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Evaluate the potential of bird-friendly cocoa agroforests in Mukono, Luwero and Kayunga districts in Uganda

Thesis submitted for the award of the academic degree of Master 120 in "*Science géographiques – orientation générale à finalité approfondie*"

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ABSTRACT

Agriculture is a major threat for biodiversity. Its intensification and expansion, to improve crop production, mainly occur in biodiversity-rich areas such as the tropics and biodiversity hotspots. This leads to habitat fragmentation and reduction, reducing species mobility and ecosystem connectivity. Among the species threatened by these changes are birds. Birds are useful in ecosystems due to the ecosystem services they provide. However, some agriculture types, like agroforestry, can combine yields and sustainability. Cocoa is a crop that can be cultivated under these agroforests, and which have a potentially high conservation value, especially for forest birds. Forest birds are among the most threatened species. As other birds, they provide ecosystem services and ensure ecosystem processes. A way to conserve forest bird biodiversity and cocoa yields would be the creation of a bird-friendly cocoa label. That's why I tried to evaluate the potential of a bird-friendly cocoa near the Mabira forest reserve, in the Mukono, Luwero and Kayunga districts, in Uganda.

To do this, I selected birds present in the study area. Then, I used the model RangeShifter, a stochastic Individual-Based Model, capable to simulate birds' behaviour and movement in interaction with their habitat. Due to the lack of data, some parameters were estimated thanks to behavioural ecology and literature. Then, I compare birds' movement and behaviour between two scenarios: the first with bird-friendly cocoa and the second with full-sun intensive cocoa.

It appears that bird-friendly cocoa can improve the conservation of less specialised forest birds. Indeed, there are more of them in bird-friendly cocoa than full-sun cocoa. However, the conservation of forest specialist species is not improved by bird-friendly cocoa. They do not go out of the primary forest, except at its edges. This suggests that bird-friendly cocoa criteria proposed here need to be improved to have the potential to conserve most specialised forest species. Bird dispersion show an opposite response with the literature. Less specialised species disperse in more cells under the second scenario than the first. This may be due to their higher concentration in cocoa farms under the first scenario combined to their avoidance of full-sun cocoa under the second scenario.

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CHAPTER 1 – INTRODUCTION

Agriculture expansion is occurring on 1/3 of the earth's ice-free surface (Estrada-Carmona, 2019). Moreover, agriculture expansion and intensification are expected to increase dramatically in tropical countries this century (Laurance et al, 2014). Agriculture is known to be the main driver of biodiversity loss (Zabel et al, 2019). It induces land use and land cover change (LUCC) such as the replacement of natural habitats with human-modified habitats, leading to the loss, fragmentation, and isolation of ecosystems (Estrada-Carmona et al, 2019). These processes mainly occur in the tropics where biodiversity hotspots are located, threatening both animals and plants (Schulze et al, 2004; De Beenhouwer et al, 2013). All these species provide ecosystem services and ecological processes in tropical ecosystems. It is therefore important to conserve and protect this biodiversity (De Beenhouwer et al, 2013).

Among the species threatened by LUCC are birds. Birds are highly mobile species, able to disperse their ecosystem services easily across different landscapes (Mahendiran et Pa, 2018). Most bird species avoid agricultural areas, yet about one third of them sometimes use them, providing ecosystem services in these areas (Sekercioglu, 2012). LUCC affects birds by changing their community composition, shifting towards less specialized communities, and changing the proportions of their functional groups (Cassano et al, 2012; Bennett et al, 2021; Rocha et al, 2019). These changes affect ecosystem services of agroforests and agricultural areas (Sekercioglu, 2012). However, not all birds are equally sensitive to LUCC (Jarrett et al, 2021).

Just like general agriculture, the expansion of cocoa cultivation is also a threat to biodiversity (Bennett et al, 2021). Most of the world's cocoa production takes place in sub-Saharan Africa (Sanderson et al, 2022). Cocoa is mainly cultivated by smallholder farmers and there are various ways of growing it. Indeed, cocoa cultivation can range from highly intensive, such as full-sun cocoa, to extensive, such as rustic agroforests (De Beenhouwer et al, 2013). These agroforests, with the correct practices set, can reduce the trade-off between biodiversity conservation and cocoa yields (Blaser et al, 2018).

Combining bird conservation and cocoa cultivation is possible with certification and sustainability standards (Tscharntke et al, 2015). For example, Bird-friendly coffee certification is already showing its effects on migratory bird conservation (Rathmell, 2017). Bird-friendly certification creates a label that encourages on-farm practices that generates and maintain habitats for birds. In exchange, farmers receive premium prices from cocoa companies. Bird-friendly cocoa has a strong potential for biodiversity conservation (Waldron et al, 2015; Tscharntke et al, 2015). Yet, standards for such certification are not yet adopted in the sector and there is no clear certification yet (Cocoa Coop –

RSTC, n.d.). Thus, exploring its potential in a cocoa-growing country with a rich birdlife can provide important insights into the creation of such a scheme. Uganda, a sub-Saharan Africa country rich in biodiversity, is home to 413 forest-dependent bird species, ranging from forest specialists to forest visitors (Bolwig et al, 2006). It also contains primary forest reserves, known to harbour unique bird species (Arnold et al, 2021), such as the Mabira forest reserve located in the Mukono district of Central Uganda.

Thus, the objective of this master thesis is to "*Evaluate the potential of bird-friendly cocoa agroforests in the Mukono, Luwero and Kayunga districts in Uganda*". The methodology is based on the simulation of the movement and behaviour of forest birds under two different scenarios: In scenario 1, all cocoa farms in the study zone are bird-friendly cocoa agroforests. In scenario 2, cocoa farms are all full-sun cocoa monocultures. A stochastic Individual-Based Model (IBM) simulates the behaviour of the birds and their interaction with the landscape to obtain their use of the different land covers and their dispersion in the landscape.

The hypothesis underlying the research question are the following:

1. Bird-friendly cocoa have the potential to improve the conservation of forest birds and this potential decreases from forest visitors to forest specialists
2. Bird-friendly cocoa increases the dispersal of birds in the landscape, especially for forest specialists who find more suitable habitats in these agroforests than in classic agroforests.

CHAPTER 2 – LITERATURE REVIEW

2.1) LUCC AND BIODIVERSITY CRISIS

LUCC is occurring all over the world. It is a major contributor to the biodiversity crisis, especially in the tropics (Arnold et al, 2021; Cassano et al, 2012; De Beenhouwer et al, 2013). Indeed, tropics harbour a high level of species diversity favoured by a stable climate during millions of years (Barros et al, 2019). This biodiversity is now increasingly threatened day by day by LUCC (Arnold et al, 2021). The main cause of LUCC is agriculture. Every year, 12.3 million ha of forest are cleared to increase crop production (FAO,2010). Most of the times, intensively managed monocultures or pastures replace primary forests and other natural habitats. Intensification leads to the modification of primary forests' surface and structure and creates habitat fragmentation, which separates populations into many small local populations without interconnectivity between the subpopulations (Githiru et Lens, 2004). Moreover, it reduces suitable living areas for many species (Cabral et al, 2021; Estrada-Carmona et al, 2019), resulting in critical biodiversity loss because small size remnants cannot support a viable population for many species due to the lack of resources and space (Edwards et al, 2021; Waltert et al, 2005). Indeed, there is a threshold under which the extinction risk is important (Aben et al, 2014). Intensification and expansion not only change primary forest, but also transforms the entire landscape. Agricultural landscapes affect the surrounding primary forests too (De Beenhouwer et al, 2013; Bennett et al, 2021). Thus, primary forests and biodiversity that lives there face an uncertain future. However, some crops, such as cocoa have a role to play to reduce the impact of agriculture on biodiversity (Arnold et al, 2021; De Beenhouwer et al, 2013).

2.2) ABOUT COCOA

Theobroma cacao L. is a tree from the humid tropical lowlands (Schroth et al, 2011). Almost all its production occurs in biodiversity hotspots (Sanderson et al, 2022). There are 6-7 million cocoa farmers around the world and 70-80% of them are smallholders with farms of 0.5-4ha (Vaast et Somarriba, 2014; Mortimer et al, 2018). 70% of the world's cocoa production comes from sub-Saharan Africa (Sanderson et al, 2022) where yields are in the range of 300-600kg/ha (Vaast et Somarriba, 2014) and where cocoa represent one of the primary crops, especially in West-African countries (Mortimer et al, 2018). Despite its importance, cocoa receives relatively little attention from scientists for quantitative biodiversity reviews compared to coffee or other crops (Bennett et al, 2021).

Smallholders cultivating cocoa usually combine sustainable yields and biodiversity conservation thanks to higher canopy cover (De Beenhouwer et al, 2013; Schroth et al, 2011). They traditionally grow cocoa under partially cleared forest with remaining trees providing shade for the crops, two layers of canopy, flowering and fruiting plants providing food and habitats for many animal species (Arnold et al, 2021; Asare et al, 2014). Thus, about 70% of cocoa is grown with some level of shade, which can optimize yield and reduce environmental degradation (Mortimer et al, 2018; Vaast et Somarriba, 2014). However, the growing demand for cocoa beans and fluctuating market prices threaten these sustainable practices (De Beenhouwer et al, 2013). Indeed, there is a growing demand of 1% per year for cocoa beans, promoting cocoa intensification and expansion (Vaast et Somarriba, 2014).

Cocoa intensification leads to a decrease in the shade levels and sustainability to improve yields, but this goal is not necessarily reached. This reduction of shade is accompanied by a decrease in species richness, caused by the changes in structure and processes induced by tree clearing (Vaast et Somarriba, 2014). Full-sun cocoa also increases pest and disease pressure and soil degradation due to the loss of ecosystem services from intensification and deforestation. Then, farmers move further in the core forest looking for a better soil, leaving behind depleted land and impoverished biodiversity (Bennett et al, 2021). However, this intensification does not necessarily increase cocoa yields. Over the past 50 years, cocoa yields have stagnated, but production has doubled (Vaast et Somarriba, 2014). The expansion of cocoa monoculture was then the only way to meet the growing demand (Sanderson et al, 2022). This has led to pioneer front expansion and a global removal of 14-15 million ha of tropical forest because of cocoa expansion in the past 50 years (Vaast et Somarriba, 2014). Traditional cocoa plantation still exists, but now, cocoa cultivation ranges from picking fruit on the wild tree to intensive full-sun plantations (De Beenhouwer et al, 2013).

2.3) BIRDS' RESPONSES TO LUCC

Birds, like many other species, are threatened by LUCC. Yet, birds play a highly important role in forest health. They provide ecosystem services from all the categories: regulation (e.g., pest control, seed dispersal, scavenging), provisioning (eggs, feathers, fertilizers, etc.), and cultural (like bird watching and photography) (Gaston et al, 2018; Mahendiran et Pa, 2018). Birds can also link ecosystem functions, move matter or energy between ecosystems and are considered as ecosystem-engineers (Mahendiran et Pa, 2018). This is not only about resident birds but also about migratory birds. Indeed, even if they do not stay the entire year in the tropics, they also bring ecosystem services. In Latin America, for example, their species richness in positively correlated to pest reduction (Bael et al, 2008).

The relationship between cocoa production and bird diversity has received little scientific attention so far and existing studies have mostly focussed on the Neotropics (Arnold et al, 2021; Bennett et al, 2021; Reitsma et al, 2001) or Paleotropics (Abrahamczyk et al, 2008; Clough et al, 2009; Clough et al, 2011; Bennet et al, 2021) instead of the Afrotropics (De Beenhouwer et al, 2013), where most cocoa is produced. In addition, studies assessing the impact of agricultural intensification on multiple biological taxa are also scarce (De Beenhouwer et al, 2013).

LUCC, by clearing trees and altering ecosystems, alters matrix composition and configuration, which has a significant effect on the mobility of birds (Estrada-Carmona et al, 2019). For example, it is dangerous for some birds to cross large open-land areas. In this kind of landscape, they are more vulnerable to predators, like raptors, because they cannot hide under the canopy of trees or in bushes (Boesing et al, 2018). Moreover, intensive land use provides less food or nesting opportunities (Edwards et al, 2021; Waltert et al, 2005). Furthermore, open-land areas act as a barrier for the dispersion of birds. These areas, surrounding the natural forests, create severe edge effects. The contrast between the two land uses is high and can modify the microclimate, creating a more unfavourable environment for birds (Cabral et al, 2021). Birds can also get trapped in landscape fragments if there is no suitable habitat around (Aben et al, 2012; Estrada-Carmona et al, 2019). Matrix composition also affects bird communities. Old primary forests and secondary forests contain a unique composition of species, including highly specialized birds (Arnold et al, 2021). Next, forest clearing induces a shift to less specialized bird communities, composed of common and widespread species (Sekercioglu, 2012; Kupsch et al, 2019). In addition, these changes also alter birds' functional groups, modifying ecosystem processes, biological flows, and ecosystem services (Barros et al, 2019; Deikumah et al, 2013). For example, large-bodied frugivores are among the most vulnerable bird species. Their loss would result in reduced dispersal of large fruit seeds, increasing the vulnerability of the plant (Jarrett et al, 2021).

Birds respond differently to LUCC depending on their specialization, diet, or status (migrant or resident) (Newbold et al, 2013) (Figure 1). Forest specialists, which are highly forest-dependent birds, are more diverse in natural forests (Clough et al, 2009). In tropical landscapes, their populations decline with forest covers below 72% (Figure 1) and with increasing agricultural intensification (Jarrett et al, 2021). Birds that are forest generalists and forest visitors with, respectively, medium and low forest dependence are less affected by LUCC (Jarrett et al, 2021; Kupsch et al, 2019). Regarding the response of birds based on their diet, it appears that nectarivores, frugivores, and insectivores, especially ant-followers (Kupsch et al, 2019), suffer more from LUCC than herbivores or granivores (Newbold et al, 2014; Bennett et al, 2021). On the other hand, granivores are less diverse in forest or forest-like habitats due to reduced food resources (Clough et al, 2009). Migratory birds are less vulnerable to LUCC due to their greater dispersal abilities (Sekercioglu, 2012) but their abundance decreases with intensification (Bennett et al, 2021). However, they are more present in human-modified landscapes than in primary forests (Greenler et Ebersole, 2015). Resident birds show a preference for forested habitat (Waltert et al, 2005).

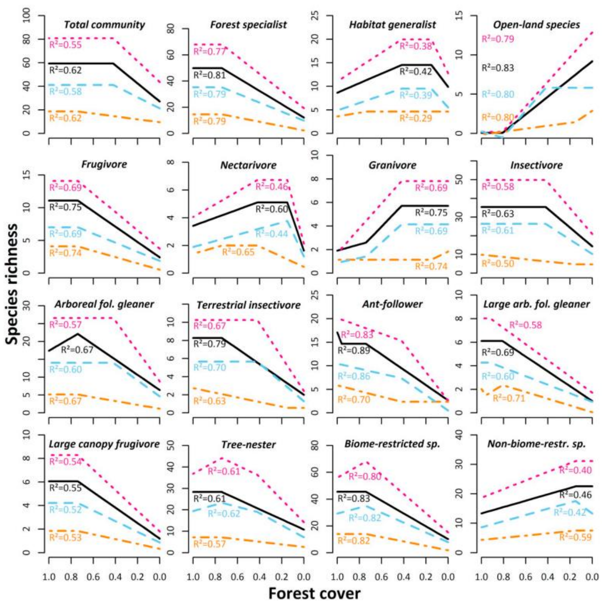


Figure 1 – Response patterns of within-microhabitat (orange), between-microhabitat (skyblue), observed (black) and estimated within block (pink) species richness to changes in forest cover in most studied bird groups (Kupsch et al, 2019)

Thus, reducing landscape and on-farm intensity is important for bird conservation in fragmented ecosystems where habitat quality and connectivity are crucial (Aben et al, 2012). There is a need to create forest-like habitats, that combine both agricultural production and bird conservation (Estrada-Carmona et al, 2019). Agroforestry systems could be a solution to achieve these two goals where intensive systems cannot support both (Melo et al, 2013). In addition, diversified farming systems can provide diverse income sources for farming households and potentially improve households' livelihoods (Arnold et al, 2021; De Beenhouwer et al, 2013).

2.4) THE POTENTIAL OF AGROFORESTS

Agroforests associate trees with farming practices (Torquebiau, 2000). They can be wildlife-friendly farming systems. Agroforests have a more complex structure, a higher tree cover, are more resilient against pests and diseases (Mortimer et al, 2018) and harbour more ecosystem services, functions, and processes than conventional plantations (Abrahamczyk et al, 2008). They can provide habitats and increase connectivity in tropical landscapes, contributing to landscape-level biodiversity increase (Bennett et al, 2021; Cassano et al, 2012). Agroforests are even more important in heterogeneous and fragmented landscapes, where they help preserving species (Greenler et Ebersole, 2015) and functional diversity (Rocha et al, 2019). Cocoa agroforests can play a major role in bird conservation (Cabral et al, 2021; Greenler et Ebersole, 2015). However, its conservation potential depends on various characteristics such as shade tree cover or tree species composition (Abrahamczyk et al, 2008; Douglas et al, 2014).

A higher shade tree cover has a positive impact on bird community composition in cocoa agroforests (Bennett et al, 2021). It changes the farm's ecosystem structure and can create favourable local conditions to host more diverse insects and foraging species (Cabral et al, 2021). Shade trees provide ecosystem services such as improving soil fertility, reducing pest and disease incidence, and sequestering carbon (Sanderson et al, 2022). They can also diversify the farmer's income by obtaining timber, fruits, or other valuable goods. All of this increases the resilience and sustainability of the farm (Vaast et Somarriba, 2014). Previous studies show that a 40% shade cover can reduce trade-off between cocoa yield (Blaser et al, 2018; Jezeer et al, 2017), overall bird species richness (Kupsch et al, 2019), and other biological, climatic, or agricultural variables (Figure 2). Furthermore, 40% shade tree cover is considered as an acceptable shade cover for bird-friendly coffee (Gobbi, 2000). Yet, as previously mentioned, most specialized bird species require more than 72% shade cover to reach their maximum richness. Some of them do not even reach their maximum richness until 100% forest cover, in other words, they need core primary forests to survive (Figure 1).

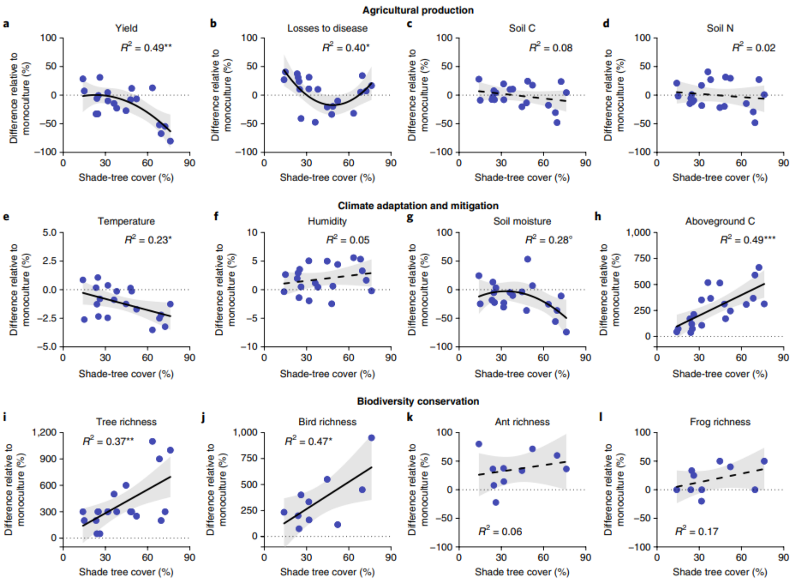


Figure 2- "The effects of agroforests on agricultural production, climate adaptation, climate mitigation and biodiversity along a gradient of shade-tree cover" (Blaser et al, 2018).

Conservation of remaining native trees also impacts birds, particularly specialists and endangered species (Figure 3). In Sulawesi, the number of remaining native trees seems to be the most important variable for bird diversity and community composition, but forest visitors do not seem to be affected by this variable (Abrahamczyk et al, 2008). Native trees may offer food sources such as invertebrates (Helden et al, 2012), flowers (Holbech, 2009), or fruits (Abrahamczyk, 2008). They also provide nesting and perching sites and protection for birds (Douglas et al, 2013; Cabral et al, 2021). Native trees attract more forest specialist birds than exotic trees, with the latter offering poorer resources (Douglas et al, 2013). Native trees also maintain ecological processes better than exotic trees (Morante-Filho et al, 2016; Sanial et al, 2022). One of the criteria for bird-friendly coffee, to significantly influence bird conservation, is to have 10 native tree species on the farm including a minimum of 1.4 individuals of each species per hectare (Gobbi, 2000).

