (Mabika & Mafongoya, 1997).

I predicted that:

1. Predation rate (bird attack marks or missing pest models) will i) correlate positively with insectivore abundance, and negatively with distance to forest fragments, and ii) the strength of the positive effect of bird abundance on predation rates will decrease with increasing distance from forest fragments.
2. Insect-eating bird abundance will correlate negatively with increasing distance to a forest fragment.

I also investigated whether bird predation rate on pest mimics varies across:

(i) crop types (Bambara nuts and groundnuts); even though these crops are both legumes, Bambara nut is a more hardy crop than groundnut and is also grown on a smaller scale. This may determine what types of insect pest attacks them. A study has shown that 65% of the problem of insect pests of Bambara nuts is exacerbated by late planting (Mabika & Mafongoya, 1997). Therefore, I would expect Bambara nuts to harbour fewer pests because they were planted early.

(ii) colours of mimics, because these may be confounding variables in predation rates affecting detection. This could also help identify which pests are most likely to be controlled using birds.

4.2 Materials and Methods

4.2.1 Study site

The experiment was conducted during the wet season from August to December 2018 in the same study site used for the exclosure experiment reported in Chapter 3. These are 10 farmlands surrounded by 4 forest fragments.

4.2.2 Crop plant propagation

My field assistants bought seeds of Bambara nuts and groundnuts from the local market and planted into garden-soil-filled polythene bags measuring 32 × 40 cm in the nursery at Ngel-Nyaki Forest Reserve. Each seed type was planted into 90 polythene bags, making a total of 180 polythene bags (three seeds/bag). The bags were protected against birds and rodents using a cage of wire netting with pore size of 0.8mm x 1.2mm. Plants began to sprout after 10 days of planting seeds, but complete germination of all seeds was observed after 15 days. Three weeks after planting, all seedlings were moved to farmlands and placed along 15 line transects, with each transect measuring 300 m, making a total of 4500 m of transects. The distance between transects was up to 200 m. Each of the 15 transects was further divided into three sections. I placed one groundnut plant and one Bambara nut plant in each section, with a minimum increasing distance of 50 m across sections. In total, six crop plants (i.e., three replications for each crop plant) were placed in every section of each transect.

4.2.3 Predation set-ups

To estimate bird predation rates, I constructed plasticine models of non-toxic brown and green caterpillars (hereafter referred to as caterpillars) and non-toxic grey beetles (hereafter referred to as beetles) and grey larvae as baits for birds. Caterpillars, beetles and larvae were all made to the same size, (diameter - 3.5 mm and length 25 mm; Gray & Lewis, 2014; Wahid & Kevan, 1995) and as close to the shape of their real-life counterparts as possible. I then attached the mimics to the plant leaves using UHU all-purpose adhesive glue. I placed six mimics on the leaves of each experimental crop plant, amounting to a total of 540 mimics. I monitored the 540 mimics daily for 12 weeks along transect sections to record bird attack marks and/or the number of missing mimics. At the end of every week, all plasticine mimics were collected for identification of bird predation marks, and thereafter remoulded into prey shapes and replaced on the crop plants. Bird attack marks were identified under a magnifying hand lens and compared with images in the literature (Howe et al., 2009; Low et al., 2014; Tvardikova & Novotny, 2012). Caterpillar, beetle and larvae mimics were considered predated if they were missing or had a distinct beak mark that looked like a bird attack mark.

4.2.4 Bird identification

Using focal observations, I conducted 10-minute point counts of birds in each section of the 4500-m transect. In each section, survey points were located a minimum of 50 m apart and spatially overlapped with the plasticine mimics placement area following the methodology of Roels et al. (2018). My field assistants and I surveyed each section four times per week between 6:30 am and 10:30 am. During each survey, all birds detected by sight or sound within a 25-m radius were recorded. Birds flying through or over the count circle were not counted. Following the methodology of Wattel (1993), all bird species that included insects as part of their diet, even though insects may not be a primary component of their diet, were included in the dataset. Thus, all species used for analysis are species that are capable of eating either caterpillar-sized, beetle-sized or larvae-sized insects.

4.2.5 Data analyses

All data obtained were analysed using the R statistical package version 3.5.0 (R Core Team, 2018). I used general linear mixed-effects models (GLMM) to test whether i) the rate at which the mimics were attacked or removed by birds depended on bird abundance, ii) whether proximity to forest fragment affected the predation rate, and iii) to what extent predation rates vary with crop type or mimic colour.

Prediction 1:

Model 1A: I modelled bird predation rate (bird attack marks) on pest mimics as a function of insect-eating bird abundance; section (i.e. section of each transect) was included as a random effect, insect-eating bird abundance as a fixed effect and included the interaction between insect-eating bird abundance and distance (proximity to forest), to test whether the relationship between predation rate and distance depends on the presence of birds. I included mimic colour and crop type as fixed factors in the model to determine any variation with prey colour and crop type. If insect-eating birds are important in determining the index of crop–pest predation rate, then I predict that there will be higher predation rates with higher abundance of insect-eating birds. If proximity to forest fragments increases the predation rate effect of insect-eating birds, then I predict that this positive correlation between insect-eating bird abundance and predation rates will become less positive with increasing distance from forest fragments (that is, a negative interaction between distance and insect-eating bird abundance).

Model 2A: A second model was constructed using Model 1A but without distance, to test for an overall main effect of insect-eating bird abundance on predation rates. I predict that predation rates will be positively correlated with insect-eating bird abundance.

Model 3A: A third model was constructed using Model 1A but without insect-eating bird abundance, to test for an overall effect of proximity of the forest on predation rates. I predict that there will be a negative relationship between distance to a forest fragment and predation rates.

Models 1B, 2B & 3B: I repeated each of the three models (1A, 1B and 1C) with the alternative index of predation rate- missing mimics (count of mimics that were not found). The predictions are the same as for bird attack marks.

Prediction 2:

Model 4: I used GLMM's to test if forest proximity affected insect-eating bird abundance. I modelled insect-eating bird abundance as a function of distance from forest fragment; sections were included as random effects, with distance as a fixed effect; crop type and mimic colour were included as fixed effects. I predict that insect-eating bird abundance will decrease with increasing distance from forest fragments.

4.3 Results

Overall, I recorded a total of 1397 attack marks on 416 pest mimics over the 12 weeks, of which 1349 (97%) were bird attack marks and 48 (3%) were unidentified. Eighty mimics were missing (15% of the total mimics), and 45 (8% of the total mimics) were damaged. A total number of 5,930 insect-eating birds were recorded from 38 species across the 15 transects. Overall, results suggest that insect-eating birds were important and had a substantial main effect on pest predation rate on plasticine mimics.

4.3.1 The relationship between predation rate and insect-eating bird abundance (Prediction 1).

(a) Bird attack marks and insect-eating birds

Results from the linear mixed-effect model showed the number of bird attack marks (as an index of predation rate on pest mimics) on pest mimics increased with increased insect-eating bird abundance (Table 4.1; Table 4.2 and Figure 4.2). From the overall model in Table 4.1, the interaction between insect-eating bird abundance and distance shows that the positive effect of insect-eating bird abundance on prey mimics becomes less strong the further from the forest fragments, as predicted (Figure 4.1).

Results from the linear mixed-effect models showed the number of bird attack marks was significantly higher in pest mimics placed on groundnuts than on Bambara nuts (Table 4.1; Table 4.2). Results from Table 4.1 also show that, although the number of bird attack marks was highest on the brown mimics, this was not significantly different from other colour mimics. This suggests that insect-eating birds did not show a significant preference for one colour over the other.

Results from the linear mixed-effect model showed the number of bird attack marks (as an index of predation rate on pest mimics) decreased as proximity to a forest fragment increased for both crop types – ground nut and Bambara nut (Table 4.3; Figure 4.3). There was a substantial main effect of distance from the forest fragment, such that there were lower predation rates on plasticine mimics further away from forest fragments, as predicted (Table 4.3, Figure 4.3).

Table 4. 1: Model 1A. The relationship between bird attack marks (as an index of predation rate) on pest mimics and insect-eating bird abundance.

Variables	Estimate	SE	*t*	*p*
(Intercept)	3.79	0.30	12.54	**<0.001**
Distance	−0.00044	0.00010	−4.56	**<0.001**
Insect-eating bird abundance	0.080	0.013	6.20	**<0.001**
Bambara nut	−0.57	0.14	−4.11	**<0.001**
Green mimics	−0.064	0.17	−0.38	0.702
Grey mimics	−0.066	0.17	−0.38	0.703
Distance*Insect-eating birds	−0.000019	0.000010	−1.88	**0.061**

Note. Full model; Bird attack marks = insect-eating birds + distance + crop types + colour of mimics + insect-eating birds*distance, random = ~1|section, method = "ML". Groundnuts and brown mimics are set as the intercept. Significant p–values are given in bold.

Table 4. 2: Model 2A. The relationship between bird attack marks (as an index of predation rate) on pest mimics and insect-eating birds.

Variables	Estimate	SE	*t*	*p*
(Intercept)	2.05	0.24	8.65	**<0.001**
Insect-eating bird abundance	0.13	0.015	8.45	**<0.001**
Bambara nut	−0.58	0.14	−4.11	**<0.001**
Green mimics	−0.057	0.17	−0.33	0.740
Grey mimics	−0.092	0.17	−0.53	0.599

Note. Model; Bird attack marks = insect-eating birds + crop types + colour of mimics, random = ~1|section, method = "ML". Groundnuts and brown mimics are set as the intercept. Significant p–values are given in bold

Table 4. 3: Model 3A. The relationship between bird attack marks and forest proximity across crop types.

Variables	Estimate	SE	*t*	*p*
(Intercept)	5.35	0.27	19.62	**<0.001**
Distance	−0.00088	0.00010	−9.20	**<0.001**
Bambara nut	−0.58	0.14	−4.13	**<0.001**
Green mimics	−0.043	0.17	−0.25	0.803
Grey mimics	−0.092	0.18	−0.52	0.601

Note. Model; Bird attack marks = distance + crop types + colour of mimics, random = ~1|section, method = "ML". Groundnuts and brown mimics are set as the intercept. Significant p–values are given in bold.

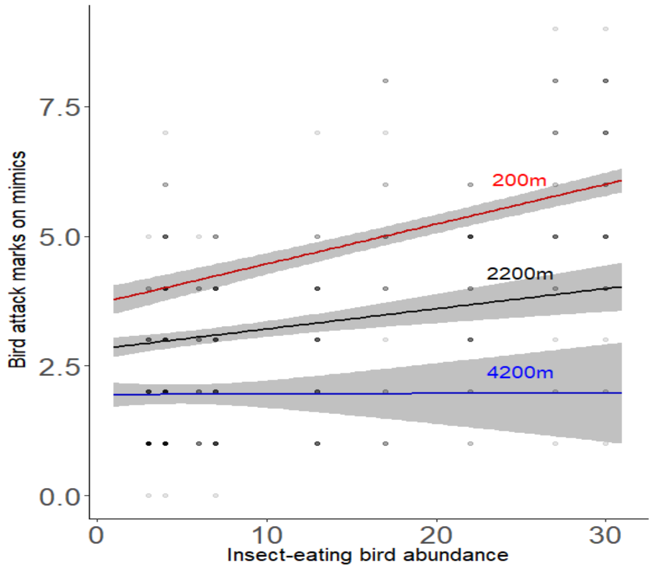


Figure 4. 1: The interaction between distance from a forest fragment and insect-eating bird abundance, generated from Table 4.1: Model 1A Crop was set to A and the colour to brown, and we plotted three separate lines for close distance at 200m, intermediate distance at 2200m and a far distance at 4200m. The gradient becomes less steep away from the forest fragments, showing that the positive effect of insect-eating bird abundance on prey mimics depends on proximity to forest.

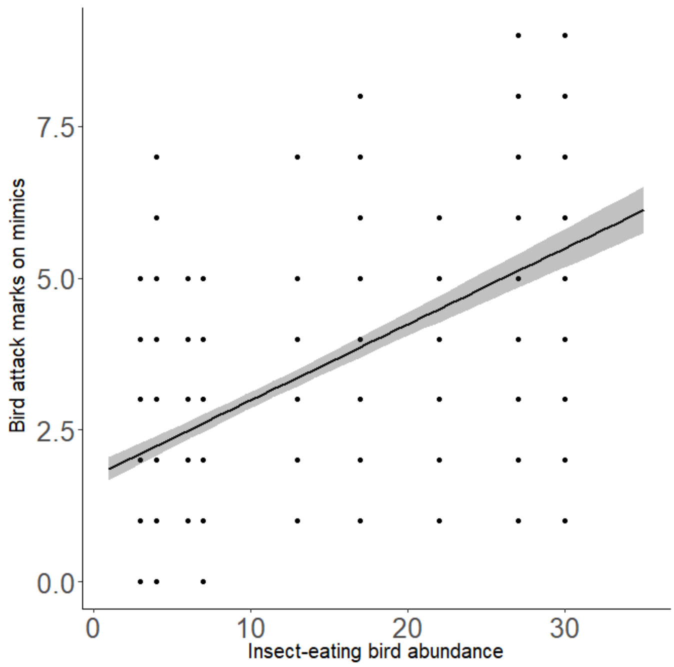


Figure 4. 2: Relationship between bird attack marks on pest mimics and insect-eating bird abundance. This predicted line is fitted from Table 4.2: Model 2A.