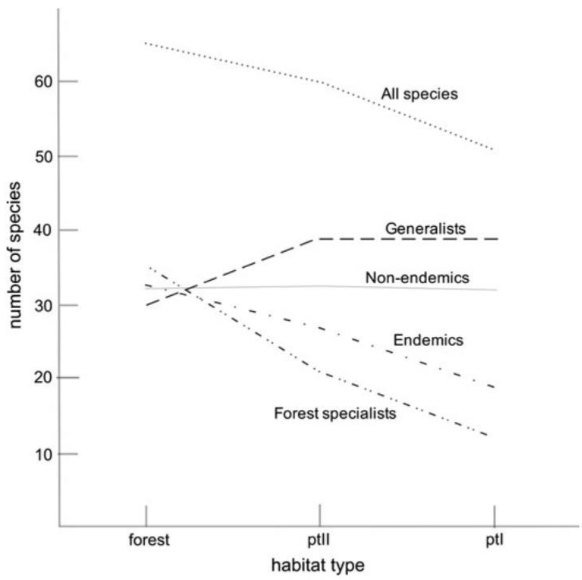


Figure 3 – "Number of bird species in the three habitat types (forest = near primary forest, ptII = plantations with remnants forest trees, ptI = plantations without remnants trees)" (Abrahamcyk et al, 2008).

Shade tree cover and the presence of native trees are then the most important variables for bird conservation in cocoa agroforests (Abrahamczyk et al, 2008; Bennet et al, 2021) but they have other functions besides bird conservation that will increase farm sustainability and resilience (Vaast et Somarriba, 2014).

Agroforests may retain species not found in primary forests and harbour similar species richness or abundance than these forests (Greenler et Ebersole, 2015). Yet, agroforests do not replace old-growth primary forests (Jarret et al, 2021; Asare et al, 2021; Greenler et Ebersole, 2015). Jezeer et al (2017) show that the total number of bird species decreases by 11% from old primary forest to agroforest. This change is up to 46% from agroforest to plantation in both cocoa and coffee all over the world (Jezeer et al, 2017). It is accompanied by a shift in population assemblage and composition between the two habitats (Cassano et al, 2012; Bennet et al, 2021; Rocha et al, 2019). Preserving large, undisturbed forests is therefore important for most specialized species. Nevertheless, as in Indonesia, it is possible to support up to 60% of forest specialists and endemics species in a properly managed cocoa agroforest (Abrahamczyk et al, 2008). In addition, conservation of large undisturbed forests and shaded agroforests will improve the forest cover at the landscape scale, which is very important to prevent more generalist birds from replacing more specialist birds (Bennett et al, 2021).

2.5) THE BIRD-FRIENDLY CERTIFICATION

The concept of combining bird conservation through agroforestry systems in the tropics with corporate sustainability efforts is not common yet also not unknown. Despite the considerable conservation value for birds through cocoa production systems (Waldron et al, 2015; Tscharntke et al, 2015; Schroth et al, 2011), bird conservation is not part of any adopted sustainability certification, system or program (CocoaCoop – RSTC, n.d.).

The cocoa's high potential value for bird conservation is linked to the habitats that cocoa agroforests provide for forest-dependent species (Reitsma et al, 2001). As previously mentioned, bird-friendly cocoa certification does not exist yet, but Bird-friendly coffee does. The Smithsonian Migratory Bird Center (SMBC) created the bird-friendly coffee certification in 1996, but its focus is on migratory birds' habitat conservation (Smithsonian Global, n.d.). However, its criteria are viable for farms and useful for migratory birds (Gobbi, 2000). The objective of this type of certification is to reduce biodiversity loss by promoting bird-friendly and sustainable coffee farming practices. For the farmer, this certification ensures premium prices and compensation for ecosystem services provided by his or her practices and a possible decrease in yields due to the shade coverage increase (Perfecto et al, 2005). In addition, farmers who join certification programs can create local networks to improve knowledge circulation or create spill over effects on surrounding farms, increasing farmers resilience at a larger scale (Rueda et Lambin, 2013). Certification programs can also impact consumers' willingness to pay. However, this willingness to pay (for 12oz of coffee) is lower for bird-friendly coffee (2.20$) than for organic (5.80$) or pesticide-free (3.60$) coffee, but its value is higher than shade grown coffee (1.80$) (Gatti et al, 2022). Migratory birds can play a role in the consumers' willingness to pay. Birdwatchers are the first targets for bird-friendly certifications. Despite they only represent a small proportion of the consumers, in North America, a study based on a population of 5,000 birders, show that 49% of them consider bird habitats when buying coffee and 9% buy Smithsonian Bird-friendly coffee. (Williams et al, 2021). The uptake of bird-friendly products, such as coffee, may be enhanced with a better communication about its impacts on bird habitats and its differences with other standards (Williams et al, 2021).

2.6) BIRDS' MOVEMENT MODELLING

Understanding how environmental changes, such as deforestation, the creation of forest-like corridors, or farmers joining Bird-friendly certification program and changing their practices, will affect birds is therefore important for future landscape and conservation management (Estrada-Carmona et al, 2019). In recent years, models capable to simulate animal responses in different landscapes have emerged. RangeShifter (Aben et al, 2014) and CircuitScape (McRae et al, 2013) are two examples of such models. They are promising tools for understanding animal-environment interactions. These models, combining an Individual-Based Model (IBM) and a cost-surface landscape, can predict animal movement in a heterogeneous landscape. They are also based on Stochastic movement simulator (SMS), which can translate animal-landscape interactions at different scales. However, these models are sensitive to some of their parameters (Aben et al, 2014). Thus, these parameters must be carefully estimated but there is a lack of data in behavioural ecology. Nonetheless, some of the parameters used in this type of model can be estimated using metabolic ecology theories, supported by compiled data (Brown et al, 2004).

CHAPTER 3 – MATERIAL AND METHODS

The methodology can be separated into three parts. The first concerns the selection of bird species. Due to the Covid-19 pandemic, no field trip was possible. Therefore, the identification of bird species present in the study area was done remotely. The second part deals with the model inputs (land cover map, scenarios, model parameters) and their estimation. The last part deals with the statistical analysis of the results.

3.1) BIRDS' SPECIES SELECTION

MATERIALS

The identification of the Ugandan bird species was performed using QGIS. The inputs were shapefiles. The first shapefile contained the distribution of all the birds of the world, downloaded from "*birdlife.org*", and called "*AllSpecies.shp*". This shapefile comprised the distribution, origin, presence, and seasonality of more than 11,000 bird species. The second shapefile was the spatial extent of Europe and the third one the spatial extent of the study area, located in Mukono, Luwero and Kayunga districts (See Figure 4). They were all downloaded from "*gadm.org*".

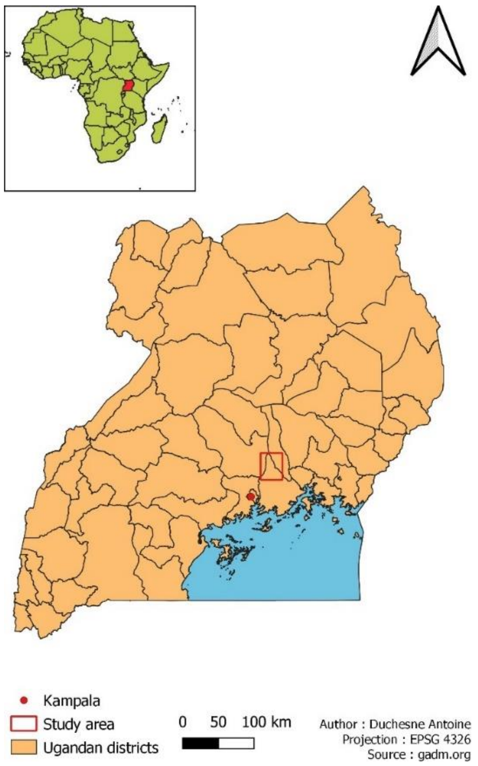


Figure 4 - Study area in Uganda, located in the Mukono, Kayunga and Luwero districts of Central province

METHODS

Bird species were selected using spatial rules and attribute selection in QGIS. First, the *“Extract by location”* tool was used to extract all bird distribution shapefile intersecting the Mukono district. The output layer was named *“StudyAreaSpecies.shp”* and contains both resident and migrant birds.

Next, the selection of migratory birds was made from *“StudyAreaSpecies.shp"*. In QGIS, the *"Extract by location"* tool was used again to extract birds whose distribution overlapped Europe and the districts’ extent. Europe extent was added to take migratory birds into account. After that, there were still some non-migrant birds that had very wide ranges but should not be considered because the focus was on tropical and migratory bird species. To eliminate these birds, the *"Extract by Expression"* tool was used for the seasonality of birds contained in the shapefile. Only resident birds that are present outside of the breeding season (*Seasonal = 3*) and migratory birds, only present during a part of the year (*Seasonal = 4*), were selected.

Resident species were selected based on their presence and range size. The *"Extract by Expression"* tool was used to select resident species (*Seasonal = 1*) and birds with a distribution area of less than 1,500,000 km^2. (*Range < 1,500,000*). This step eliminated birds with a large range, considering them as large-distributed, not tropics-restricted, and less relevant species from a conservation standpoint.

Then, birds that were not related to tropical forests, degraded forests, agroforests, or plantations were removed. The websites "*Worldspecies.org*", "*Birdlife.org*", and "*Birds.net*" provide information on the birds' primary and suitable habitats, forest dependence, weight, and diet. Then, additional deletions were made. First, non-forest dependent species were removed because the focus here is on forest-dependent species and their conservation. Second, species for which data about body mass were not available were also removed because body mass was used for parameter estimation.

The final list of birds consisted of 38 species with 33 resident and 5 migratory species (See Appendix 1). Each species was given an ID to differentiate in the model. The three-digit number is related to forest specialization (1 = forest specialist; 2 = forest generalist; 3 = forest visitor) and the two-digit and single-digit numbers differentiate them within that specialization.

3.2) RANGESHIFTER

MODEL DESCRIPTION

RangeShifter is a stochastic individual-based model (IBM) capable of representing the dispersal movement of animals in a gridded landscape following simplified rules (Palmer, Coulon et Travis, 2011). RangeShifter was only able to run simulations for one species at a time. The movement rules depended on four parameters: 1) the animal's perceptual range (PR), which was the scale at which it perceived and responds to its environment; 2) the directional persistence (DP), describing animals' tendency to follow a correlated path; 3) the goal bias (GB), which covered animals' tendency to move toward a particular direction; and 4) the size of the animal's memory (MS), which represented the distance at which DP is maintained. The combination of these four parameters and the cost values of the surrounding cells influenced the direction in which the animal took its next step (Aben et al, 2014; Palmer, Coulon et Travis, 2011).

Here, the focus was on two out of the three main components of RangeShifter: population dynamics and dispersal behaviour. This model can help to understand how a given species will respond to environmental changes, landscape management, or conservation practices. This model linked the landscape to the response of the targeted species through the parameters needed to represent animal movement and behaviour (Bocedi, Palmer et Travis, 2020).

RangeShifter can be used at different levels of complexity (Bocedi, Palmer et Travis, 2020). Here, complexity was low due to the lack of data and the large number of bird species represented in this study. Model inputs were literature-based. Some important assumptions were required due to the lack of data, especially regarding movement ecology and dispersal behaviour.

LAND COVER MAP

The land cover map was created from Landsat 8 bands, had a resolution of 30m and was uploaded from "*usgs.gov*". The date of the image was March 10th of 2019 because there were fewer clouds on that image.

The land cover map was created using supervised classification. The methodology was the same as Hernandez (2022). The creation of the training areas was done manually, using RGB composites to help differentiate specific land cover. The "*Supervised classification*" tool was run to create five land cover classes. In addition to all Landsat8 bands, NDVI, brightness, wetness and greenness were also used for this classification. The land cover classes created were: Primary Forests, Agriculture (including annual and perennial crops and pastures), Wetlands (including peatlands and rivers), Urban areas, and

Agroforests. Next, the raster was smoothed to remove small errors and single residual pixels. Once the smoothing was completed, 100 random points were created to evaluate the accuracy and quality of the classification. The latter was estimated using the Kappa coefficient. Its value reached 88%.

Then, the resolution of the raster was changed from 30x30m to 100x100m for two reasons. The first was to avoid scaling problems for the carrying capacity in RangeShifter. Carrying capacity was a RangeShifter parameter that calculates the number of birds present per hectare using cell size. Some bird species had a low carrying capacity and 100x100m cells ensure at least one bird per cell. The second reason, explained below, was the size of the cocoa farms.

Next, 5,000 cocoa plots were artificially added among the agroforest cells as this number seemed sufficient to see an effect in the changes explained below. The "*Random Points*" tool was used to add them to the landscape. Then, they were converted into rasters with the "*Rasterize*" tool. The use of 100x100m raster cells was still relevant because the typical area of cocoa farms is between 0.25 and 5ha (Vaast and Somarriba, 2014). With these cocoa farms, the land cover map now contains six different classes (Figure 5).

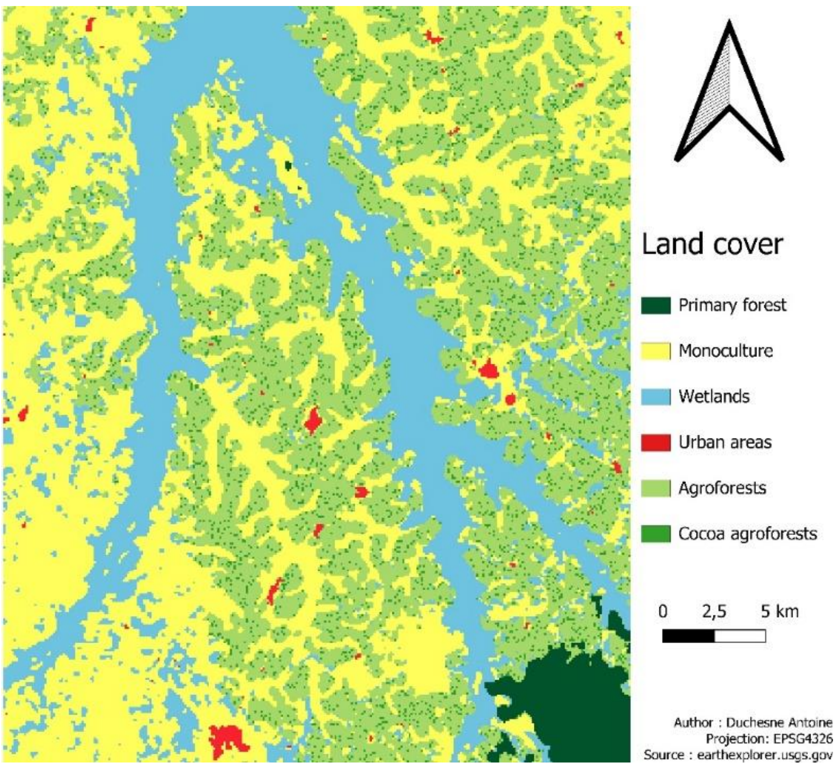


Figure 5 - Land cover map of the study zone

SCENARIOS

To assess the potential of bird-friendly cocoa in the study area, two different scenarios were constructed. In scenario 1, the 5,000 artificially added cocoa farms implemented bird-friendly practices. These practices were based on two main theory-based variables: a 40% shade cover (Jezeer et al, 2017; Kupsch et al, 2019; Sanial et al, 2022; Gobbi, 2000) and a minimum of 12 native tree species per hectare (Vaast et Somarriba, 2014).

In scenario 2, these 5,000 cocoa farms were full-sun cocoa cultures. Full-sun cocoa practices were based on the fact that only cocoa was grown on the plot without intercropping.

PARAMETERS

As previously mentioned, the two main components of RangeShifter here were the population dynamics and the dispersal behaviour.

POPULATIONS DYNAMICS

For this study, the population dynamics model was set on asexual. This means that only females drove the population dynamics and there were enough males for reproduction (Bocedi, Palmer et Travis, 2020). This choice reduced the need for input data for the model by removing genetics and population stage dynamics that were less useful for the goals of this study.

Thus, the inputs needed for population dynamics were the number of breeding seasons, set to 1 for all species due to lack of data, the difficulty of estimating the number of breeding seasons for tropical birds (Norris et Lopez, 2011), and the fact that a lot of birds only have one breeding season (Birdlife datazone (n.d.); Les oiseaux (n.d.))

Maximum population growth (*Rmax*) was set to 1 for all birds to assume stable population growth. The focus here was not on population demographics but on connectivity and the ability of cocoa patches to support and conserve birds. In addition, estimation of *Rmax* using body mass (Sibly et al, 2012) yields values lead to rapid population growth, creating a bias for birds' dispersion.

The competition coefficient, which describes how population density is regulated (Bocedi, Palmer et Travis, 2020), was set to its default value to assume a compensatory competition effect and due to a lack of data.

Habitat carrying capacity (*K*), was estimated with body mass. Russo et al (2003) found a relationship between the weight of Amazonian birds and their maximum *K*. This relationship was found for granivorous, insectivorous, and frugivorous species. The response of nectarivores was assumed to be the same as the overall response of all bird species due to a lack of precise data. Second, the maximum value of *K* varied among land cover intensities based on the ecological characteristics of the birds. The characteristics that had the greatest impact on the response of birds to land cover change were their diet, their status (resident or migrant), and their forest specialization (Newbold et al, 2013). Newbold et al (2013) assessed the effect of each of these ecological traits on the probability of presence among land cover intensities. The probability of presence was used to assess the variation in *K* among different land cover, assuming that *K* was at its maximum in primary forests. Thus, there were three values of carrying capacity for each species. One for primary forest, one for low-intensity land cover (bird-friendly cocoa and agroforests), and one for high-intensity land cover (monocultures). We assumed that wetlands had the same *K* as monoculture due to lack of data and the fact that we were focusing on forest birds.

DISPERSAL BEHAVIOUR

Dispersal behaviour described how species moved across the landscape based on their own characteristics and the cost value landscape. Only limited data were available on movement ecology and dispersal behaviour. Therefore, this section also relied on assumptions.

The emigration probability, which was the probability of leaving a patch after each step, was defined as density independent for less complexity and due to a data gap. Its value was set to 0.50 because birds were considered highly mobile species, dispersing easily across the landscape (Mahendiran et Pa, 2013).

Step mortality was the probability of dying after one step. This value was set to 0 to assume constant populations, parallel to maximum population growth.

Perceptual range (PR) was the distance at which the individual could estimate the surrounding landscape. The scale at which birds responded to their environment depended on their body mass (Thornton and Fletcher, 2013). Additionally, keeping small PR distances lead to better model predictions (Aben et al, 2014) and 100 meters was the maximum distance birds were willing to travel in a non-forested matrix for a single flight (Aben et al, 2012). However, there was a lack of specific data on the perceptual range of birds. Thus, the 100m PR values in Aben et al (2012), which used visual cues for one small forest bird, were used here while retaining the relationship to body mass (See Table 1). Birds lighter than 60g had a PR value of 1, birds weighing between 61g and 1kg had a PR value of 2, and birds heavier than 1kg had a PR value of 3.

Directional persistence (DP) was the tendency to follow a correlated trajectory. When DP is low, RangeShifter performance was, again, higher but there was a lack of data to estimate this parameter. Then, the DP value was set to 2 as in Aben et al (2014).

Memory size (MS) was the tendency to move in a certain direction. The estimation of this parameter faced a large gap in the literature, but the model predictions were better when MS was small (Aben et al, 2014). Therefore, its value was set to 1, which was the default value.

Goal bias represented the tendency to head in a particular direction. Here, no goal was attributed to birds.