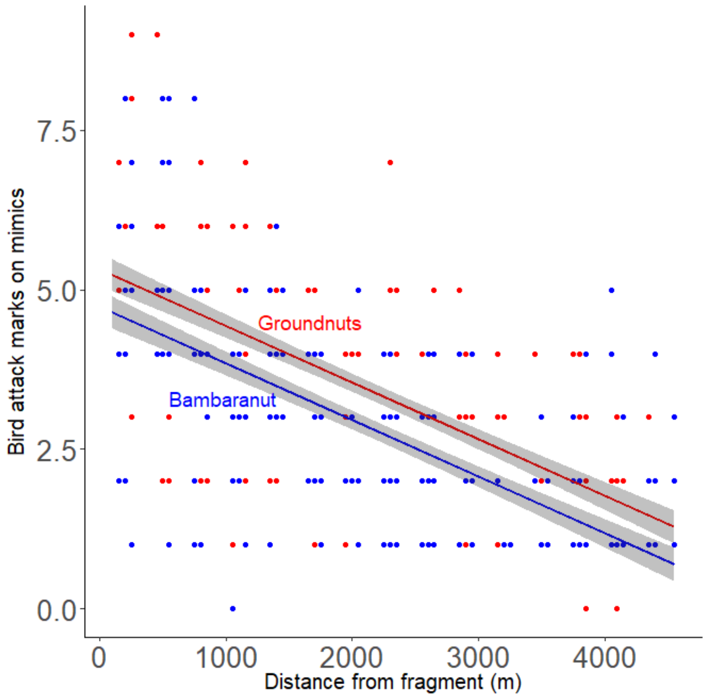


Figure 4. 3: Correlation between bird attack marks on pest mimics and distance of crops from forest fragments. These predicted lines were fitted from Table 4.3: Model 3A.

(b) Missing pest mimics and insect-eating birds

Results from the GLMM showed that the number of missing pest mimics (as an index of predation rate on pest mimics) increased with increased insect-eating bird abundance (Table 4.4; Table 4.5 and Figure 4.5). From the overall model in Table 4.4, the interaction between insect-eating birds and distance (proximity) showed that the positive effect of insect-eating bird abundance on number of missing prey mimics becomes less strong further from the forest fragments (Figure 4.4).

Results from the GLMM showed missing pest mimics decreased as forest proximity increased for both crop types; ground nut and Bambara nut (Table 4.6; Figure 4.4).

Table 4. 4: Model 1B. The relationship between number of missing pest mimics (as an index of predation rate) and insect-eating bird abundance.

Variables	Estimate	SE	*t*	*p*
(Intercept)	0.93	0.50	1.87	0.067
Distance	0.00021	0.00020	1.052	0.297
Insect-eating bird abundance	0.083	0.024	3.38	**0.001**
Bambara nut	−0.025	0.21	−0.12	0.907
Green mimics	0.024	0.26	0.094	0.926
Grey mimics	−0.077	0.25	−0.31	0.760
Distance*Insect-eating birds	−0.000027	0.000012	−2.37	**0.021**

Note. Full model; Missing pest mimics = insect-eating birds + distance + crop types + colour of mimics + insect-eating birds*distance, random = ~1|section, method = "ML". Groundnuts and brown mimics are set as the intercept. Significant p–values are given in bold.

Table 4. 5: Model 2B. The relationship between number of missing pest mimics (as an index of predation rate) and insect-eating birds.

Variables	Estimate	SE	*t*	*p*
(Intercept)	1.26	0.35	3.56	**0.001**
Insect-eating bird abundance	0.045	0.017	2.61	**0.011**
Bambara nut	-0.018	0.21	-0.082	0.935
Green mimics	0.051	0.27	0.19	0.849
Grey mimics	-0.11	0.26	-0.43	0.668

Note. Model; Missing pest mimics = insect-eating birds + crop types + colour of mimics, random=~1|section, method="ML". Groundnuts and brown mimics are set as the intercept. Significant p–values are given in bold.

Table 4. 6: Model 3B. The relationship between missing pest mimics and forest proximity across crop types.

Variables	Estimate	SE	*t*	*p*
(Intercept)	2.34	0.32	7.32	**0.000**
Distance	−0.00026	0.00012	−2.23	**0.029**
Bambara nut	−0.047	0.22	−0.22	0.829
Green mimics	0.10	0.27	0.36	0.722
Grey mimics	−0.20	0.26	−0.76	0.450

Note. Model: Missing pest mimics = distance + crop types + colour of mimics, random = ~1|section, method = "ML". Groundnuts and brown mimics are set as the intercept. Significant p–values are given in bold.

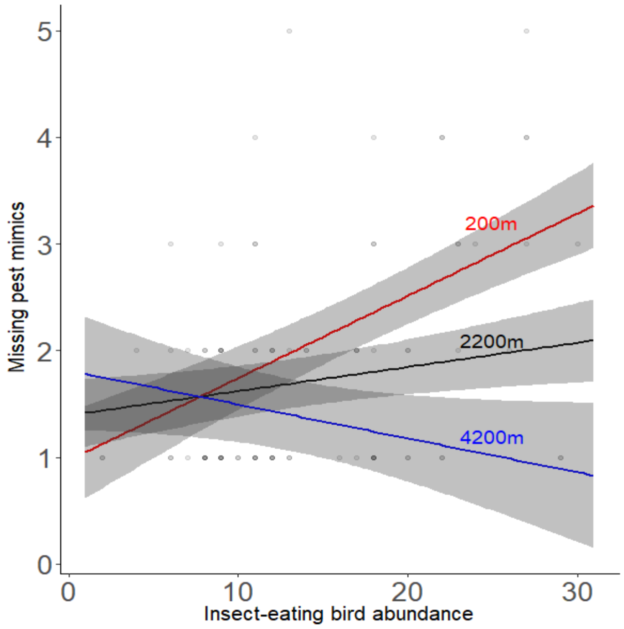


Figure 4. 4: The interaction between distance to forest fragments and insect-eating bird abundance on number of missing prey mimics, generated from “Table 4.4: Model 1B”. Crop was set to A and the colour to brown, and we plotted three separate lines for close distance at ‘200m’, intermediate distance at ‘2200m’ and a far distance at ‘4200m’. These lines show how the gradient becomes less steep further away from the forest fragments.

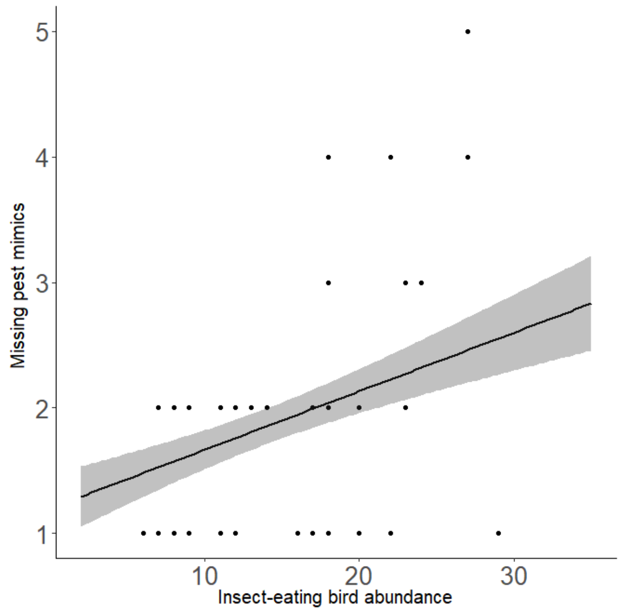


Figure 4. 5: Relationship between missing pest mimics and insect-eating bird abundance. This predicted line is fitted from “Table 4.5: Model 2B”.

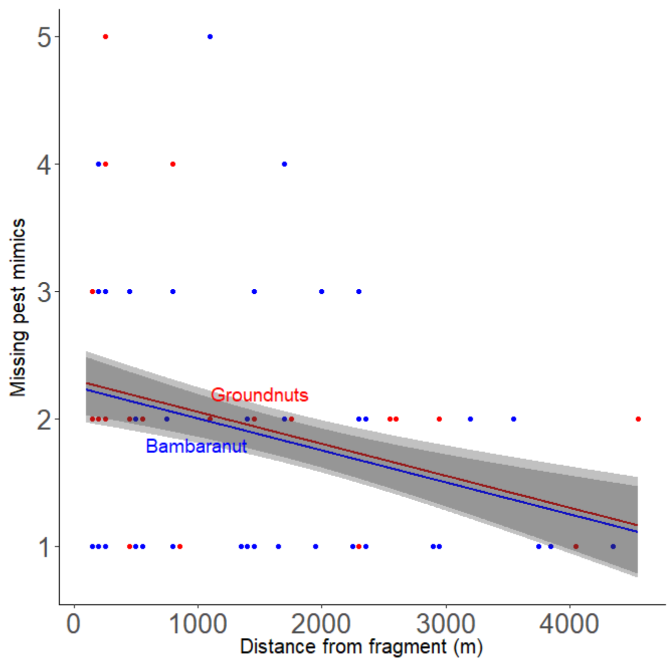


Figure 4. 6: Correlation between missing pest mimics and distance of crops from forest fragments. Predicted lines were fitted from "Table 4.6. Model 3B"

4.3.2 The relationship between insect-eating bird abundance and distance to forest fragment (Prediction 2)

Results from the linear mixed effect model showed that insect-eating bird abundance decreased as distance from a forest fragment increased (Table 4.7; Figure 4.7).

Table 4. 7: Model 4. The relationship between Insect-eating bird abundance and forest proximity.

Variables	Estimate	SE	*t*	*p*
(Intercept)	15.64	1.08	14.45	**<0.001**
Distance	−0.0020	0.00039	−5.042	**<0.001**
Bambara nut	0.0029	0.34	0.0086	0.993
Green mimics	0.013	0.41	0.032	0.974
Grey mimics	−0.016	0.41	−0.039	0.969

Note. Model: Insect-eating bird abundance = distance + crop types + colour of mimics, random = ~1|section, method = "ML". Groundnuts and brown mimics are set as the intercept. Significant p–values are given in bold.

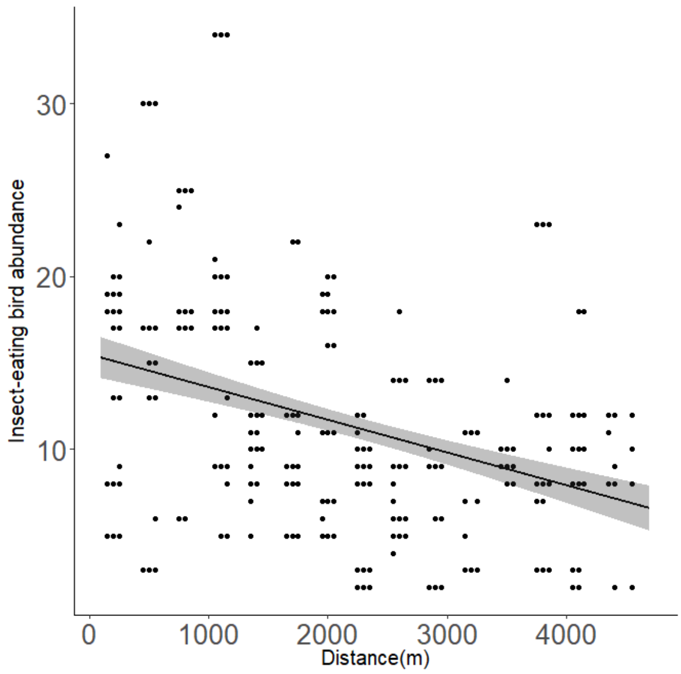


Figure 4. 7: Correlation between insect-eating bird abundance and distance from forest fragments. This predicted line is fitted from “Table 4.7: Model 4”.

4.4 Discussion

Plasticine prey mimics have been widely used to assess predation rates by birds on insects in temperate and tropical habitats (Berger & Wirth, 2004; Howe et al., 2009; Koh, 2008; Lövei & Ferrante, 2017; Mäntylä et al., 2008). Mimics can provide a direct and quantifiable measure of predation (Howe et al., 2009), and the traces left by different predators are identifiable, making them ideal for testing hypotheses (Lövei & Ferrante, 2017). There are, however, no published records from West African agricultural landscapes on the level of insect pest control through predation by birds. This knowledge gap needs redressing. In this study, I discuss results from a plasticine mimics experiment, providing the first supporting evidence that birds suppress insect pests in Nigerian farmlands. This is particularly important for subsistence farmers, who have limited economic access to external resources (Zhang et al., 2018) and are constrained by the cost and availability of insecticides (Banjo et al., 2003; Sekercioglu, 2012). My results generally supported all three of my main predictions (see 4.1). Insectivorous birds were responsible for the highest proportion of predation on plasticine mimics relative to unidentified attack marks from other predators, and proximity to forest fragment was a key factor associated with both increased predation rates and abundance of insectivorous birds. These findings suggest that a decline in insectivorous birds in the area, through, for example, loss of forest habitat, may have a negative impact on their role as insect predators. It is therefore important to maintain and conserve birds and forest fragments within this ecosystem, as has been shown in other areas (Sekercioglu, 2010).