Habitat cost was one of the most important parameters in the model (Aben et al, 2014). It could be estimated by methods depending on field captures (Estrada-Carmona et al, 2019) but this was not possible due to no field excursion. Therefore, habitat cost values were based on Aben et al (2014), keeping a low contrast between land cover values for better performance, and information gathered from the literature (Kupsch et al, 2019; Gobbi, 2000; Sanial et al, 2022; Jarret et al, 2021; Bennett et al, 2021; Clough et al, 2009; Douglas et al, 2013; Holbech, 2009; Abrahamczyk et al, 2008) (**Erreur ! Référence non valide pour un signet.**). Note that, for migratory bird species, the cost values (in green) were decreased by 1 (but never equal 0) for each land cover and specialization (**Erreur ! Référence non valide pour un signet.**). The dispersal and greater mobility of long-distance migratory birds made them less likely to be threatened by land-use change (Sekerciolgu, 2012).

Table 1 - Land cover cost values for resident and migratory birds

Resident birds	Primary forest	Monoculture	Wetlands	Urban areas	Agroforest	Cocoa agroforest
Forest specialists	1	6	4	500	4	2
Forest generalists	1	5	3	500	3	1
Forest visitors	1	3	3	500	2	1
Migrant birds	**Primary forest**	**Monoculture**	**Wetlands**	**Urban areas**	**Agroforest**	**Cocoa agroforest**
Forest specialists	1	5	3	500	3	1
Forest generalists	1	4	2	500	2	1
Forest visitors	1	2	2	500	1	1

The last part of the dispersal behaviour concerned the settlement of the birds. The minimum number of steps was set to 0 and birds will stop at the end of the model.

The parameters' values that are not described here are available in the appendix (See Appendix 1).

SIMULATION

The last parts of the model were the simulation options. The model ran for 250 years for each bird species among the two scenarios, which was more than twice the time after which the number of cells occupied by birds reached a plateau. In addition, it also allowed birds to disperse across the landscape for a longer period.

Finally, it was necessary to define the initialization parameters. At the beginning of the simulation, birds were randomly distributed in 20% of their suitable habitats with a density equal to half of their carrying capacity. This latter value was the proportion in which the animal population spends most of its time (Saether et al, 2008). Forest specialist birds only started in primary forests for a total count of 600 cells. Forest generalists and forest visitors started in primary forests and agroforests but not in cocoa plots for a total count of 9,000 cells.

The selected outputs were the following:

- Range, providing the number of occupied cells by the bird population for every year.
- Heat maps, providing the number of visits of a bird population for every cell.

3.3) ANALYSIS

OCCUPIED CELLS

To detect whether changes in land cover creates differences in bird species dispersal, the mean number of occupied cells for each species was compared between the two scenarios using a t-test. In RStudio, the function "*shapiro.test*" allowed to see if the data distribution was normal or not. Following the central limit theorem, the sample size of 250 observations was sufficient to consider the sample distribution as normal (Depiereux, 2019). Then, the function "*var.test*" analysed the data's variance. All the data variances were not equal. Then, the argument about variance equality in the "*t.test*" function was set on TRUE or FALSE following the previous results.

COCOA FARM USE

For each bird, a t-test was also done to compare the number of visits in cocoa farms between the two scenarios. The same functions than for occupied cells were applied. The function "*shapiro.test*" was still unused because the number of samples here was equal to 5,000.

LAND COVER VISITS

The number of visits per land cover and per scenario was analysed with a two-way Anova. The objective of this analysis was to see if the scenario and the land cover influenced the birds' number of visits. The variances of the data were considered as equal, following the function "*var.test*" in RStudio.

CHAPTER 4 - RESULTS

4.1) OCCUPIED CELLS

DESCRIPTION

Figures 6 to 10 show, in the study region, the evolution of cells occupied by each bird population over 250 years in the two scenarios (1= Bird-friendly cocoa; 2= Monoculture cocoa). In the first 10 years, most species showed a sharp increase in the number of cells they occupied. Only cell occupation of three bird species (ID 101, 201 and 204) decreased in these early years (Figure 6 and Figure 7). A table with the species' ID, their names and attributes is available in the appendix (Appendix 1). After the first sharp increase or decrease, it appeared that birds reached an equilibrium in the number of cells they occupy.

The difference in occupied cells between the two scenarios was highly variable. In some cases, the two values were nearly equal as for Bird 202 (Figure 7), in others, they were slightly different as for bird 312 (Figure 10) and still in others , they were proportionally very different as for Bird ID 104 (Figure 6).

ANALYSIS

Almost all birds' IDs showed a different response with a very high significance in occupied cells evolution between the two scenarios, represented by "(***)" in the figures (Appendix 2). Only bird IDs 103 and 212 did not show a significant difference in this evolution, represented by "(/)" in the figures (Appendix 2). This means that the scenario had an impact on bird's dispersal. However, the presence of bird-friendly cocoa did not seem to improve bird species' dispersal in every case. On the contrary, these graphs showed that scenario 2 led to a greater cell occupation more often than scenario 1. This effect was clearer for forest generalists and forest visitors but fuzzier for forest-specialists.

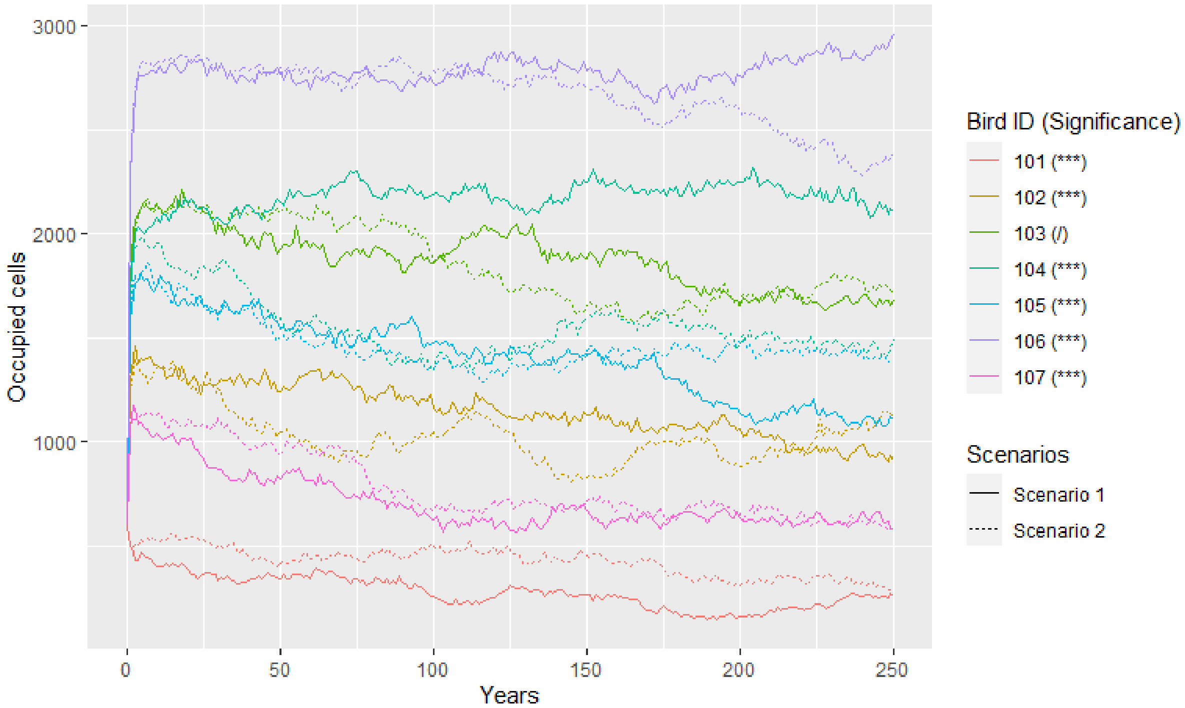


Figure 6 – Forest specialist birds occupied cells evolution between scenario 1 and scenario 2

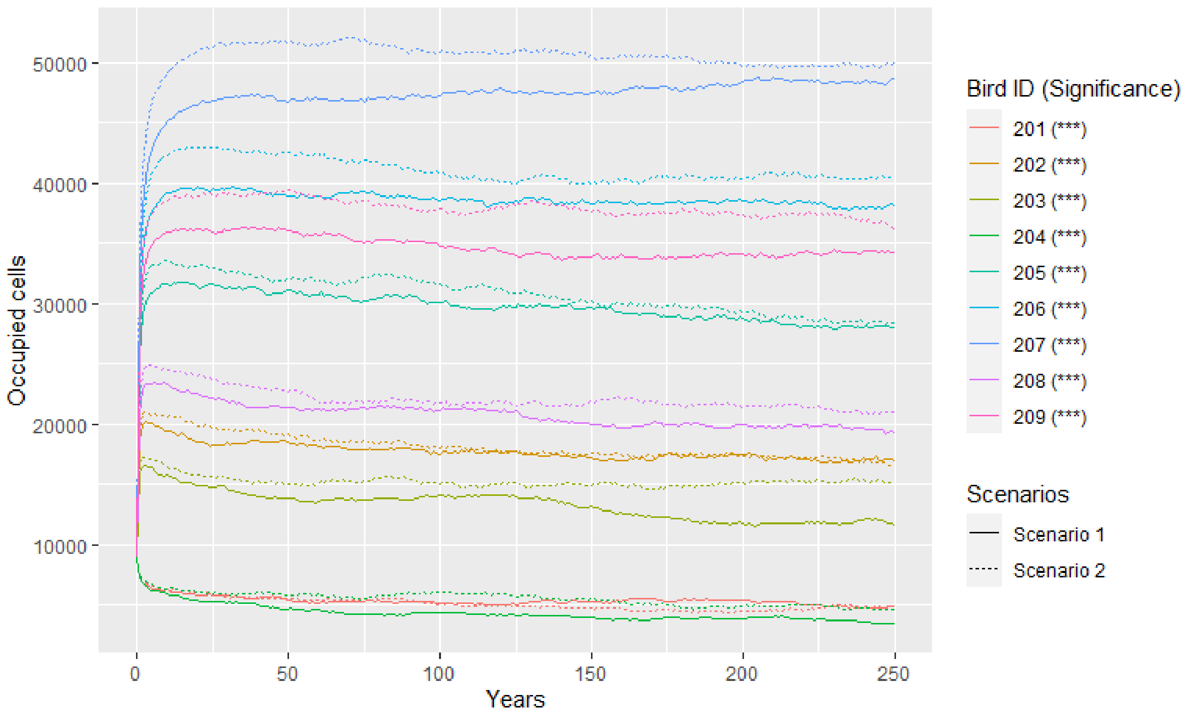


Figure 7 - Forest generalist birds occupied cells evolution between scenario 1 and scenario 2 (Part 1)

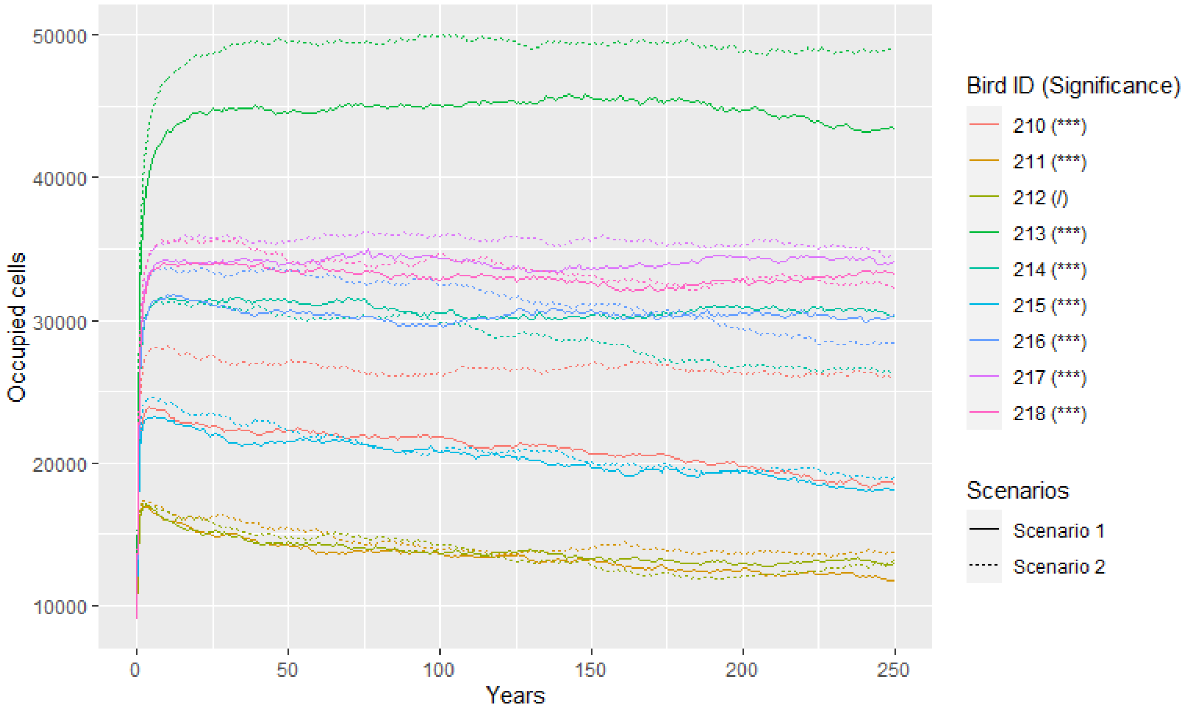


Figure 8 - - Forest generalist birds occupied cells evolution between scenario 1 and scenario 2 (Part 2)

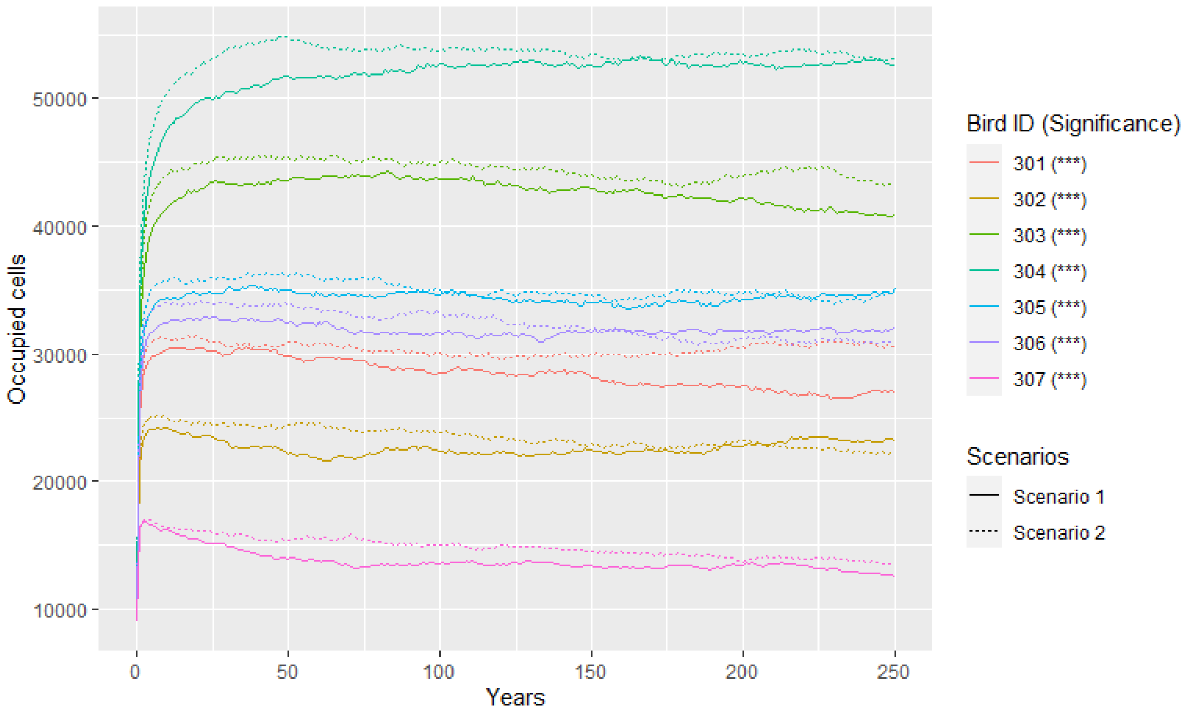


Figure 9 - - Forest visitor birds occupied cells evolution between scenario 1 and scenario 2 (Part 1)

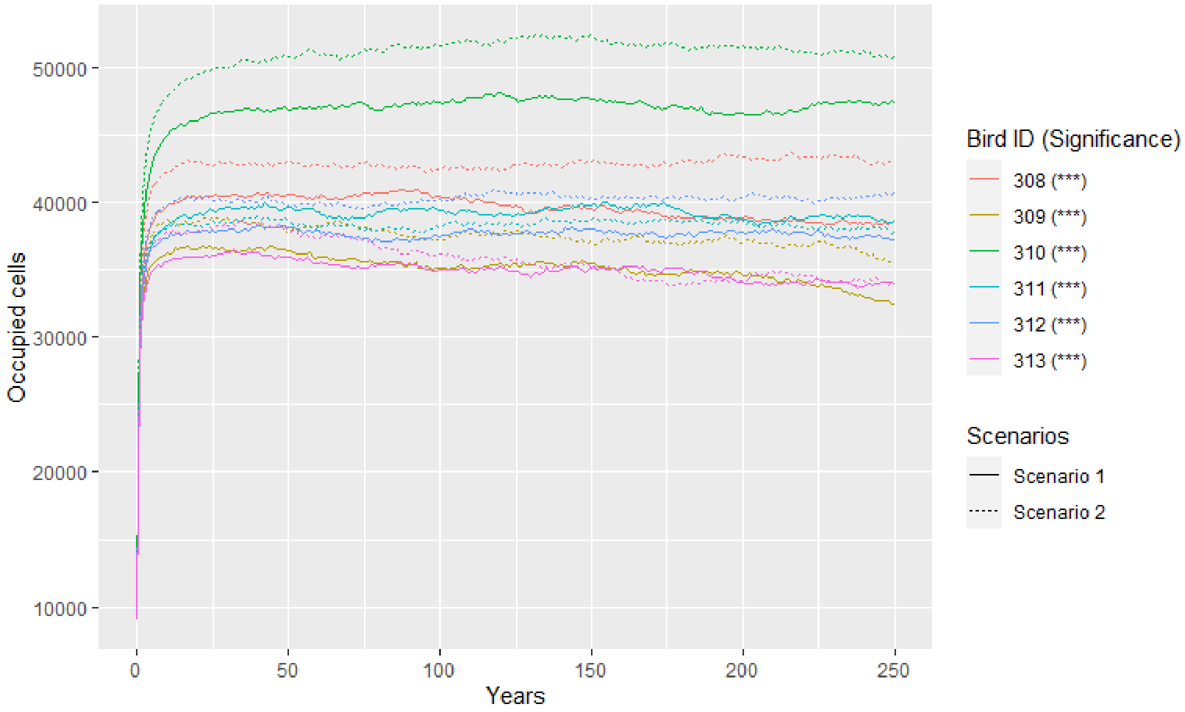


Figure 10 - - Forest visitor birds occupied cells evolution between scenario 1 and scenario 2 (Part 2)

4.2) HEAT MAPS

DESCRIPTION

Heat maps represented the number of times a cell was visited by a bird population. The heat maps produced by RangeShifter have been processed in QGIS for better visualisation (Figures 11 to 16). The more a cell was visited, the more its colour tended towards red. The less a cell was visited, the more its colour tended towards green. Only heat maps for three bird species (one forest specialist, one forest generalist and one forest visitor) were represented in this part. These maps were also represented under the form of boxplots for each bird and each scenario for a better comparison between the land cover visits (Figure 17,Figure 18 and Figure 19). All the other heat maps and graphs can be found at the end of the document (Appendix 2 and Appendix 3).

First, it appeared that forest specialist rarely left the primary forest. When they did, they did not move far from it under any scenario. Except for primary forest land cover, only a few cells had no-zero values for these birds (Figure 17).

Second, forest generalists and forest visitors often passed through cocoa farms in scenario 1, where this land cover recorded the highest number of visits but avoided them in scenario 2 (Figure 18 and

Figure 19). Outside of cocoa farms, generalists and visitors primarily used agroforests and primary forest, in all scenarios. However, their use of the latter land covers was either equal in both scenarios or greater in scenario 2.

ANALYSIS – COCOA USE

All the bird species showed a different number of visits of cocoa farms between the two scenarios, except for bird IDs 105 and 107. This was due to their restricted dispersal. These birds almost stayed in primary forest, and it was logical not to see a difference between the two scenarios for them. Moreover, forest specialist birds showed the higher p-values, reinforcing this explanation.

Forest generalist and forest visitor birds used significantly more bird-friendly cocoa than full-sun cocoa. The forest specialist species' response was less clear because of the two non-significant results but five of the seven forest specialists followed this trend.

ANALYSIS – LAND COVER VISITS

For all the bird species, land cover had a very high significant effect (***) on the number of visits. The scenarios had a very high significant effect (***) for most of the bird species. Bird 213 showed a very significant effect (**) while the scenarios did not show any significant effect for birds 103, 106, 208, 209, 302 and 309. Finally, for all the bird species, except one (bird 106), the interaction between land cover and scenario has very high significant effects on the number of visits. All the graphs representing the graphs and significance can be found in the appendix (Appendix 2 and Appendix 3).

The very high significant effect of land cover on birds' visits seemed logic because these land cover had different cost-values in the model and this model is very sensitive to this value (Aben et al, 2014).

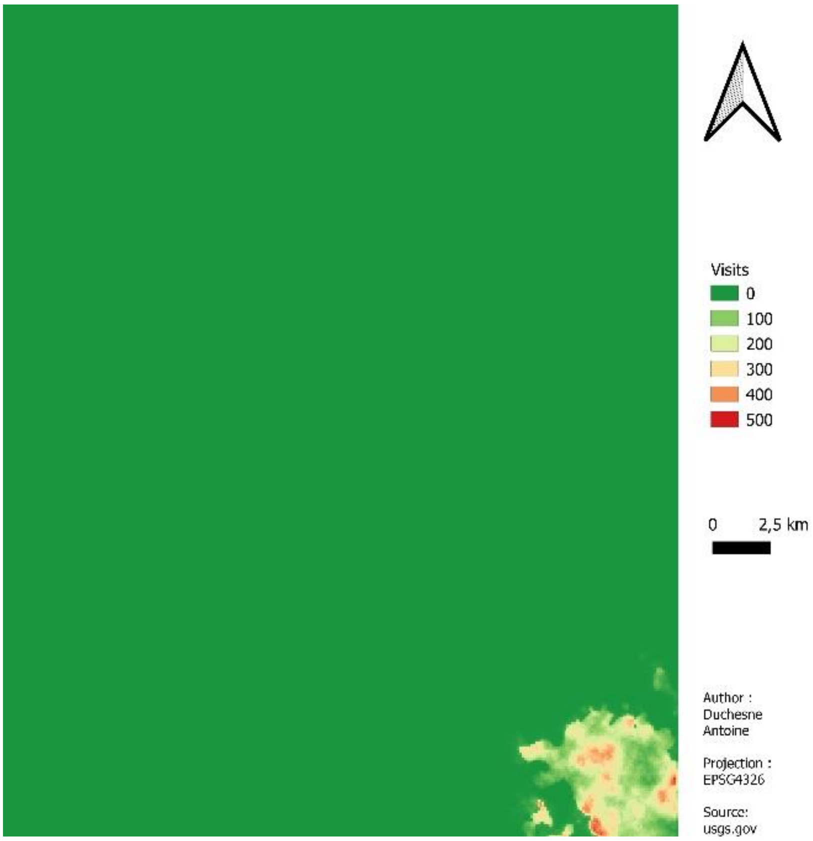


Figure 11 – Heat map representing the number of visits per cell for a forest specialist bird (ID=103) in scenario 1

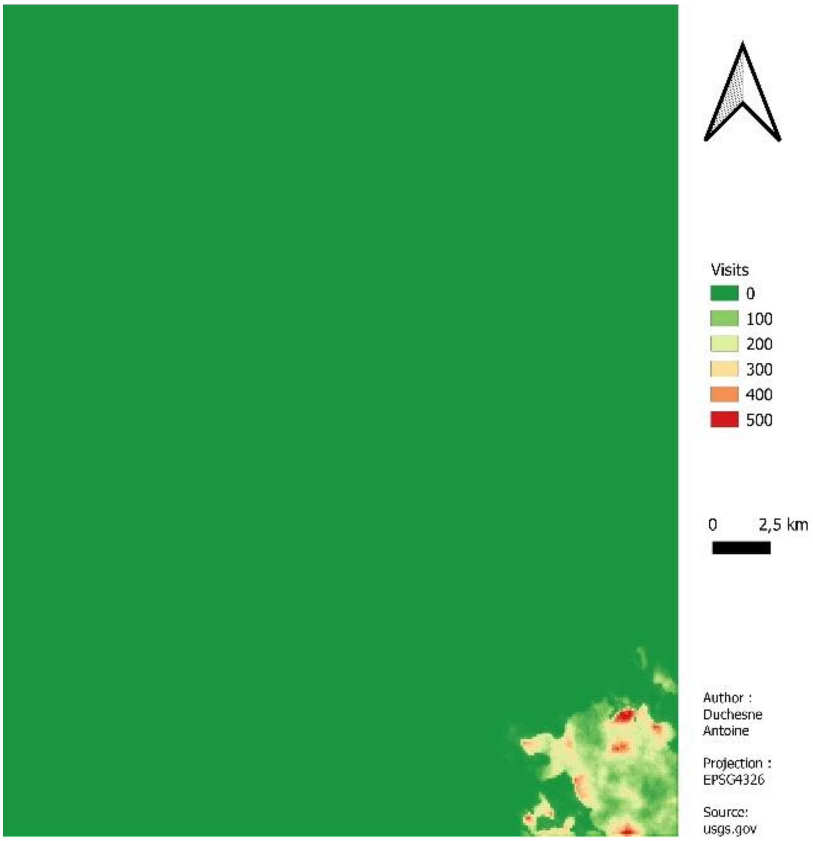


Figure 12 - Heat map representing the number of visits per cell for a forest specialist bird (ID=103) in scenario 2

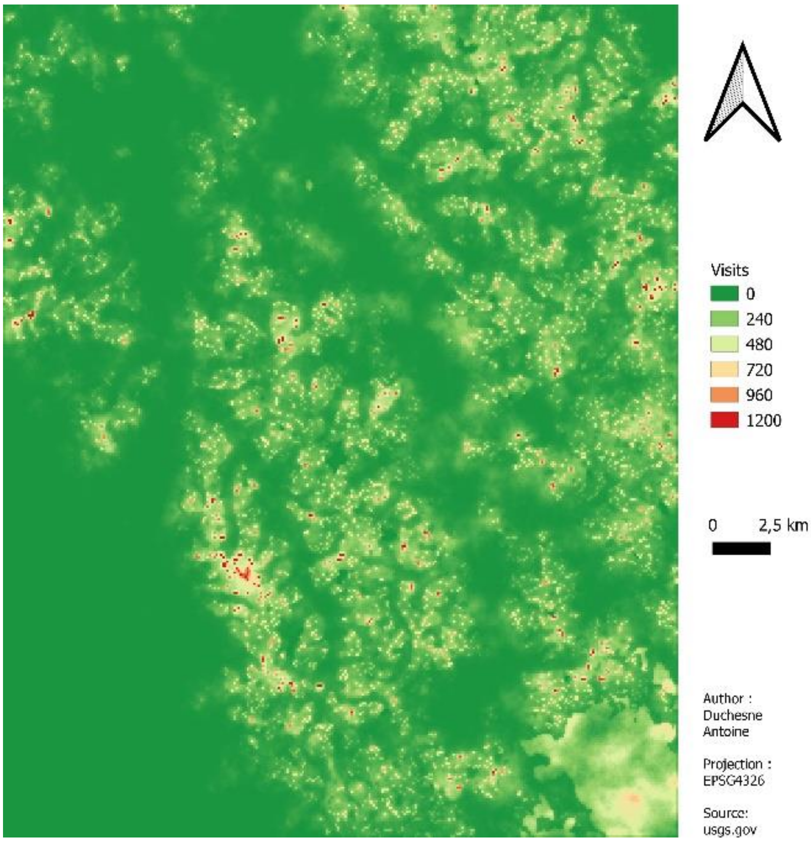


Figure 13 - Heat map representing the number of visits per cell for a forest generalist bird (ID=209) in scenario 1

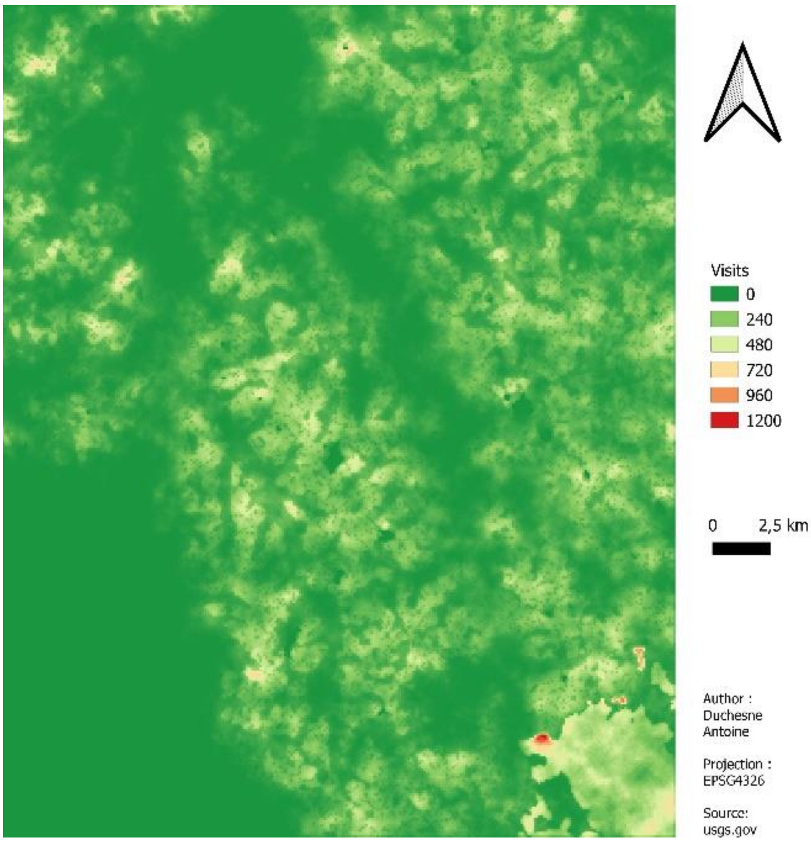


Figure 14 - Heat map representing the number of visits per cell for a forest generalist bird (ID=209) in scenario 2

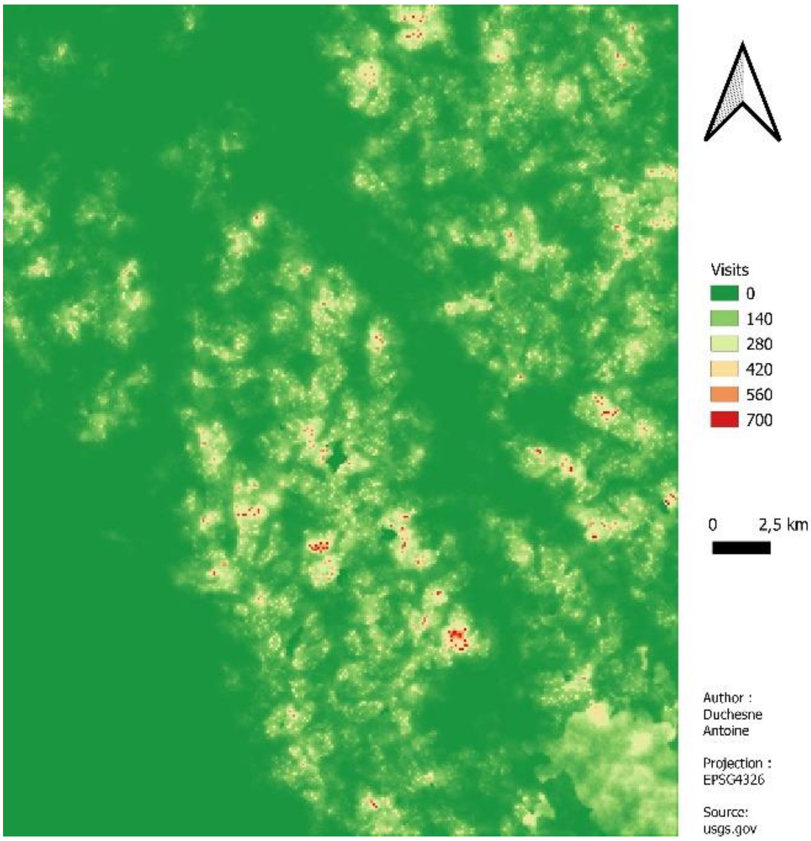


Figure 15 - Heat map representing the number of visits per cell for a forest visitor bird (ID=312) in scenario 1

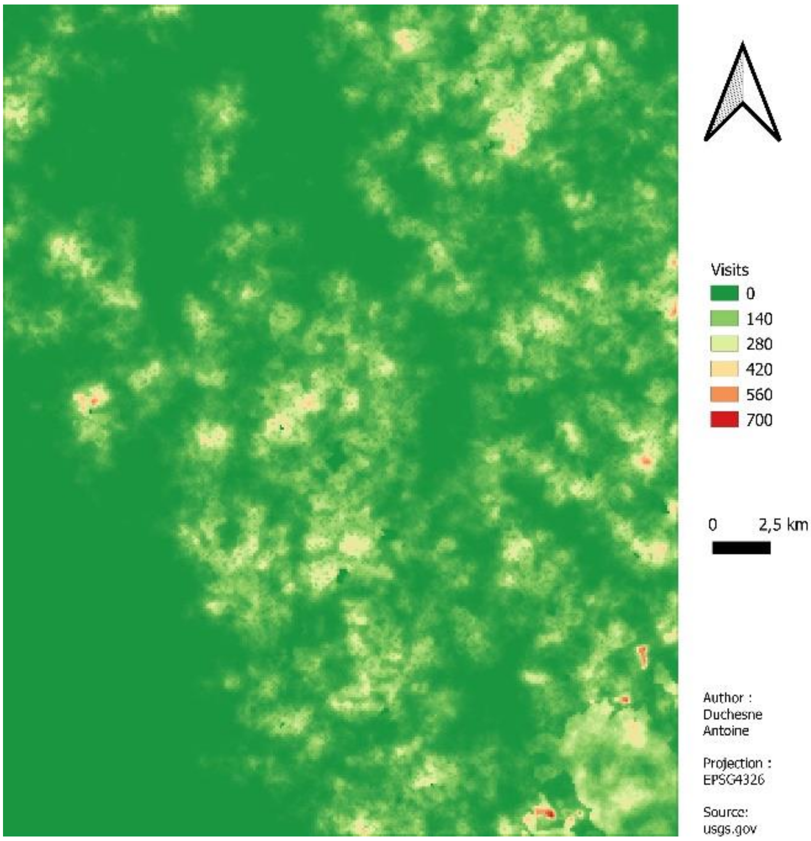
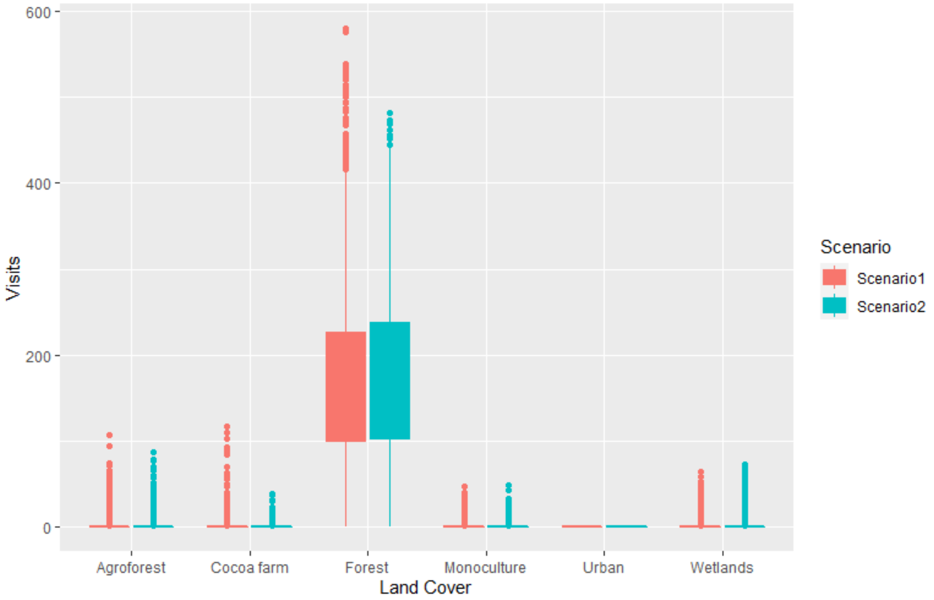
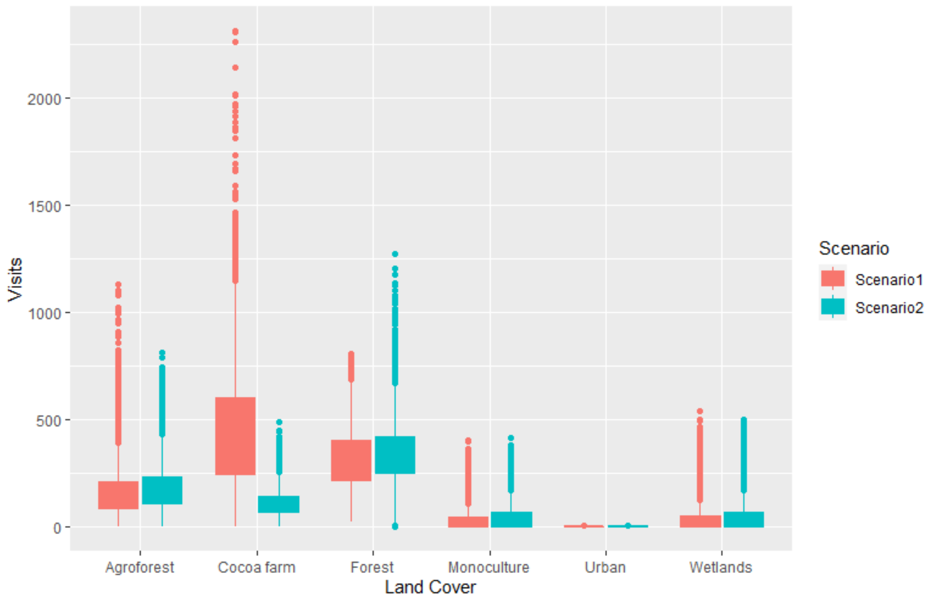


Figure 16 - Heat map representing the number of visits per cell for a forest visitor bird (ID=312) in scenario 2



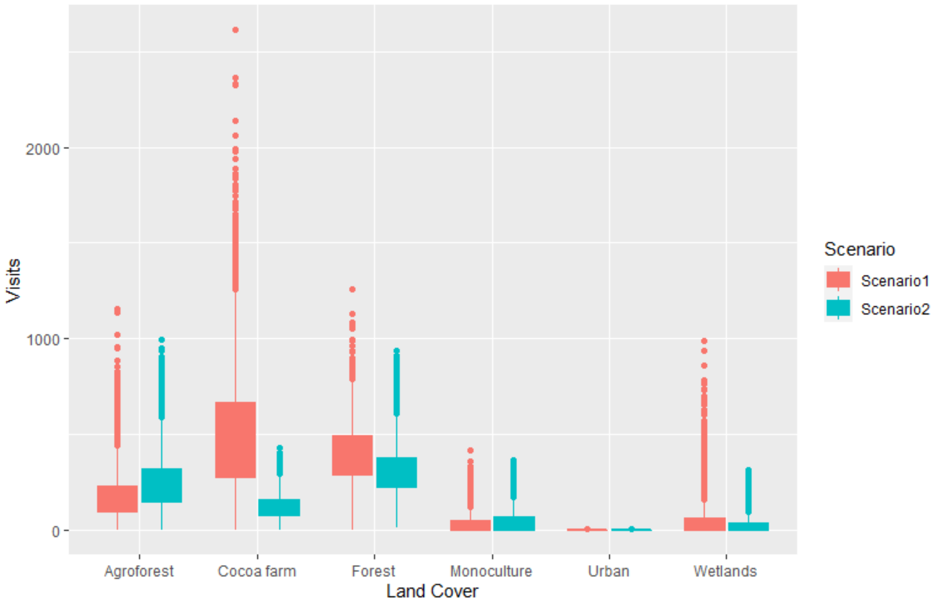

```
Response: Sim103
                      Sum Sq     Df    F value Pr(>F)
LandCover          184035721      5 1.4418e+05 <2e-16 ***
Scenario                 220      1 8.6020e-01 0.3537
LandCover:Scenario     21531      5 1.6868e+01 <2e-16 ***
Residuals           58549969 229348
```

Figure 17 – Visits number by landcover and scenario for a forest specialist bird (ID=103) and its ANOVA results




```
Response: Sim209
                       Sum Sq     Df    F value Pr(>F)
LandCover          1576863750      5 44769.1156 <2e-16 ***
Scenario                 1960      1     0.2782 0.5979
LandCover:Scenario  316046959      5  8972.9647 <2e-16 ***
Residuals          1615625157 229348
```

Figure 18 – Visits number by land cover and scenario for a forest generalist bird (ID=209) and its ANOVA results




```
Response: Sim312
                       Sum Sq     Df   F value    Pr(>F)
LandCover          2313137272      5 50618.726 < 2.2e-16 ***
Scenario               376657      1    41.212 1.368e-10 ***
LandCover:Scenario  480095613      5 10506.004 < 2.2e-16 ***
Residuals          2096115192 229348
```

Figure 19 – Visits number by landcover and scenario for a forest visitor bird (ID=312) and its ANOVA results

CHAPTER 5 – DISCUSSION

5.1) CONSERVATION POTENTIAL AND ITS DECREASE

The number of visits per land cover between scenarios for each bird can partially confirm the first hypothesis. This latter expected that "*Bird-friendly cocoa have the potential to improve the conservation of forest birds and this potential decreases from forest visitors to forest specialists*".