4.4.1 Bird predation rates and insect-eating bird abundance

Bird attack marks on pest mimics, and pest mimic removal significantly increased with increasing abundance of insect-eating birds, confirming my first prediction that bird attack marks and pest mimic removal will positively correlate with the abundance of insect-eating birds. My findings are consistent with those of other studies using plasticine mimics in tropical agroforestry systems. Researchers (Bael et al., 2008; Clough et al., 2009; Maas et al., 2015; Ndang'ang'a et al., 2013; Roels et al., 2018; Ruiz-Guerra et al., 2012) have found a strong correlation between insectivorous bird abundance and bird predation rates (bird attack marks on, and removal of pest mimics). Despite the fact that I may have recorded attack marks that had not been made by birds, these were less than 4% of marks. This confirms that insect-eating birds were responsible for most of the predation on my pest mimics and corroborates the findings of other experiments on artificial mimics that compared predation rate across different taxa (Garfinkel & Johnson, 2015; Milligan et al., 2016). One explanation for the greater efficacy of birds is that predatory arthropods (e.g., wasps and other insects) may be unable to remove the glued portion of mimics. However, other tropical studies have reported contradictory findings. For example, Floren et al. (2002), Roslin et al. (2017), Sam et al. (2015) and Seifert et al. (2015), all found that arthropods were the principal predators of artificial mimics. An explanation for this could be that most of these studies were carried out in the understorey of non-montane tropical forest, and birds are relatively unimportant predators of arthropods in tropical forest understorey (Van Bael et al., 2003). In contrast, my experiment was conducted in farmlands located in the tropical montane region, and previous studies in montane regions have shown that insect-eating birds tend to be dominant rather than arthropods (Sam et al., 2015; Tvardikova & Novotny, 2012). Moreover, consistent with my findings, there are many other studies from tropical montane regions that showed higher predation on prey mimics by birds (Drozdová et al., 2013; Sam et al., 2015). My finding, with implications for bird predation on insect pests suggests that birds within the Nigerian forest-agricultural landscape, could make a strong contribution towards ecosystem services (Sekercioglu, 2006). Therefore, a decrease in the abundance of these birds could lead to trophic cascading effects, increasing insect populations and thus herbivory levels (Ruiz-Guerra et al., 2012). Moreover, studies have already shown that insectivorous birds are among the most threatened birds in the world, because they are sensitive to forest fragmentation and disturbance (Buechley et al., 2015; Tobias et al., 2013). Therefore, it is vital to promote the conservation of these birds, as well as other associated species, and forest patches within the Nigerian agricultural landscape.

4.4.2 Birds attack marks across crop plants and pest mimic colours

The higher predation rate on mimics placed on groundnut versus Bambara nut plants may be due to bird foraging patterns. Birds may have a more accurate search image for groundnut pest mimics, which could lead to a higher rate of pest detection among groundnut crops (Garfinkel & Johnson, 2015). My result therefore suggests that bird predation on insect pests associated with groundnuts can be of high economic importance. Groundnut is a common food, as a nut but also as an important source of vegetable oil and fats in West Africa (Ndjeunga et al., 2003), and an important cash crop grown in Africa (Zakari et al., 2014). In the early 1900s Nigeria was the highest groundnut-exporting country in Africa, and was ranked fourth in groundnut production globally (Ajeigbe et al., 2014; Finlib.com, 2019), but a combination of insect pests, drought and diseases has led to a decline in groundnut production since then (Ajeigbe et al., 2014). It is therefore essential to know if birds control insect pests on groundnuts crop plants. No previous studies have measured bird predation rate on groundnuts or Bambara nuts globally, although there are studies on other economic crops (e.g., coffee and cocoa) that harbour similar insect pests such as caterpillars (e.g., *lepidopteran* larvae) and coffee berry borer beetle (*Hypothemus hampei*; Kellermann et al., 2008; Maas et al., 2015; Perfecto et al., 2004). These studies support my findings that showed insect-eating birds effectively reduce insect pests, which may have a positive effect on crop yield.

I found higher bird attack marks on the brown mimics, but this variation was not significantly different from the green and grey mimics, indicating that insect-eating birds did not show a significant preference for one colouration over another. My finding is contrary to the assumption that green plasticine seems to be perceived by predators as the more palatable and more undefended prey (Howe et al., 2009). Clearly, I showed that brown mimics are perceived as palatable and non-toxic by visually oriented predators just as green plasticine mimics are (Seifert et al., 2015). Therefore, all insect pests mimicked in this experiment (caterpillars, beetles and larvae) may be equally controlled by insect-eating birds on the farmlands. It is also possible that in this study, the slight trend for higher bird predation on the brown mimics is because they may resemble the real-life counterparts of two major insect pests of ground nuts: groundnut aphid (*Aphis craccivora*), brown in colour, and the groundnut leaf miner (*Aproarema modicella* (Deventer)), brownish-green in colour. If true, then the presence and abundance of insect-eating birds on groundnuts on farmlands may control these insect pests. This is very important for farmers in Africa, particularly in Nigeria, because aphids are known to be the vectors of groundnut rosette disease and can cause yield losses of up to 40% of groundnuts (Ajeigbe et al., 2014).

4.4.3 Birds attack marks and distance to forest fragments

Many studies in temperate and tropical agricultural landscapes have linked efficacy of bird predation on insect pests, with proximity to forest (Bianchi et al., 2006; Clough et al., 2009; Lemessa et al., 2015; Maas et al., 2015; Puckett et al., 2009; Roels et al., 2018). In my study, I also found evidence that proximity to forest is an important determinant of the probability of pest predation rates by birds. This result suggests that insect-eating birds using the forest fragments also forage in farmlands and eat insect pests. Forest may offer protective cover from predators (Sunderman, 1995), so that as birds fly farther away from forest, their probability of being predated increases (Puckett et al., 2009). I found a negative interaction between distance to forest and abundance of insect-eating birds, suggesting that proximity to forest fragments is a key factor associated with the observed increased bird predation on pest mimics. The fact that the positive effect of insect-eating birds on pest mimic predation becomes less steep farther from the forest fragments (Figures 4.1 & 4.4) suggests that the forest fragments themselves facilitate the pest control services of the insectivorous birds on farmland. Birds may nest or roost in the forest fragments and venture into the farmlands to forage more efficiently (Jirinec et al., 2011). In this way forest fragments, by sheltering insect-eating birds as well as other mobile insect predators may contribute to pest control services (Karp et al., 2013; Milligan et al., 2016; Wenny et al., 2011).

Based on the same kind of evidence I provide here, other studies elsewhere have recommended the protection of forest fragments near farm edges for bird conservation purposes (Garfinkel & Johnson, 2015; Harvey et al., 2005; Hinsley & Bellamy, 2000; Mäntylä et al., 2008; Pulido-Santacruz & Renjifo, 2011; Roels et al., 2018; Vickery et al., 2002). This has been successfully practised in the Neotropics, and it holds great potential for the forest fragments to provide ecosystem services such as pest control, fibre, fuel, natural windbreaks and material shelter (Rosenzweig, 2003). The results of my study again suggest that Nigerian farmers can benefit from maintaining these sources of bird habitats. These benefits can be economically significant and may help contribute towards achieving food security in Nigeria. My results therefore provide key knowledge for smallholder farmers who may be keen to take advantage of the biocontrol services of birds in these agricultural landscapes.