The response and behaviour of forest specialists are in line with the literature. First, the results show that forest specialists rarely leave the primary forest. The significant difference of cocoa farms visits between the two scenarios, for five out of the seven forest specialists, only concerns farms located near forest edges. This is because these birds largely prefer primary forests to human-modified landscapes or other land covers (Jarrett et al, 2021; Clough et al, 2009; Boesing et al, 2018). Secondly, according to the literature, forest specialist bird richness is higher close to the forest edges. They are principally present in these edges plus primary forests (Clough et al, 2009) and their richness decrease with distance to primary forest (Muhammad et al, 2013). In the results, when these birds leave the forest, they do not move far from it. However, the results here show a stronger effect than what is found in the literature. Indeed, the distance they cross outside primary forests is shorter than what is expected in some other studies (Muhammad et al, 2013; Clough et al, 2009). Thus, these results are consistent with the 100m distance found by Aben et al (2014). This is probably because the methodology is partially based on their advice. Thirdly, the study area contains a small primary forest patch in the central North area. When a small population of forest specialist starts there, its local population does not survive long. This is consistent with Edwards et al (2021) and Waltert et al (2005) who argue that small habitat remnants cannot maintain a viable population. Finally, the results also highlight the importance of conserving undisturbed primary forests as forest specialists are more diverse in these habitats and do not go out of them. In this study, agroforests, even if bird-friendly, cannot replace old-growth primary forest that support unique species composition (Arnold et al, 2021; Kupsch et al, 2019; Jarrett et al, 2021). However, in the literature, forest specialists are sometimes found in agroforests (Abrahamczyk et al, 2008; Bennett et al, 2021; Cabral et al, 2021).

Thus, this model can represent the behaviour of forest specialist species with some realism despite its assumptions. However, this behaviour is probably stronger because these species make little or no use of bird-friendly cocoa. The low PR value given to these species may explain this. With a low PR, birds cannot see far from the forest edges and then, cannot see near bird-friendly cocoa farms. Forest birds probably have a low PR value, especially for ground and understorey species. They cannot see far because of the dense forest where they live (Ibarra-Macias et al, 2011). Even when forest specialists move from the forest interior to the forest edges, their PR does not necessarily increase. Indeed, these gaps and edges are brighter than forest interior and these birds may be blinded because of their eye structure (Stratford et Robinson, 2005). However, only little is known about the PR of forest interior birds (Ibarra-Macias et al, 2011). Another reason for the stronger behaviour of forest specialists in the model is the contrast between adjacent land cover (Barros et al, 2019). This edge effect is less important when the two land covers have a similar structure (Boesing et al, 2018). In the study area, the primary forest is mainly surrounded by classic agroforests, which are considered to have a less dense and less complex structure than the primary forest. The contrast between these two habitats is high (in the methodology, primary Forest is four times cheaper than agroforests). Thus, forest specialists can be found in forest edges but cannot really cross them, as some other Brazilian birds (Boesing et al, 2018).

Probably for similar reasons, the behaviour of forest generalists and forest visitors is also well represented. Indeed, these less specialised birds are more likely to use human-modified ecosystems than forest specialists (Cabral et al, 2021). This is well represented by the cost-values. Then, these birds mainly use agroforests and primarily use bird-friendly cocoa in scenario 1. These birds use cocoa farms more often under the first scenario than under the second one. Once again, this is consistent with the literature. Even if less specialized species are less vulnerable to LUCC, they must face it. They go outside of their preferred habitats more often than forest specialists, but they do not often seem to cross large areas of monoculture and open lands. These areas create barriers to connectivity and dispersal to forest species (Waltert et al, 2005; Cabral et al, 2021). Indeed, in these areas, they are vulnerable to hunters and predators (Boesing et al, 2018) and there are less food resources for them (Newbold et al, 2014). As for forest specialists, their tendency to not going far from their preferred habitat may be due to the PR value found by Aben et al (2014).

The first hypothesis is there partially confirmed because, on one hand, bird-friendly cocoa can improve forest bird conservation but, on the other hand, this conservation is only possible for forest generalists and forest visitors, not for forest specialists. Moreover, the conservation potential of bird-friendly cocoa is the lowest for forest specialists (almost null) but, due to analysis limitations, it is not possible to say if this potential is greater for forest visitors than for forest generalists.

5.2) BIRDS' DISPERSAL

The results of the evolution of occupied cells between the two scenarios contradict the second hypothesis. It expected that "*Bird-friendly cocoa increases the dispersal of birds in the landscape, especially for forest specialists who find more suitable habitats in these agroforests than in classic agroforests* ".

For forest generalists and forest visitors, dispersion is higher in scenario 2 than in scenario 1. On one hand, this may be due, to the repulsion of birds from full-sun cocoa farms when surrounded by classic agroforests. Less specialised birds avoid these full-sun cocoa farms and prefer to find a more suitable habitat around such as agroforests. On the other hand, the lower dispersal in scenario 1 may be due to the attraction of bird-friendly cocoa farms, combined to their higher K-value. Birds are attracted to these cells and try to stay in or near them. They do not move away unless they are forced to (e.g., because of overpopulation). This results in a reduced dispersal due to a greater concentration on these bird-friendly cocoa farms. Bird-friendly cocoa agroforests can then probably provide important habitats for more disturbance-tolerant forest bird species, such as forest generalists or forest visitors (Graham et Blake, 2001). This is because it contains a denser canopy cover and remnants trees. However, this effect may be greater as the size of these patches increases (Waltert et al, 2005; Graham et Blake, 2001).

Another reason to explain this may be that the passage redundancy does not always improve connectivity (Estrada-Carmona, 2019). Indeed, heat maps show that less specialised birds reach their maximal density in bird-friendly cocoa farms, which can alter species mobility (Estrada-Carmona et al, 2019).

An additional possible explanation is that the landscape connectivity for less specialised birds is already at its maximum under agroforests. So, these species simply prefer to move to the most attractive habitats. Matthysen (2005) also raises the possibility that habitat quality and thus, preferences, play a role in birds' dispersal. The latter explanation is only viable for less specialised species. Forest specialist, in general, do not show a clear pattern of dispersal. Indeed, they remain in the primary forest or at its edges and changes in the scenario do not affect them much. Their landscape connectivity conditions are more complex and demanding than for forest generalists or forest visitors. They cannot disperse as easily as other birds due to contrasts in land cover types (Boesing et al, 2018).

The sharp increase of occupied cells at the beginning of the runs is probably due to the K-value. Birds with a high K-value provide a dense and concentrated source of birds, with more birds ready to disperse in all directions, at the beginning of the simulation. The dispersal potential is then probably related to the K-value. On one hand, the higher the K-value, the sharper the initial increase. On the other hand, the three bird species that show an initial decrease have low K-values due to their large size. They, therefore, do not have the same dispersal potential than smaller birds. Relationships between occupancy and abundance or population size are found in the literature. A study on British birds shows that population size is the only consistent predictor of occupancy (Gaston et Blackburn, 2003). In Brazil, a higher density source population of birds increases the spill over opportunity (Boesing et al, 2018). A positive relationship between abundance and occupancy is found for many taxa, including birds (Gaston et al, 2000). Thus, it could be a general pattern in the study of ecology (Gaston et al, 2000).

Finally, the results contradict the second hypothesis because the number of occupied cells is higher under scenario 2 than under scenario 1. First, bird-friendly cocoa does not increase, or even change, dispersion for forest specialists because they stay in primary forests. Second, bird-friendly cocoa reduces the number of cells that less specialised species occupy. This is the opposite than what is found in the literature, saying that agroforests, such as bird-friendly cocoa, increase landscape connectivity (Bennet et al, 2021; Cassano et al, 2012). However, scenario 1 may lead to a decrease in the number of occupied cells but connectivity may not only be linked to this number. For example, connectivity is also dependent on spatial configuration and planning, which can increase this connectivity (Estrada-Carmona et al, 2019).

5.3) METHODOLOGICAL REFLEXIONS

STUDY AREA

The study area and its land cover configuration could create biases. First, the only primary forest site is located at the South-Eastern end of the map. This location, combined with methodological choices to make birds start in their preferred habitat for more realism, concentrate the forest specialists in this corner of the map. It can create a bias because their initial distribution is not as wide as for forest generalists or forest visitors, which started in both primary forests and agroforests. These are present all over the study area. Moreover, primary forests cells only represent 3% of the total extent of the study area, which leads to smaller bird populations for forest specialists. Thus, they still have a lower dispersal potential than other birds because of this reduced extension.

BIRDS LIST

The data used for the selection of birds may also create biases. Some bird species may have an insular distribution within their range. This means that their distribution is concentrated in some small areas within their spatial distribution. Thus, they may not be present in the study area (Wesselingh, 2021).

Then, in the resident bird selection criteria, the removal of birds with a range greater than 1,500,000 km^2 is not based on the literature. This criterion is based on a visual appreciation to keep only tropics-restricted species and not to have widespread and relatively common species.

LANDCOVER MAP

The landsat8 images used for land cover classification contain only a few clouds. This reduces the errors during the supervised classification. Moreover, these clouds are on the South-West corner of the map, where birds do not disperse in the results. The whole supervised classification follows a solid methodology. First, all the bands from Landsat 8, plus, greenness, wetness, brightness and a 432 classification are used to differentiate the land covers. Second, more than 25 training zones of different sizes are created for each land cover, excepts for urban areas. Finally, the kappa value of this classification, calculated with 100 random points, is 88% which represents a good and reliable classification (Henry, 2019). The land cover map can, then, constitute a reliable representation of the reality.

The coarsening of the raster from 30x30m to 100x100m resolution, due to methodological choices, still stay relevant because the typical cocoa farms' size ranges from 0,25 to 5ha (Vaast et Somarriba, 2014). Small farms cannot, therefore, be represented at this resolution. This last point can be set aside as small cocoa farms may not have the potential to conserve birds due to a lack of resources or nest or perch site on-farm (Edwards et al, 2021; Waltert et al, 2005). Furthermore, a single cell does not necessarily represent a single farm. It may represent a gathering of smaller farms or be a part of a greater farm. However, adding 5,000 cocoa farms cells among the agroforest land cover does not lead to realistic conditions. It assumes that a ninth of the agroforests' cells in the study area are under cocoa cultivation. This choice is made in the hope of seeing an effect between the two scenarios, but it may not be realistic. This lack of reality allowed to see an effect for forest generalists and visitors but do not make forest specialists going out of their primary forests.

RANGESHIFTER AND ITS PARAMETERS

Rangeshifter has already proved its ability to simulate animal movement in a realistic way (Aben et al, 2014; Aben et al, 2016). It considers the interaction between environment and behaviour to simulate the movement and dispersal of animals in a given landscape (Aben et al, 2014). It is a better model than Least-cost path models for conservation management or planning because animals do not always know the shortest path between two locations. However, RangeShifter is based on the animal's perception and simulates its movement with this last trait (Palmer, Coulon et Travis, 2011). Yet, the model cannot tell us exactly where the animal is, but it provides a good overview of the animal's behaviour and movement (Bocedi, Palmer et Travis, 2020). Moreover, RangeShifter can only simulate the response of one bird species at a time. Thus, interactions between different species cannot be represented. RangeShifter can model intraspecific competition but not interspecific competition which would have added more realism. However, to my knowledge, there is no model like Range Shifter able to simulate more than two animal populations.

The potential of Rangeshifter to correctly represent the behaviour of a bird population with realism is dependent on the data incorporated into it (Bocedi, Palmer et Travis, 2020). Here, the model is not used to its fullest potential. The choice of a lower complexity is due to both the lack of data and the large number of birds. The choices lead to a lower need for data but also to less realism. Moreover, some parameters are simplified to avoid further bias (e.g., population growth). Yet, these simplifications make the model less data hungry and easier to run (Bocedi, Palmer et Travis, 2020)

Indeed, the choice of a stable bird population (Rmax = 1 and step mortality = 0) is made to avoid forced dispersal of the birds. RangeShifter takes into account the carrying capacity and a cell cannot hold more birds than its K-value. Thus, when a cell is full, birds will disperse to surrounding cells with space. However, with the first estimated Rmax and Step mortality (not assuming stable population), birds' growth was exponential, forcing birds to disperse because of overpopulation. In this latter case, birds followed a diffusive dispersal from their source populations and even forest specialists made a heavy use of the monocultures. This was not realistic according to the literature because forest specialists were not so numerous in high intensity land use, when they used it (Kupsch et al, 2019; Jarrett et al, 2021).

In the methodology, the K-value is estimated thanks to the weight. Here, K varies with diet but not with specialization or status because no quantitative data are found about these. Even if there is a link between land use intensity and carrying capacity, this link does not depend solely on the diet of the birds (Newbold et al, 2013). Adding birds' habitat (ground, understory, canopy…etc), specialization, status, weight or other diets (carnivores, herbivores) to the carrying capacity estimation can clearly improve the realism of this estimated value. Indeed, with increasing land use intensity, it is not only the food resources that are modified but it is the whole ecosystem structure and processes. Then, some birds may not find suitable nest or perch sites, some will be more vulnerable to predators or hunting (Boesing et al, 2018). Specialist species are more vulnerable to these changes than generalist species (Jarrett et al, 2021). Migratory birds are less vulnerable to land use intensification than resident birds (Sekercioglu et al, 2012). Finally, weight is also an important variable: large-bodied birds need more resources than small ones. Plus, they are more vulnerable to changes than smaller birds (Newbold et al, 2013; Newbold et al, 2014). Thus, these parameters must be considered when estimating K values.

The dispersal parameters are mainly estimated following Aben et al (2012). They evaluate the impact of each of these parameters on the predictive power of the model. They find that keeping low values of PR, MS and DP improves the predictive power of the model. Then, the results here are likely to have a high predictive power. Moreover, Aben et al (2012) focus on a small bird and most of the birds in this master thesis are also small birds. The predictive power may, therefore, be lower for larger birds.

Cost-value is one of the most important parameters of the model (Aben et al, 2014). Field experiments or expert opinion can assess these values. However, no field trip was possible for this master thesis and no bird specialists were available. Aben et al (2012) advise to keep low contrast between the different cost values to improve the predictive power of the model. Following this, the cost-values are assigned based on the cost values from Aben et al (2012), which focus on the same landscape type, and modified for the study area following the opinion made with readings on the subject. Despite the extensive reading, I am not an expert on tropical birds, and this could lead to bias in the results. In addition, the cost-values are only based on specialisation and status, which simplifies their estimation. As with carrying capacity, cost-values should be based on specialisation and status, plus diet, habitat, or weight. This would add more realism and accuracy but require more data and calculations.

For the initialisation of the model, each bird population started at half-K densities, according to the literature (Saether et al, 2008), and in 20% of their preferred habitat cells. This percentage is chosen arbitrarily and is not based on the literature. Birds are not present in 100% of their preferred habitats. A start at 20% of their preferred habitat seems to provide a sufficient original population for low density birds and not too much for high density birds.

RangeShifter appears to represent the behaviour of different birds, following their specialization, with good reliability. However, due to the different initial conditions, the reliability of the model to represent the response linked to diet or status cannot be discussed as well as the reliability of the response to specialization. However, at first glance, granivores do not seem to be less numerous in the forest or agroforest than frugivores or insectivores as what can be seen in the literature (Clough et al, 2009; Kupsch et al, 2019). Indeed, the diet response to land use change is not set on the cost value but on the carrying capacity, which can then translate this effect in a less visible way. Then migratory birds appear to disperse somewhat more than other species, which is consistent with previous results (Bolwig et al, 2006; Greenler et Ebersole, 2015).

5.4) PERSPECTIVES

To go further, it can be interesting to add more details and complexity to the current methodology, as already proposed for the cost-value or the carrying capacities estimations. This would provide more reliable results and information for improved conservation management and planning. A field trip appears essential to get a better idea of the context and to understand the reality. Moreover, further research in behavioural ecology is needed to better understand the relationship between habitat use, traits, movement behaviour and the species' response to environmental changes (Habel et al, 2019). This will allow for improved assessments of parameters that are not measurable in the field.

A next step in the research underlying this Master thesis can be the evaluation of the ecosystem services provided by bird-friendly practices. First, the direct services, processes and functions provided by bird-friendly practices can be assessed. Secondly, services provided by birds attracted by these practices can be evaluated. For birds, the quantification of some of their ecosystem services such as, for example, fertilization or seed dispersal, can be estimated thanks to Gaston et al (2018). His results show how birds abundance affects the ecosystem services contribution.

Rather than quantitatively evaluating the services generated by these practices, it may be interesting to evaluate the interest for the cocoa farmer. These services can be translated into an economic or social value. Then, a cost-benefit analysis can be done to see the effects of these practices on a farm. Moreover, cocoa companies can create a bird-friendly label with clear standards for cocoa to promote these practices and offer premium prices to farmers.

Finding a way to reduce the contrast between primary forest and agroforests may be of interest for the conservation of forest specialist birds. Birds move easily in a low contrast matrix (Boesing et al, 2018). Thus, going further with bird-friendly certification practices can take forest specialists out of their forest. A 40% canopy cover does not seem sufficient for this, but this value is chosen to reduce the trade-off between yield and biodiversity. Increasing the canopy cover, plus adding food sources and nesting and perching sites for forest specialist can then attract more of them (Kupsch et al, 2019). More than on-farm practices, off-farm practices can also be useful. Indeed, birds are affected by landscape composition and not only by the local composition (Cabral et al, 2021). For example, the creation of suitable forest corridors, as in Estrada-Carmona et al (2019), may move them out of the primary forest and improve their conservation. However, the placement of these corridors must be done carefully and on the best sites for this (Asare et al, 2014).

This methodology can also be used for open habitat species. It can then provide results on possible complementary use of the landscape. However, for these bird species, some parameters must be reviewed. For example, the PR is likely to be higher for open habitat species (Ibarra-Macias et al, 2011).

Finally, all but one bird species are least concerned by extinction. The African grey parrot is the only endangered species (iucn, n.d.). Then, in a context of biodiversity crisis, adding more endangered species can improve the relevance of this study to understand the potential of bird-friendly cocoa for threatened species.

CHAPTER 6 – CONCLUSION

To conclude, the results of this thesis showed that bird-friendly cocoa might be beneficial for bird conservation. Yet, its potential impact on forest specialist birds may be limited and almost null. These birds only stay in primary forests or occur at their edges. What is happening outside of these forests, even the apparition of bird-friendly cocoa farms in the landscape, does not change their behaviour. These farms may not improve forest specialist connectivity due to their contrast with primary forest or their spatial configuration. However, bird-friendly cocoa has the potential to conserve forest generalists and forest visitors. They prefer to use these bird-friendly agroforests rather than classic agroforests. Bird-friendly cocoa results in less numerous occupied cells for forest generalists and forest visitors due to its attractiveness and conservation potential. Bird-friendly cocoa can reduce their dispersal but increase their concentration in the farms' cells. However, their passage redundancy on these bird-friendly cocoa farms does not always mean that connectivity is improved. When the cocoa farms turn into full-sun monoculture, less specialised birds avoid them and then, disperse more in the landscape.

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APPENDIX

APPENDIX 1 - BIRDS ID LIST

This list contains the parameters used in the model and the birds' characteristics.

ID	Specie Name	Name	Family	Primary Diet	Forest dependency	Weight (g)	Status	Emigr	PR	DP	MS	GB	K	K(L)	K(I)
101	Bycanistes subcylindricus	Black-and-Whithe Casqued Hornbill	Hornbills	F	H	1177	R	0.50	3	2	1	0	1	1	1
102	Phoeniculus bollei	White-headed Wood Hoopoe	Woodhoopoes	I	H	55	R	0.50	1	2	1	0	8	8	6
103	Rhinopomastus castaneiceps	Forest Wood Hoopoe	Woodhoopoes	I	H	24	R	0.50	1	2	1	0	16	15	12
104	Dendropicos poecilolaemus	Speckle-breasted Woodpecker	Woodpeckers	I	H	28	R	0.50	1	2	1	0	14	13	11
105	Illadopsis albipectus	Scaly-breasted Illadopsis	Ground babblers	I	H	32	R	0.50	1	2	1	0	13	12	10
106	Phylloscopus budongoensis	Uganda Woodland Warbler	Leaf-Warbiers	I	H	9	R	0.50	1	2	1	0	33	31	25
107	Oriolus Oriolus	Eurasian Golden Oriole	Oriolidae	I	H	70	M	0.50	2	2	1	0	7	7	6
301	Tricholaema lacrymosa	Spot-flanked Barbet	African barbets	F	L	23	R	0.50	1	2	1	0	16	15	14
302	Lybius guifsobalito	Black-billed Barbet	African barbets	F	L	42	R	0.50	1	2	1	0	10	10	9
303	Ploceus pelzelni	Slender-billed Weaver	Weavers and allies	G	L	13	R	0.50	1	2	1	0	25	26	25
304	Estrilda nonnula	Black-crowned Waxbill	Waxbills, grass finches, muni	G	L	8	R	0.50	1	2	1	0	36	37	36
305	Ploceus superciliosus	Chestnut-crowned Sparrow-Weaver	Weavers and allies	G	L	21	R	0.50	1	2	1	0	17	18	17
306	Eminia lepida	Grey-capped Warbler	Cisticolas and allies	I	L	20	R	0.50	1	2	1	0	18	17	16
307	Turdoides sharpei	Black-lored Babbler	Laughingthrushes and allies	I	L	79	R	0.50	2	2	1	0	6	6	6
308	Psalidoprone albiceps	White-headed saw wing	Swallows and martins	I	L	12	R	0.50	1	2	1	0	26	25	23
309	Drepanorhynchus reichenowi	Golden-winged Sunbird	Sunbirds	I	L	15	R	0.50	1	2	1	0	22	21	20
310	Cinnyris bouvieri	Orange-tufted Sunbird	Sunbirds	N/I	L	9	R	0.50	1	2	1	0	33	33	29
311	Nectarinia kilimensins	Bronzy sunbird	Sunbirds	N/I	L	16	R	0.50	1	2	1	0	21	22	19
312	Ficedula albicollis	Collared Flycatcher	Muscicapidae	I	L	14	M	0.50	1	2	1	0	23	22	23
313	Phoenicurus phoenicurus	Common Redstart	Muscicapidae	I	L	16	M	0.50	1	2	1	0	21	20	21
201	Tauraco leucolophus	White-crested Turaco	Turacos	F	M	214	R	0.50	2	2	1	0	3	3	2
202	Chlorocichla laetissima	Joyful Greenbul	Bulbuls	F	M	50	R	0.50	1	2	1	0	9	8	7
203	Gymnobucco bonapartei	Grey-throated barbet	African barbets	F	M	63	R	0.50	2	2	1	0	8	7	6
204	Psittacus erithacus	African Grey Parrot	Parrots	F	M	401	R	0.50	2	2	1	0	2	2	2
205	Spermophaga ruficapilla	Red-headed Bluebill	Waxbills, grass finches, muni	G	M	24	R	0.50	1	2	1	0	16	16	15
206	Apalis cinerea	Grey Apalis	Cisticolas and allies	I	M	12	R	0.50	1	2	1	0	26	25	22
207	Apalis nigriceps	Black-capped Apalis	Cisticolas and allies	I	M	8	R	0.50	1	2	1	0	36	34	30
208	Campephaga quiscalina	Purple-throated Cuckooshrike	Cuckoos-shrikes	I	M	39	R	0.50	1	2	1	0	11	10	9
209	Bathmocercus rufus	Black-faced Rufous Warbler	Cisticolas and allies	I	M	15	R	0.50	1	2	1	0	22	21	18
210	Lanius mackinnoni	Mackinnon's Shrike	Shrikes	I	M	34	R	0.50	1	2	1	0	12	12	10
211	Pitta angolensis (Native non-breedin	African Pitta	Pittas	I	M	84	R	0.50	2	2	1	0	6	6	5
212	Pitta reichenowi	Green-breasted Pitta	Pittas	I	M	82	R	0.50	2	2	1	0	6	6	5
213	Apalis jacksoni	Black throated Apalis	Cisticolas and allies	I	M	9	R	0.50	1	2	1	0	33	31	27
214	Phyllastrephus hypochloris	Toro Olive Greenbul	Bulbuls	I	M	23	R	0.50	1	2	1	0	16	15	13
215	Laniarus luehderi	Luhder's Bushshrike	Helmetshrikes, bushshrikes a	I	M	43	R	0.50	1	2	1	0	10	10	8
216	Ploceus melanogaster	Black-billed Weaver	Weavers and allies	I	M	22	R	0.50	1	2	1	0	17	16	14
217	Sylvia atricapilla	Eurasian Blackcap	Sylviidae	I	M	19	M	0.50	1	2	1	0	19	18	17
218	Sylvia borin	Garden Warbler	Sylviidae	I	M	19	M	0.50	1	2	1	0	19	18	17

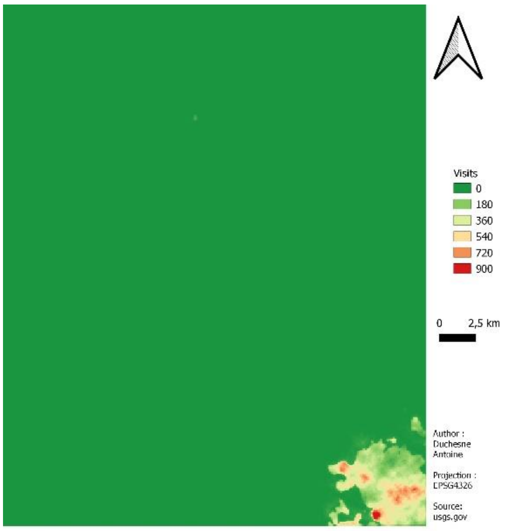
Diet: F= Frugivores, I = Insectivores, G = Granivores and N = Nectarivores
Forest dependency: H = High, M = Medium and L = Low
Status: R = Resident and M = Migratory

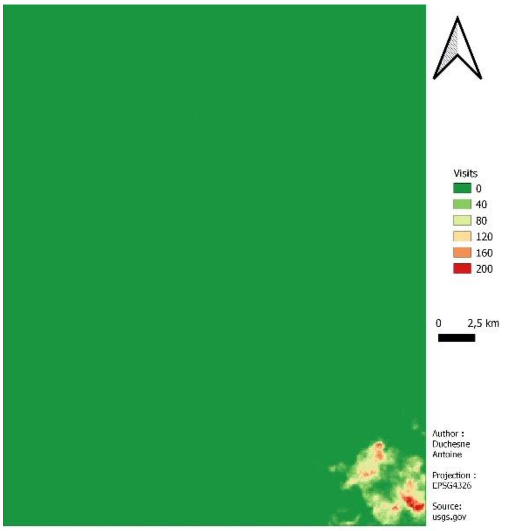
APPENDIX 2 - HEAT MAPS

The heat maps are shown following the ID number. The heat maps showing scenario 1 is on the left and scenario 2 is on the right.

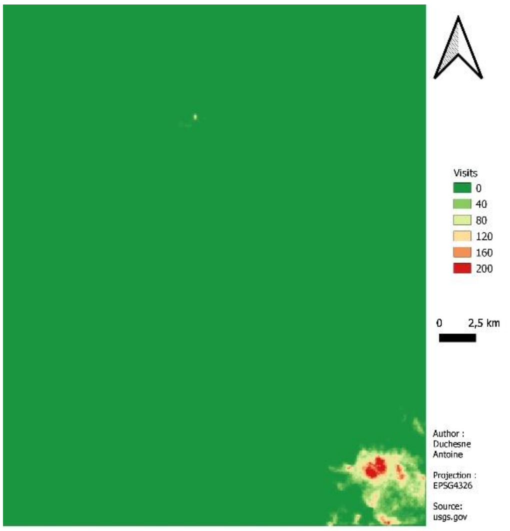
2.1) FOREST SPECIALISTS

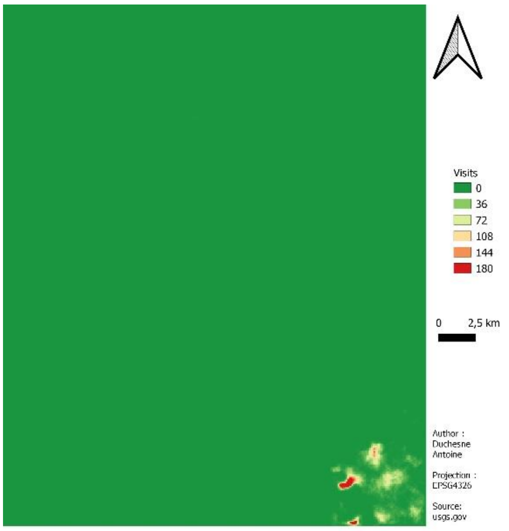
Bird 101





Bird 102





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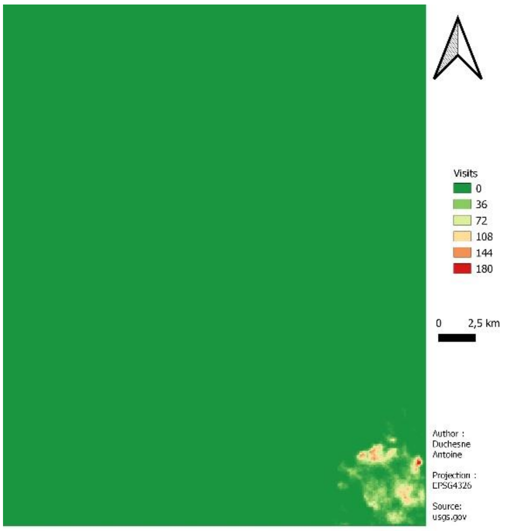

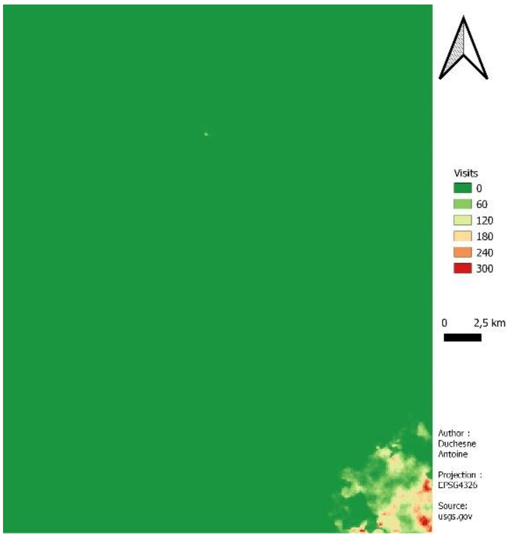

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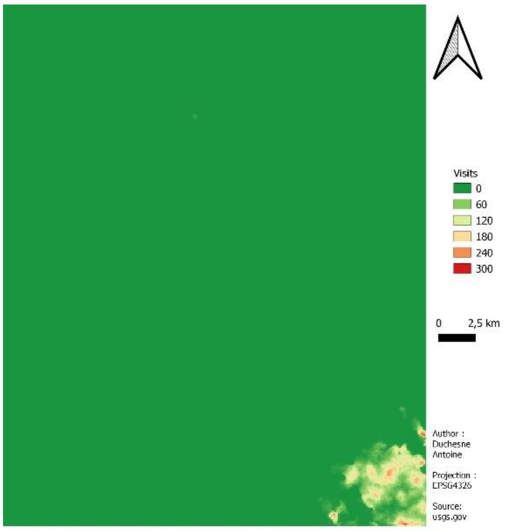

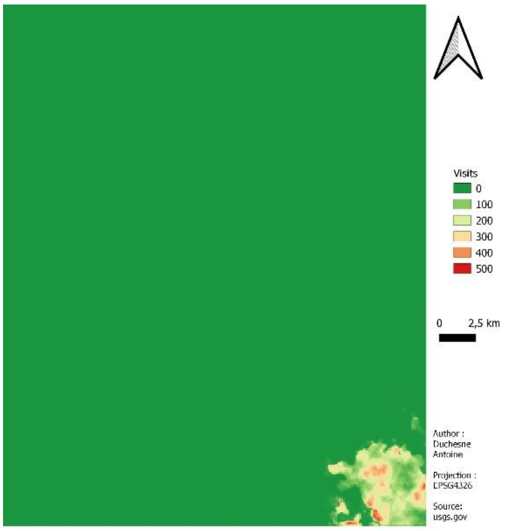

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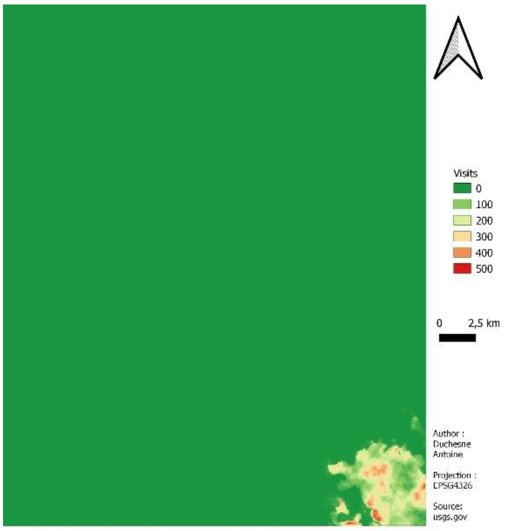

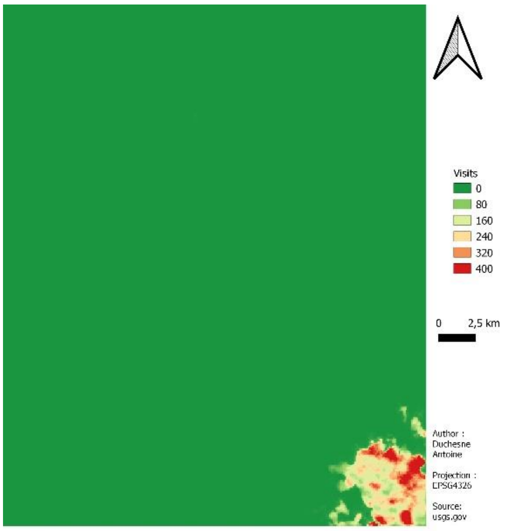

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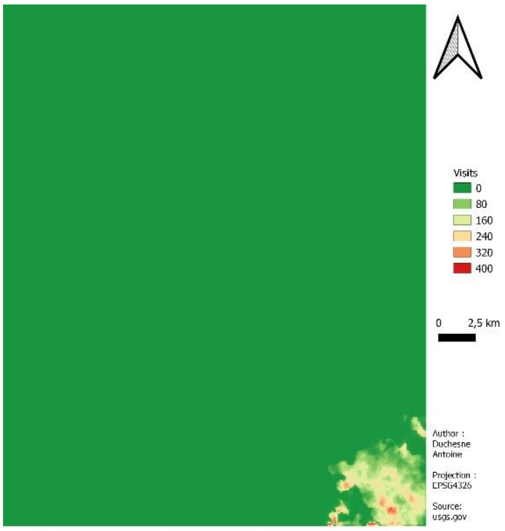

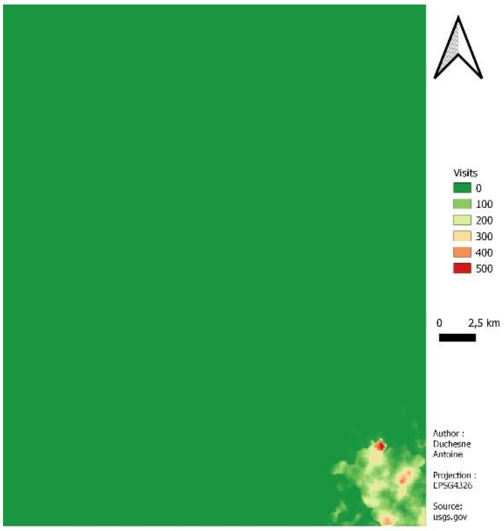

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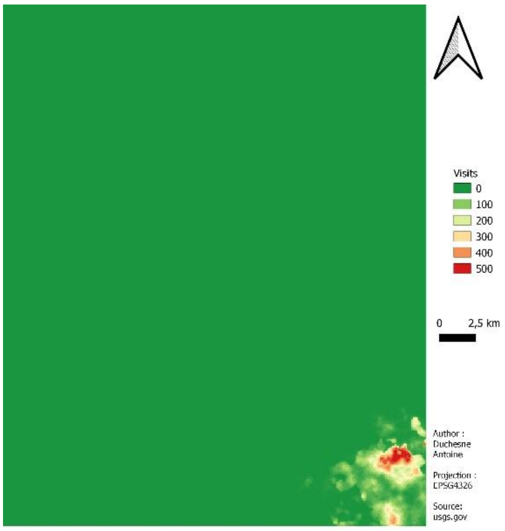
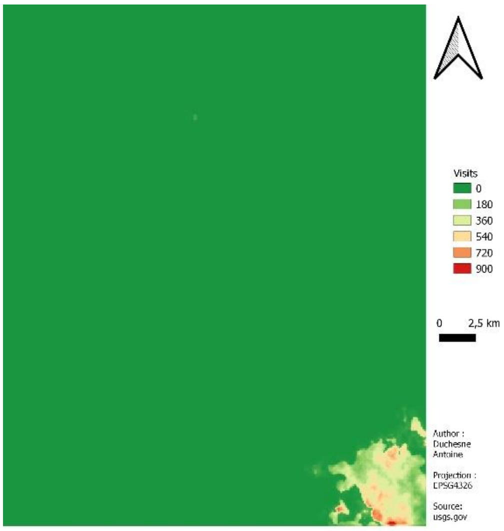
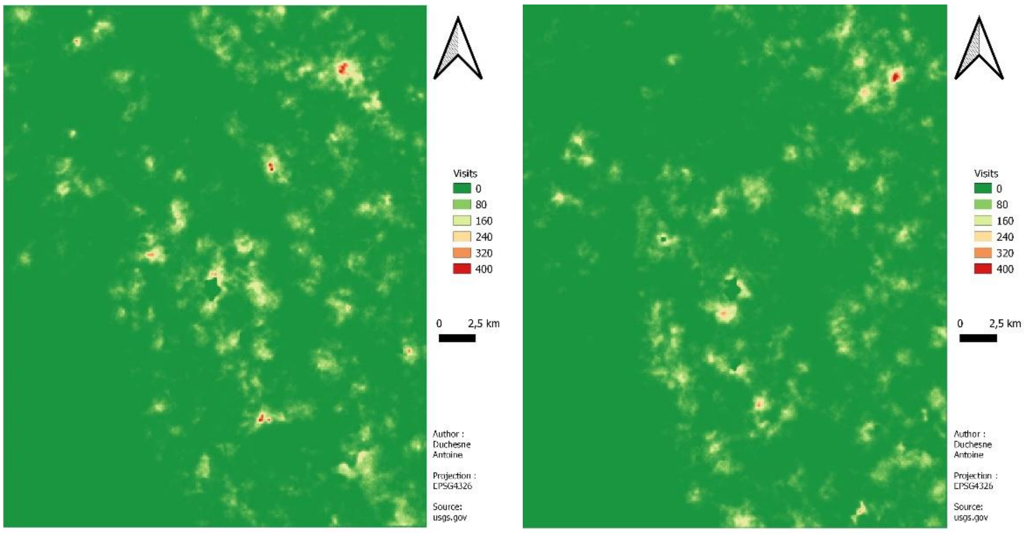