4.4.4 Insect-eating birds and distance to forest fragment

Consistent with previous studies (Bereczki et al., 2014; Jedlicka et al., 2011), the finding that the abundance of insect-eating birds decreased as distance from forest fragment increased confirmed my second prediction that the abundance of insect-eating birds would correlate negatively with distance to forest fragment. This result suggests that proximity to forest is an important variable in explaining the composition of the bird species within the Nigerian forest-agricultural landscape. The provision of pest control services by birds in Nigeria could therefore be dependent on landscape composition, that is, the position of farms relative to forest fragments (Karp et al., 2013; Kellermann et al., 2008; Tscharntke et al., 2008). The frequency of movement of the birds within the farmlands and/or between farmlands and forest will also play a role (Kremen et al., 2007; Luck et al., 2009). When adequate habitat is available for birds, bird predators may reduce the impact of potential outbreaks of insect pests (Tremblay et al., 2001). Moreover, insect-eating birds in these farmlands may not only reduce insect pests through direct mortality, but may play a role in reducing outbreaks of insect pests before they occur (Perfecto et al., 2004), through indirect effects (MacLeod et al., 2014) such as fear. Fear by birds of predators has been shown to have a major impact on pest regulation within the agricultural landscape (Van Bael et al., 2003). Therefore, further studies on Nigerian agricultural landscapes should focus on examining the potential effects of habitat fragmentation on the role of insect-eating birds as regulators of herbivorous insects (Fáveri et al., 2008; Gonzalez-Gomez et al., 2006).

4.4.5 Conclusion

The plasticine mimic experiment proved useful and informative. I showed that over a 12 week period, insect-eating birds were able to attack and remove pest mimics. I also showed that birds controlled more pests on farmlands closer to forest fragments than on those further away. This supports the hypothesis of the pest suppressive effect of landscape complexity (forest proximity in this study) associated with bird predation rates (Bianchi et al., 2006; Milligan et al., 2016; Roels et al., 2018; Zhang et al., 2018), and suggests it is applicable to West African agricultural landscapes. Overall, the results of my study make an important contribution to the literature, showing that insect-eating birds are likely to be important predators of insect pests in Nigerian farmlands. This level of ecosystem service could be of high economic importance, particularly for Nigerian smallholder farmers who traditionally control pests by sprinkling wood ash or kerosene onto plants or manually removing pests (Alghali, 1991; Amusa et al., 2003; Banjo et al., 2003; Bottenberg, 1995), and these methods are labour intensive (Zhang et al., 2018). Hence, integrated approaches to ecological agriculture (e.g., farming alongside conservation of biodiversity) should be encouraged (Green et al., 2005; McNeely & Scherr, 2003), as should less reliance by farmers on traditional control methods, such as sprinkling wood ash or kerosene onto plants (Zhang et al., 2018). My findings also suggest that biological pest control may provide sound alternative to chemical pest control for some of the Nigerian farmers who use pesticides on their farms; this can have negative impacts on human health and the environment, as has been suggested elsewhere for example, in the United States (Pimentel & Burgess, 2014). Therefore, instead of the ongoing land clearance for crop production by farmers in Africa, I recommend farmers retain areas of non-crop habitats (either grasslands or forest patches) for bird conservation in order to achieve food security. This way, they benefit from insect pest suppression on their farms by these birds (Jones et al., 2005), with positive effects on crop yield. For sub-Saharan Africa, this could be an important component in achieving sustainable food security while conserving biodiversity.

4.5 References

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4.6 Appendices

Supplementary Information:

Appendix 4.1: seeds of groundnuts and bambara nuts planted into polythene bags.

Appendix 4.2: Modelling of plasticine mimics.

Appendix 4.3: Mimics placed on crop plant

Appendix 4.2: Bird attack marks on plasticine mimics

Chapter 5: Synthesis

5.1 Background

Land clearance from subsistence farming is considered the leading cause of habitat and biodiversity loss in the tropics (Gibson et al., 2011; Laube et al., 2008; Laurance et al., 2018; Laurance & Peres, 2006; Sodhi et al., 2011; Taubert et al., 2018). According to a range of forecasts, these processes are likely to increase as the growing demand for food places increasing pressure on land over the next century (Godfray et al., 2010; Mclaughlin, 2011). Rural areas with high human populations that rely on subsistence farming are prone to fragmentations and forest loss (Donald, 2004; Wright, 2005). As elsewhere, a major challenge is combining efficient agricultural land use while conserving biodiversity (Tscharntke et al., 2012). It is therefore essential to assess biodiversity composition and identify species with different ecological roles within these landscapes (Lewis et al., 2013). Any studies that assess the potential roles of biodiversity (e.g. bird species) in providing ecosystem services, particularly for subsistence farmers in Africa is an urgent priority because African subsistence farmers are faced with the challenge of high crop yield losses, resulting from insect pests (Oerke, 2006; Zhang et al., 2018). This study is therefore important to improve our understanding of the distribution of bird species and their ecosystem effects in a fragmented forest-farmland mosaic, and to come up with the best strategy for both farmers and conservation managers in Africa.

There is a growing interest in bird composition in tropical agroforests e.g. coffee and cocoa plantations, and the value of agroforests as a habitat for birds (Buechley et al., 2015; Perfecto et al., 2004; Tscharntke et al., 2008). Studies have shown that in a wide range of agroecosystems, birds are effective controllers of invertebrate pests; e.g. in large scale farming operations and in plantations (Classen et al., 2014; Karp et al., 2013; Maas et al., 2015). Other studies in the tropics have linked bird predation success on insect herbivory in agroforests with native forest proximity e.g. (Clough et al., 2009; Daily et al., 2001; Taylor et al., 1993). Nevertheless, many of these studies have been from tropical agroforests. To what extent bird species contribute to pest control in tropical subsistence farmlands remains largely unknown (Zhang et al., 2018), especially in Nigeria where pests have a major impact on crop productivity. Therefore, it is important that we use field experiments to test these hypotheses in subsistence farmlands at varying distances from forest fragments. Such experiments could then provide conclusive knowledge of the biocontrol services provided by birds, and the value of retaining forest fragments to subsistence farmers for their crop plants.

The overall aim of this study was to describe the community composition of bird species and investigate the pest control services birds provide to subsistence farmlands. A key question was how distance from forest affects pest control on subsistence farmlands on the Mambilla Plateau, SE Nigeria. My specific objectives were;

1. To describe the bird community composition on the Mambilla plateau forest-agricultural landscape, and to list all bird species associated with farmlands and forest fragments as either 'farmland', 'forest fragment', or 'generalist' species (i.e. those which use both habitats).
2. To classify birds into their trophic functional groups based on diet and to identify groups potentially active in pest control.
3. To measure habitat variables (number of trees, number of shrubs, tree height, percentage of tree, canopy cover, trees in fruits), and measure the distance of farmlands to the nearest forest fragment.
4. To assess pest control services provided by birds to farmers and estimate their contribution to crop productivity (yield quality and quantity).
5. To investigate whether the distance of farmlands from forest fragments changes the abundance of birds and crop productivity.
6. To identify the importance of forest fragments on bird community and crop productivity on the Mambilla Plateau and suggest areas of further research based on the results of (1) – (5).