2.2) FOREST GENERALISTS

Bird 201



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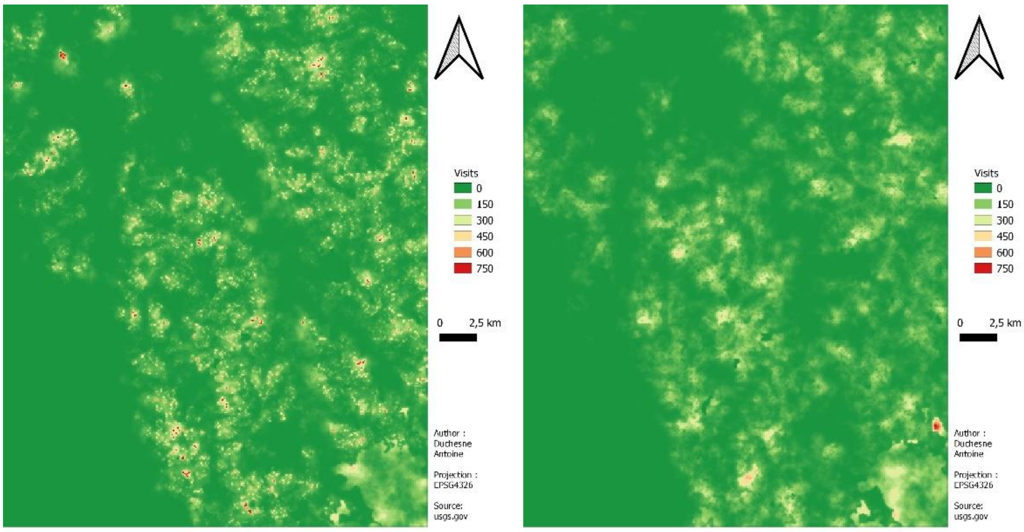

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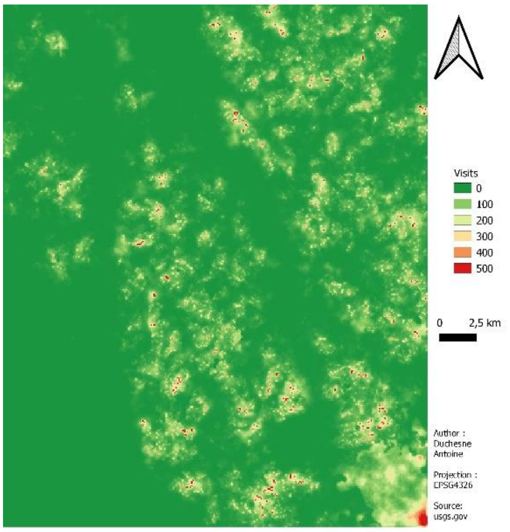

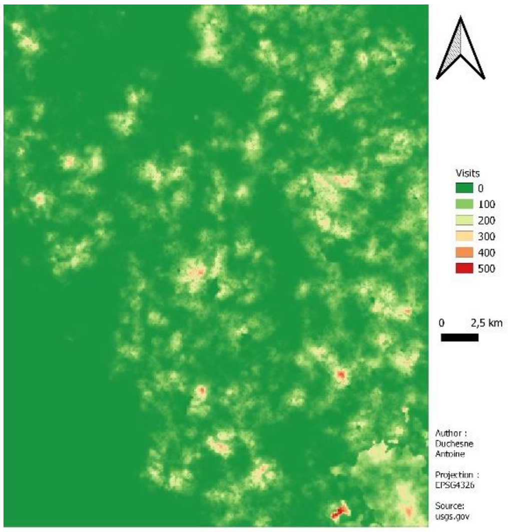

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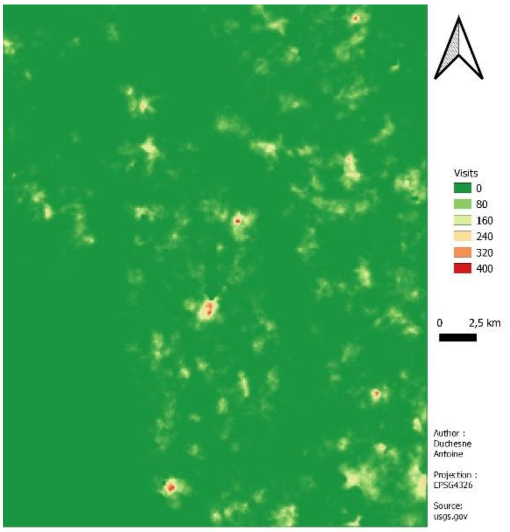

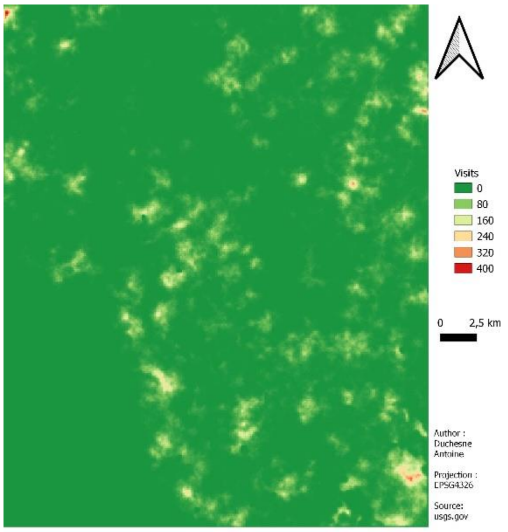

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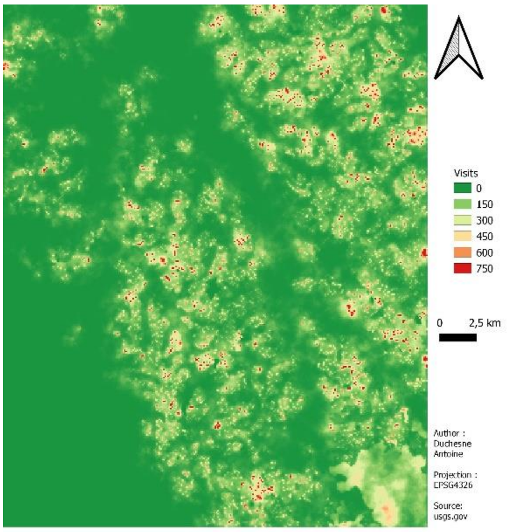

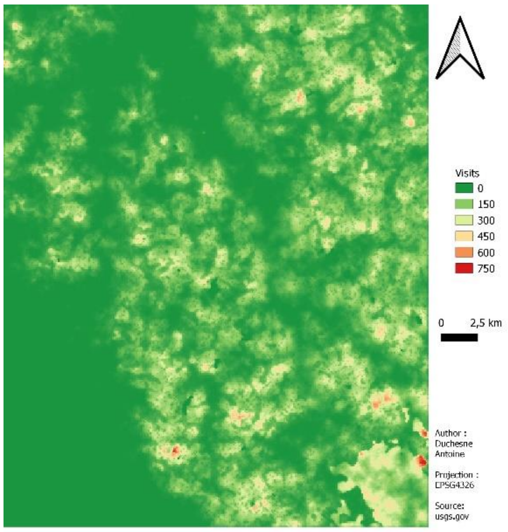

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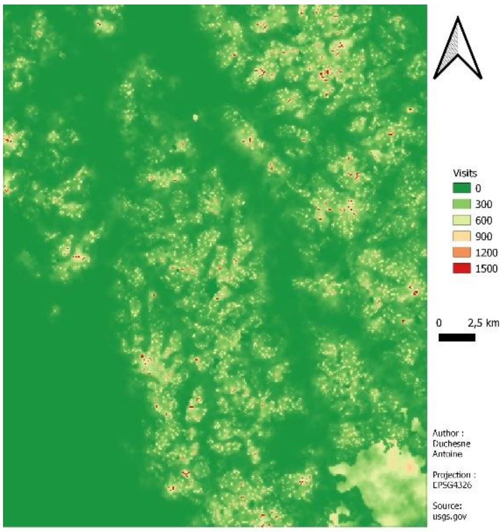

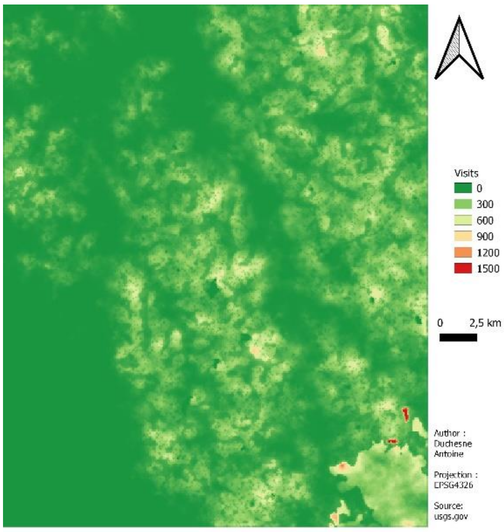

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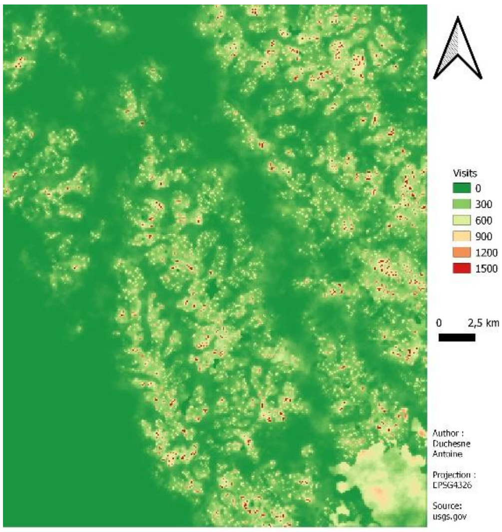

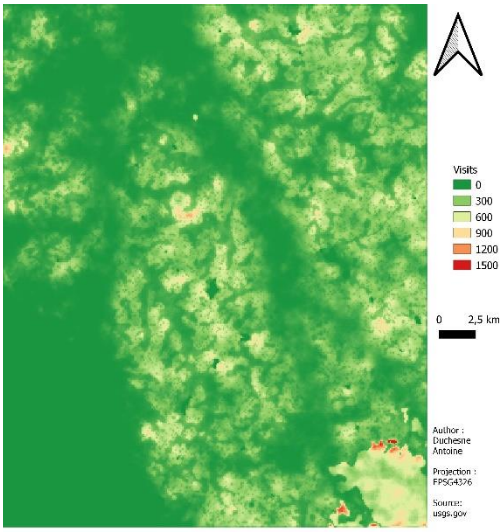

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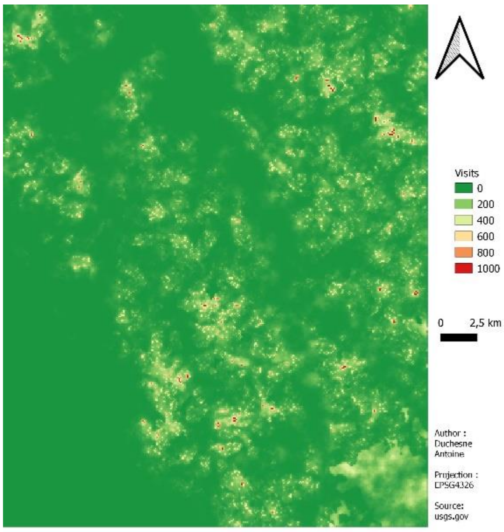

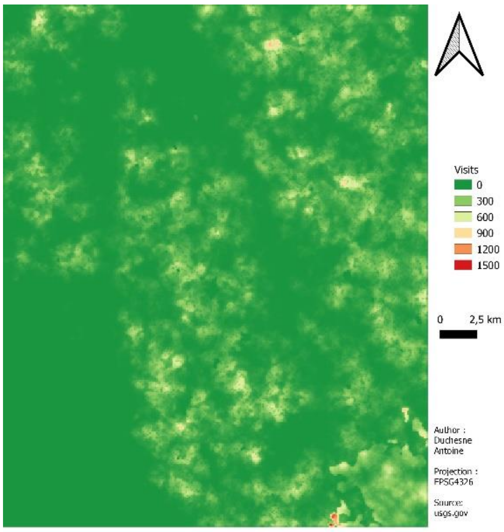

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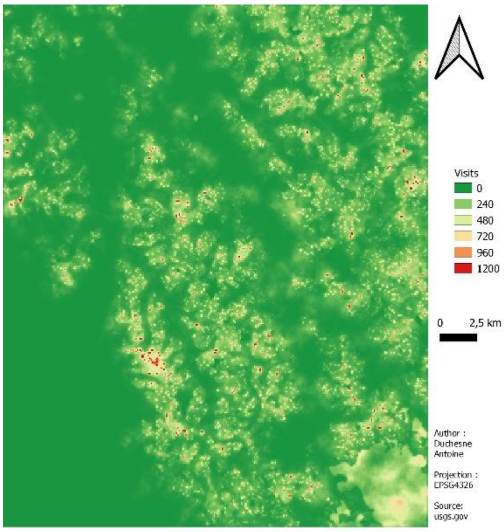

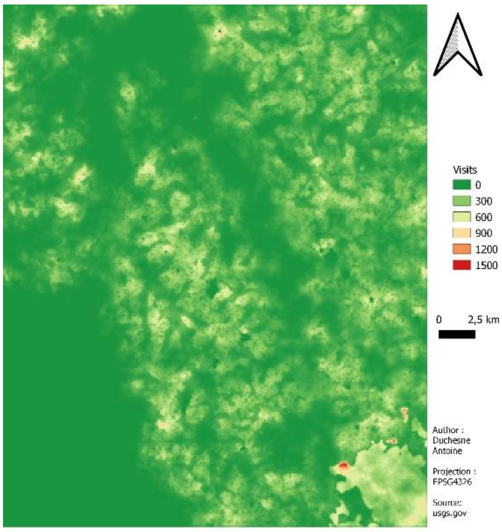

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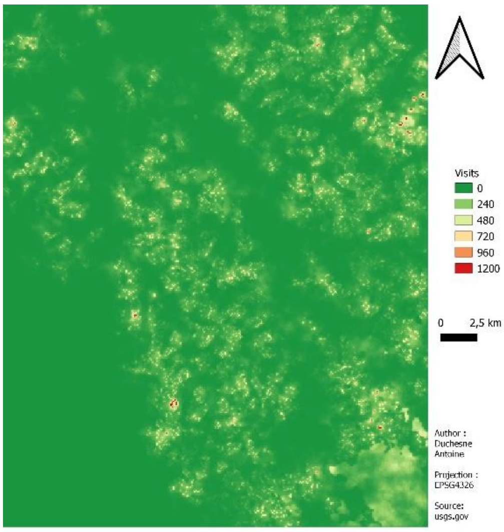

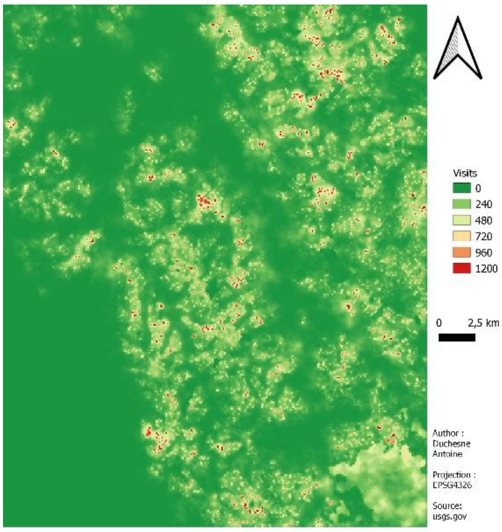

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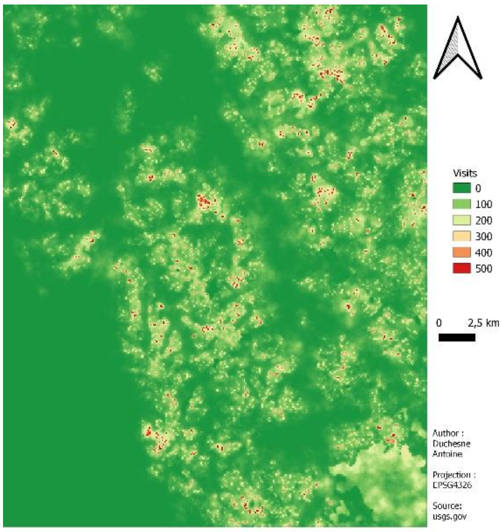

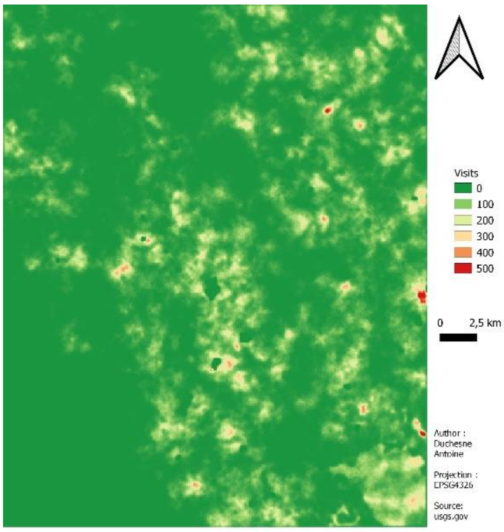

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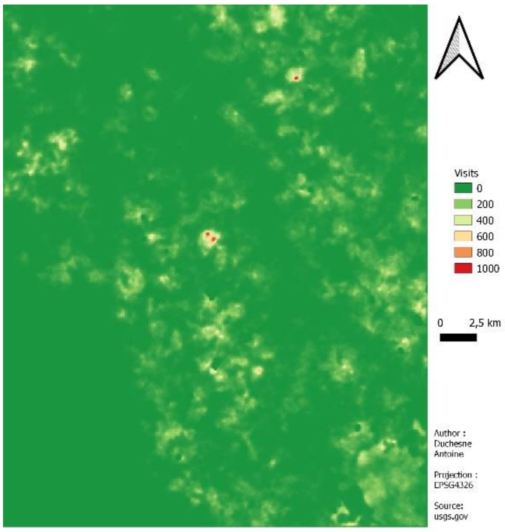

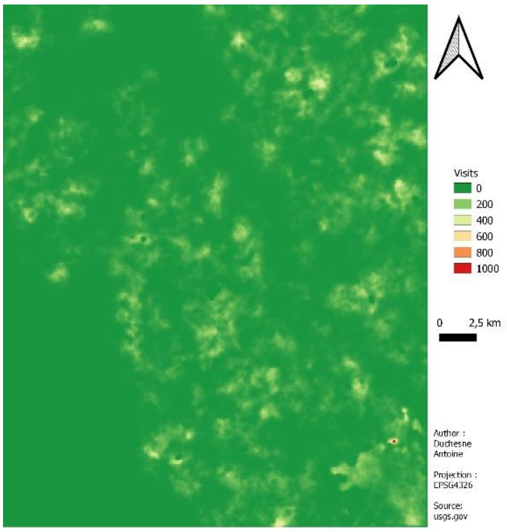

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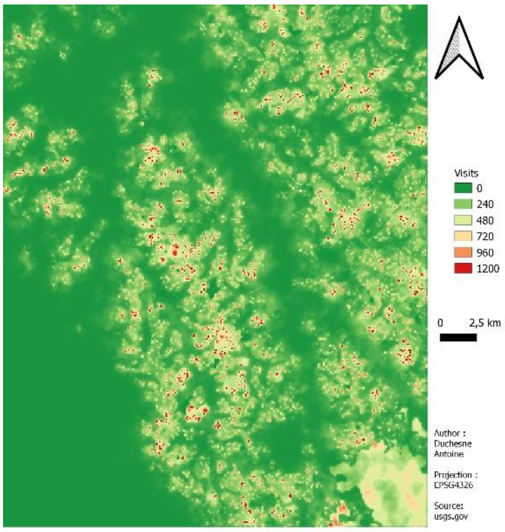