5.2 Bird community composition (Objective 1 & 2)

In this study, I provide the first comprehensive information on bird diversity on the Mambilla Plateau (Chapter 2). Previous bird studies on the plateau have produced limited checklists and inventories because they are either single-species studies or short-term surveys (Babalola et al., 2012; Disley, 2003; Nsor, 2014; Osinubi, 2012). I showed that subsistence farmlands and forest fragments of montane areas support a high diversity of bird species, highlighting the need to ensure their conservation. I recorded 202 bird species from across farmlands and forest fragments, and I showed that bird species have preferences for the different habitat types within the Mambilla forest-agricultural landscape. I identified insectivorous species as a key trophic functional group in farmlands, suggesting that these species may be valuable in pest control. My findings are similar to those of Ndang'ang'a et al. (2013) who reported that insectivorous bird species made up the highest proportion (40%) of foraging species recorded in cultivated areas, in central Kenya. These observations could be used to help change the perceptions of birds held by some local farmers, who view their presence in farmlands as crop pests (Greene et al., 2010; Lindell et al., 2012; Ndang'ang'a et al., 2013). Some of the forest specialist and forest dependant species (particularly the large frugivores, such as turacos and hornbills) were rarely recorded in the farmlands, signifying that subsistence farmlands have a limited capacity to compensate for forest loss for these groups. This result implies that the forest fragments are critical for conservation of forest specialists.

5.3 Evidence for vertebrate control of invertebrate pests on subsistence farms (Objective 4)

Many exclosure experiments in tropical agro-forest systems have attributed insect pest suppression in agroforest to insectivorous birds (Bael et al., 2008; Karp et al., 2013; Martin et al., 2013). However my results did not suggest this, and I did not show that insectivorous birds are responsible for pest control in maize farmlands (Chapter 3). While crop yield was significantly higher in open plots than bird excluded ones**,** there was no significant interaction with insectivorous species abundance. Similarly, I found only a weak and non significant effect of insectivorous birds reducing leaf damage to maize. These results suggest that birds in these subsistence farmlands do not consume sufficient insects to make a difference. However, my results did point to natural pest control in maize. So that while forest-based insectivorous birds may be unimportant, other grassland and/or farmland bird species and possibly bats, may be key to pest control. My finding corroborate those of Williams-Guillen et al., (2008) and Morrison and Lindell (2012), who found no link between insectivorous birds and pest control. There are several possible explanations for these discrepancies; (i) either there is something about the ecology of maize and/or the Mambilla Plateau subsistence farmlands that explains this lack of ecosystem service by birds, or something in my experimental design was flawed (see Chapter 3), or perhaps, a combination of both ecology and design limitations. (ii) Differences in environment; most of these previous studies were in tropical agroforest landscapes. In contrast, my experiment was in subsistence maize farms in a dry and predominantly grassland habitat. (iii) Perhaps the key biocontrol insectivores for maize crops in my study area are not birds, but bats (which are common in the farmlands of my study area). Considering that many insect pests of maize are night flying moths e.g. corn earworm moth (*Helicoverpa zea*) perhaps these insects are more vulnerable to bat predation (Kunz et al., 2011). The general discrepancy in results among exclosure experiments across tropical agricultural systems, on whether or not birds significantly reduce insect herbivory, suggests that conclusions from any single study are not necessarily transferable among different regions and land-use systems (Maas et al., 2016).

Conversely, I demonstrated that insectivorous birds were responsible for the highest proportion of predation on plasticine insect mimics relative to unidentified predators, and proximity to forest fragment was a key factor associated with both increased predation rates and abundance of insectivorous birds (Chapter 4). These results confirm the findings of previous studies (Roels et al., 2012) which showed a strong correlation between insectivorous bird abundance and bird predation rates on pest mimics. My findings, with implications for bird predation on insect pests, is suggestive that birds within this Nigerian forest-agricultural landscape, make a strong contribution towards ecosystem services (Sekercioglu, 2006). I have also shown that bird predation on insect pests associated with groundnuts could be of high economic importance e.g (Garfinkel & Johnson, 2015). Groundnut is an important source of vegetable oil and fats in West Africa (Ndjeunga et al., 2003), and an important cash crop in Africa (Zakari et al., 2014). My results may, therefore, be important in highlighting the potential importance of birds as natural pest control to Nigerian farmers.

In contrast to the assumptions that green plasticine seems to be perceived by predators as the more palatable and more undefended prey (Howe et al., 2009), I showed that brown mimics are perceived as palatable and non-toxic by visually oriented predators in a similar manner to green plasticine (Seifert et al., 2015). These results suggest that all insect pests mimicked (caterpillars, beetles and larvae) in my study, could be equally controlled by insect-eating birds on the farmlands.

5.4 Habitat variables and proximity of farmland to forest fragment (Objective 3&5)

I showed that density of trees, fruiting trees and distance of farmlands to forest fragments all strongly influenced the bird communities on the Mambilla Plateau. This pattern is consistent with other bird studies in tropical forest-farmland landscapes (Buechley et al., 2015; MacGregor-Fors & Schondube, 2011; Mulwa et al., 2012), emphasizing the need for effective conservation of forest fragments in montane regions. Thus, forest habitats in West African agricultural landscapes such as the forest fragments on the Mambilla Plateau should be protected against further clearing or habitat modification. This will provide a suitable habitat for a wide variety of bird species while providing valuable ecosystem services to the farmlands. The persistence of forest-dependent taxa, particularly bird species in fragmented landscapes also strongly relies on the connectivity of the landscapes (Aben et al., 2012). Importantly then, allowing natural recruitment of native trees and/or planting of scattered trees in subsistence farmlands should be a conservation priority. These could act as either population sinks for bird species (MacGregor-Fors & Schondube, 2011) and/or valuable corridors increasing connectivity of forest fragments in agricultural landscapes (Laurance et al., 2002; Neuschulz et al., 2011; Wethered & Lawes, 2003).

I expected that the retention of forest fragments close to farmlands would have positive effects on crop yield via increasing pest control by birds as shown in previous studies including Maas et al., (2015). I found the opposite: insectivorous birds were more abundant, and crop yields higher, farther away from the forest in Chapter 3. This is interesting because my initial results revealed that species richness declined with increasing distance from forest fragments (Chapter 2), and I showed a decline of insectivorous birds and predation rates with distance from the forest fragments in Chapter 4. Similarly, many studies have attributed decline in bird communities and pest control to distance from forest (Laube et al., 2008; Maas et al., 2015; Naidoo, 2004). One potential explanation for the contradictory findings could be that distance of my exclosures (200m - 650m) to the forest fragment may have been too small to show a decline in crop yield and bird abundance. Perhaps, with a longer distance (>650m), I might have seen a decline in crop yield and birds as shown in Chapter 2 and 4. Engelen et al. (2017) showed that distance to forest (up to 2km) had no significant effect on species composition in home gardens in south-western Ethiopia.

Here, I have demonstrated that my hypothesis that retaining forest fragments in a West African farming landscape provides beneficial pest control ecosystem services is more complicated than originally thought and may be context dependent. This emphasizes the need for making longer-term alternative evaluations of the economic benefit of forest fragments to farmers such as watershed protection (See Chapter 1).

I have identified several issues with exclosure experiments which should be addressed in future studies for more accurate results; (i) the apparent failure of the bird and insect exclusion treatment because I found crop yield in the insect and bird exclosures (theoretically eliminating insect crop damage) was lower than in the control treatments and similar to that of bird exclusion only. This suggests that insects were not actually excluded from the bird and insect exclosure treatment. For this reason, I based my conclusions only on the data from the control (open) plots versus bird excluded plots. (ii) I did not quantify the density of insects' pests or compared insects' abundance between treatments. I also did not test whether the control of insect pests by birds depended on the identity of the pests' feeding guilds (Maas et al., 2016). (iii) I only explored the relationship between maize crops and distance to natural forest fragments. Perhaps other habitats e.g. uncultivated grasslands and Eucalyptus plantations may be important habitats for birds (Kavanagh et al., 2007).

5.5 Insect pest control and African subsistence farmlands

Crop pests continue to be a major challenge to maximizing crop yield in Africa, while the outbreak of major insect pests e.g. armyworms sometimes results in complete crop failure (Day et al., 2017). A major factor determining crop loss due to pests, with a detrimental effect on food security is the fact that most rural farmers do not have access to effective pest control technology e.g. pesticides (Grzywacz et al., 2014). In some cases, development agencies donate pesticides to African countries to help deal with major outbreaks of insect pest such as the African armyworm or locusts (Grzywacz et al., 2014; Crop Life International, 2019). In this study, I have shown that an alternative to the use of chemical pesticides is natural pest control, and bird species may be important in pest control in Africa (particularly for economic crops e.g. groundnuts). This is more affordable, appropriate and sustainable compared to chemical pest control. Clearly, my study is extremely important because it is the only one carried out in West Africa and my results add to the growing literature documenting the evidence of insect pest control by bird species. Therefore, it would be valuable to explore management measures within forest-farmlands that could enhance this role (Ndang'ang'a et al., 2013). Importantly, I have shown that not all crop plants may benefit from insect pest control by birds or by retaining forest fragments close to farmlands. Therefore, farmers could be enlightened on selecting appropriate crops, or perhaps practice intercropping (Jones & Sieving, 2006), and on the need to retain non-crop vegetation (Haslem & Bennett, 2011; Tscharntke et al., 2011; Waldron et al., 2012). These may attract insectivorous species and enhance crop or habitat diversity (Benton et al., 2003). I therefore strongly recommend further studies on the economic importance of birds within the Nigerian agricultural landscape where land clearing presents serious threats to ecosystem processes and biodiversity.

5.6 Conservation of bird species and African forest fragments (Objective 6)

In accordance with many other studies (Lemessa et al., 2015; Maas et al., 2015; Roels et al., 2018), I showed that the provisioning of pest control services by birds in Nigeria could be dependent on landscape composition (e.g. distance to forest), as shown in other regions (Karp et al., 2013; Kellermann et al., 2008; Tscharntke et al., 2008). However, these results are contradictory in places, emphasising the need for further research on the economic benefits of these forest to farmers, because more needs to be known. As mentioned above, farmlands may not provide viable habitats for species found in them, so that there is a need to conserve the forest fragments in order to maintain birds populations. This is important particularly for species that rely on forests for breeding (Buechley et al., 2015), and also species that are most vulnerable to the conversion of forest into agriculture landscapes e.g. forest specialists (Boscolo & Paul, 2011).

5.7 Conservation challenges on the Mambilla Plateau.

On the Mambilla Plateau, anthropogenic fire, grazing, and farming, have been responsible for most of the more recent forest destruction (Richard, 2014). Given the benefits of forest fragments for pest control, land sharing (wildlife-friendly farming) could be the best farm management option on Mambilla in order to maintain biodiversity. In addition to planting trees on farmlands, farmers should be encouraged to consider planting some patches of native forest. These patches may be more profitable to their crops, as well as provide other ecosystem services (e.g. water quality, soil erosion, wind breaks etc.).

5.8 Areas for future research

1. A long-term study on bird species in African forest-agricultural landscape will provide details on bird community structure and their responses to environmental factors, e.g. farming, habitat fragmentation, habitat loss, and even climate change. I, therefore, recommend that future studies should seek to address this existing research gap.
2. It is important to go beyond the superficial measure of bird species richness when assessing the value of tropical forest-agricultural landscape. Measuring species groups based on habitat preference, function diversity, global distribution, conservation status and other ecological characteristics, predict ecosystem functioning better than species richness e.g. (Engelen et al., 2017; Gagic et al., 2015).
3. Early experiments in the tropics attributed insect pest suppression to insectivorous birds, which has greatly minimized the potential effects of other taxa, e.g. bats which are abundant in the tropics and feeds on similar types of prey. Therefore, it is important to test these ideas with other taxa in the future.
4. Despite the knowledge of bird species and their potential for insect pest control within the tropical agricultural landscapes, major knowledge gaps persist. For example, study sites have been biased, with the subsistence farmlands underrepresented compared to the agroforests (Bael et al., 2008; Maas et al., 2013; Martin et al., 2015). Therefore, even within the tropics, it is still unclear how transferable results are among different

regions and land-use systems, emphasizing the need for further research. Some key questions that should be addressed in future studies include; (i) are there specific characteristics of birds that determine their importance for ecosystem services? (Philpott et al., 2009). For example, do generalist or specialist species perform these functions, and are these species rare or abundant? (Maas et al., 2016). (ii) are bird predation services of equal importance in the different types of agricultural landscape? Such studies may be useful when enlightening local farmers on the implication for land clearance and the need to conserve biodiversity, particularly in West Africa where forests are being cleared at an alarming rate into farmlands, owing to increasing food security. Any study that will improve our understanding of the relationship between biodiversity (e.g. forest fragments and birds) and the delivery of pest control services to farmlands, is crucial for the development of sustainable agriculture (Birkhofer et al., 2018).

5.9 Conclusion

Overall, I found a significant diversity of bird species on the Mambilla Plateau. This means that the bird biodiversity of this forest-agricultural landscape is considerable, indicating the need to ensure that these habitats continue to do so. I show that it is likely that natural pest control occurs and may provide a sound alternative to chemical pest control for some of the Nigerian farmers. Because I had contradicting results regarding the role of birds in pest control from my maize exclosure experiment (Chapter 3) compared with the plasticine mimic experiment (Chapter 4). This suggests that birds, while providing important ecosystem services in some crops, may not necessarily be as important in others. This research highlights the need for further investigations into the role of birds, but also other taxa in biological pest control in rural West Africa.

6.0 References

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