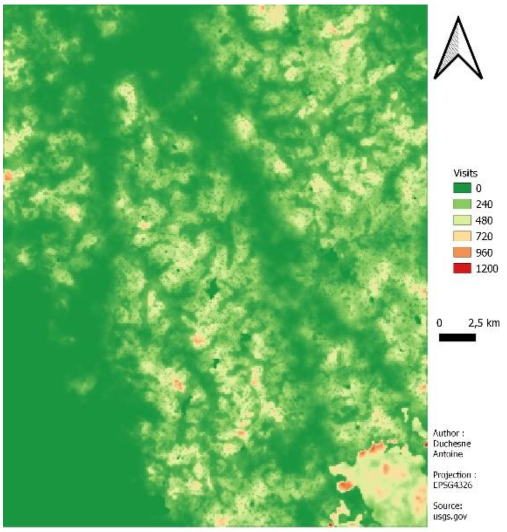

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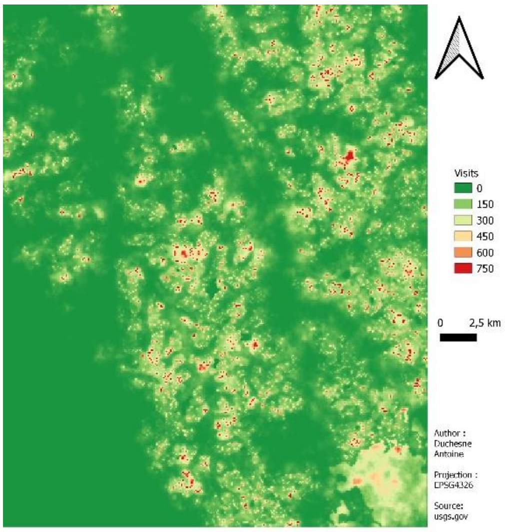
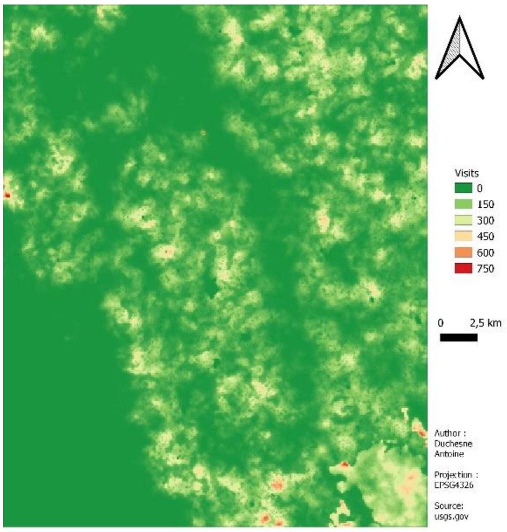
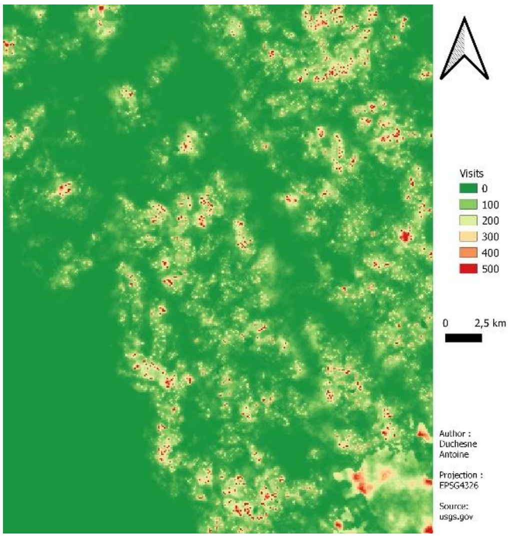
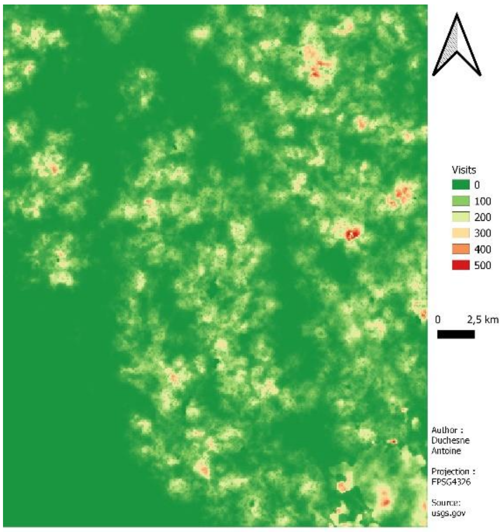


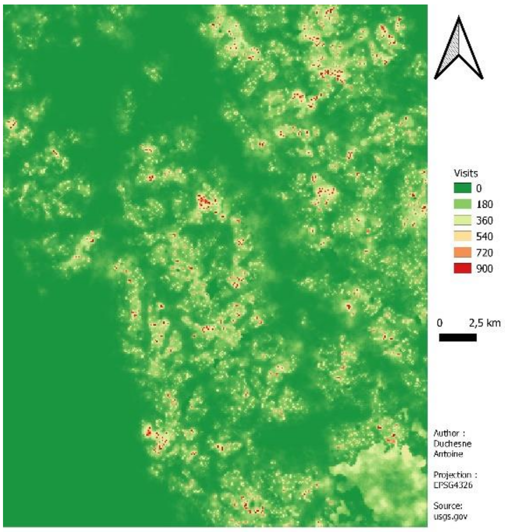


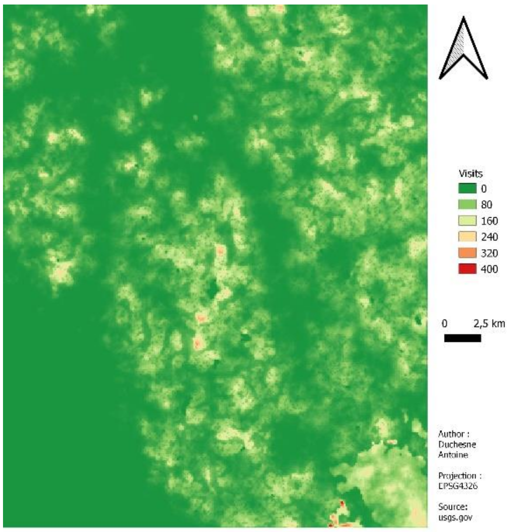
Bird 215



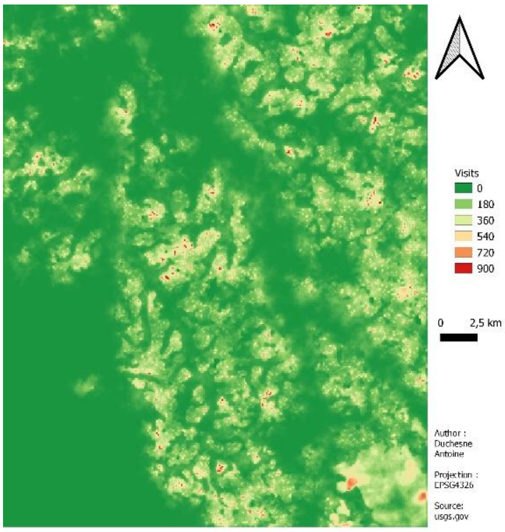


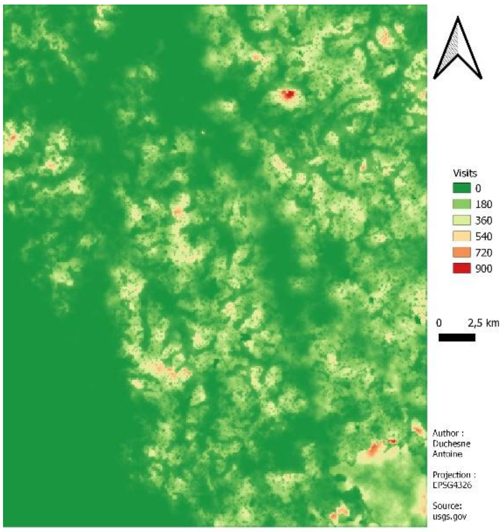
Bird 216



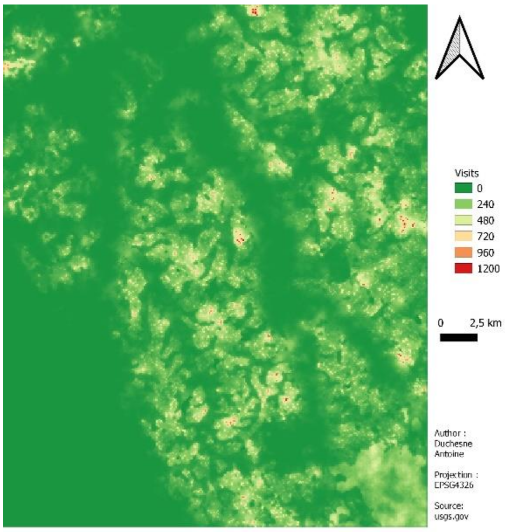


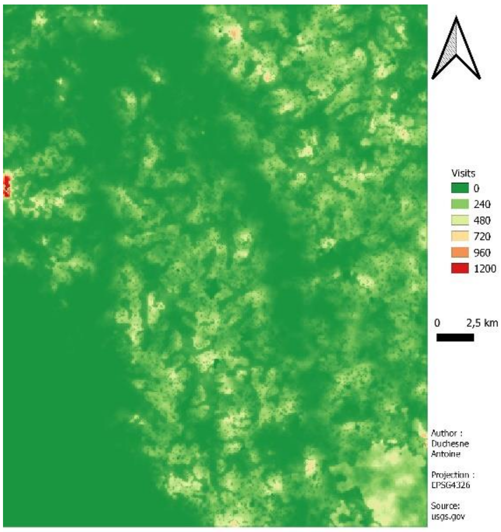
Bird 217





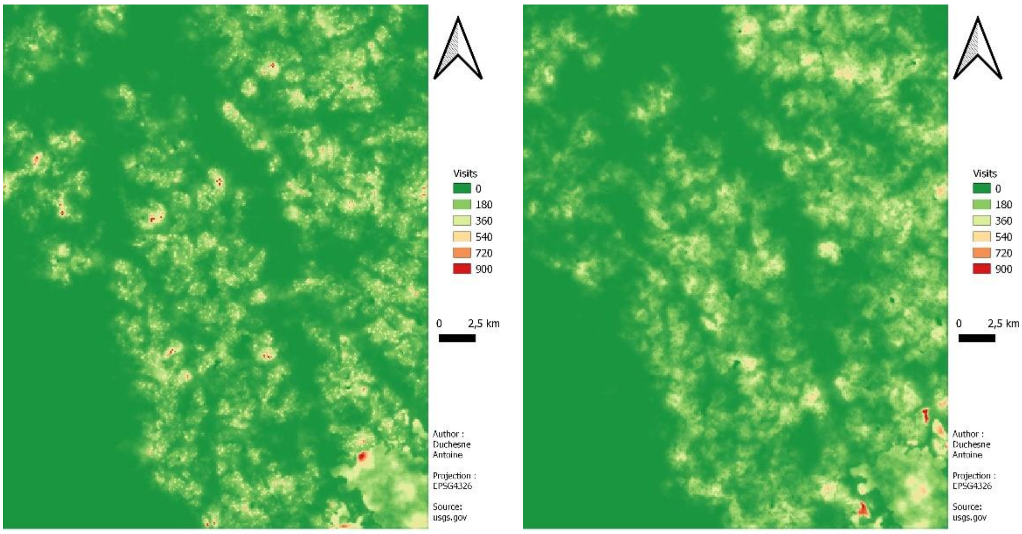
Bird 218


Visits
0
240
480
720
960
1200
0
2,5 km
Author :
Duchesne
Antoine
Projection :
EPSG4326
Source:
usgs.gov

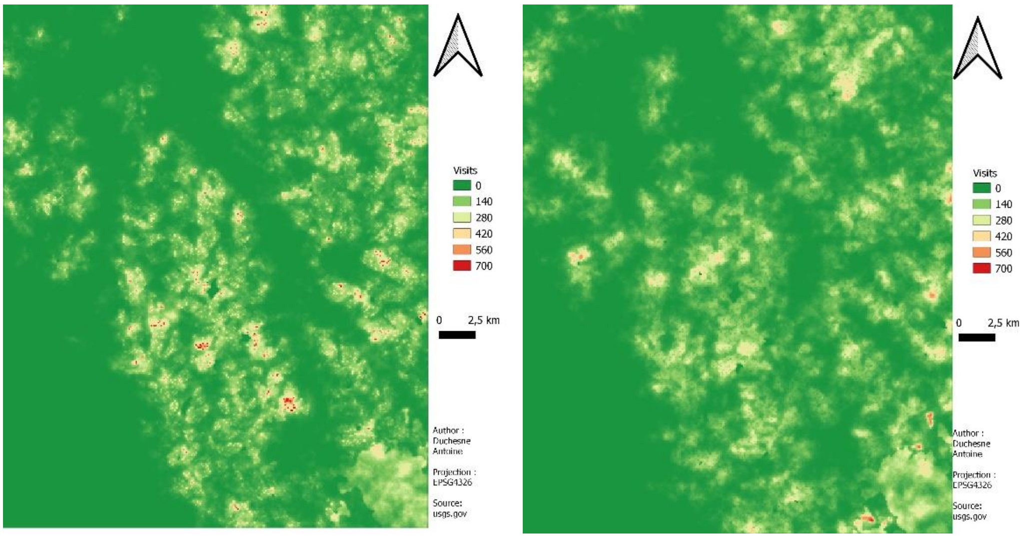

Visits
0
240
480
720
960
1200
0
2,5 km
Author :
Duchesne
Antoine
Projection :
EPSG4326
Source:
usgs.gov

2.3) FOREST VISITORS

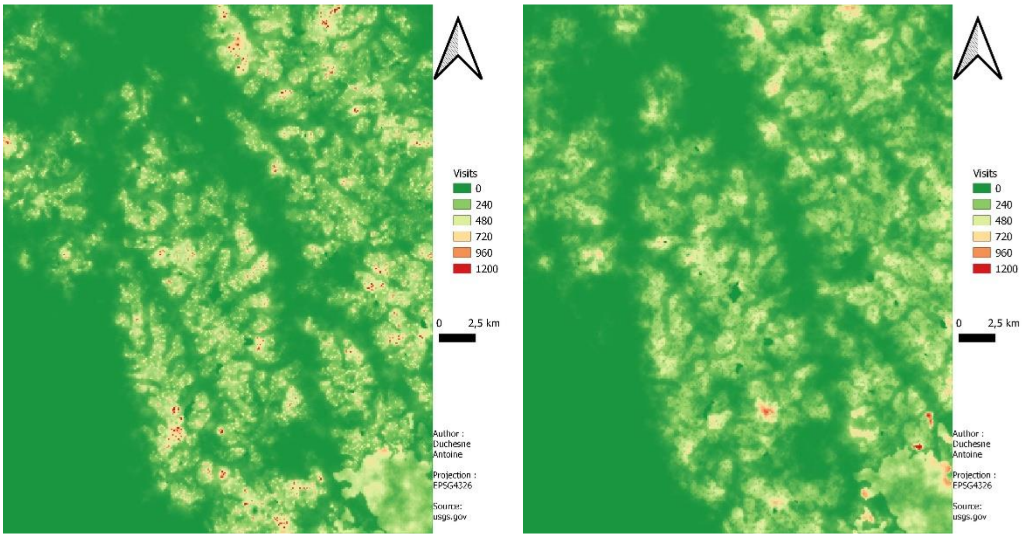
Bird 301



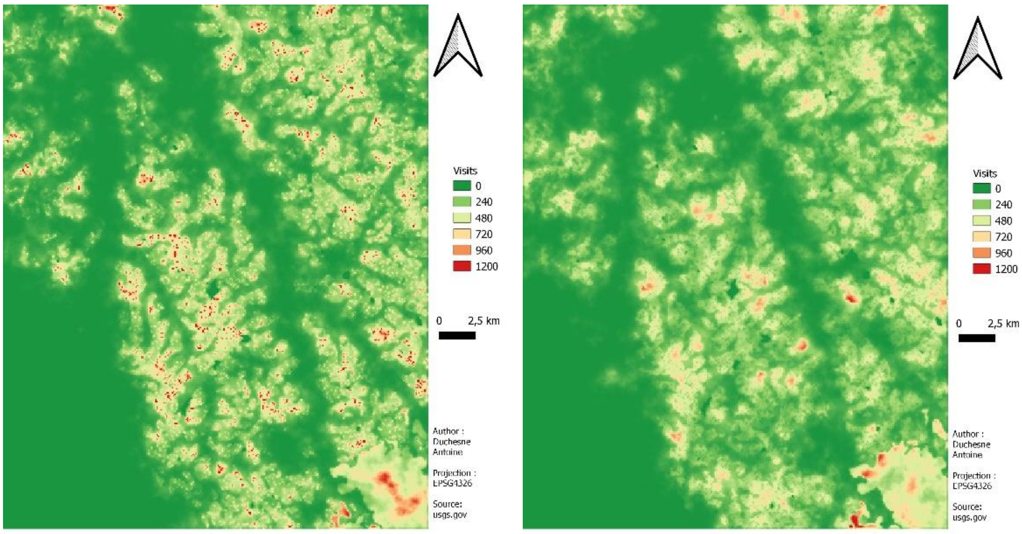
Bird 302



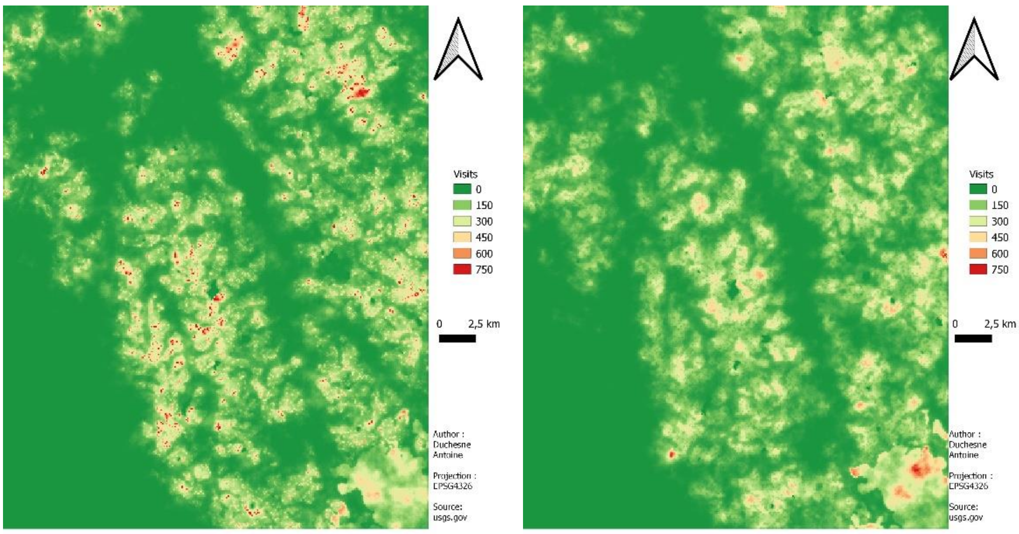
Bird 303



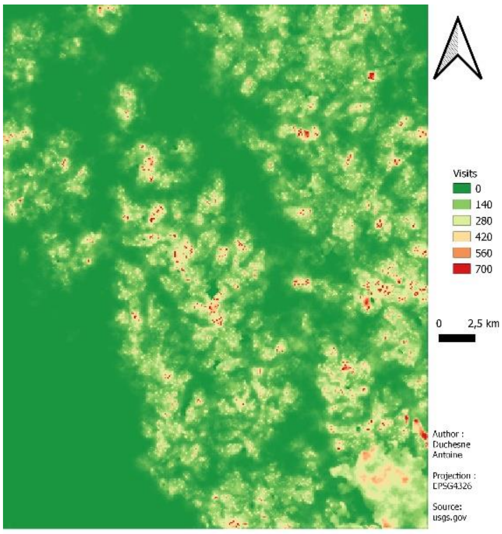
Bird 304

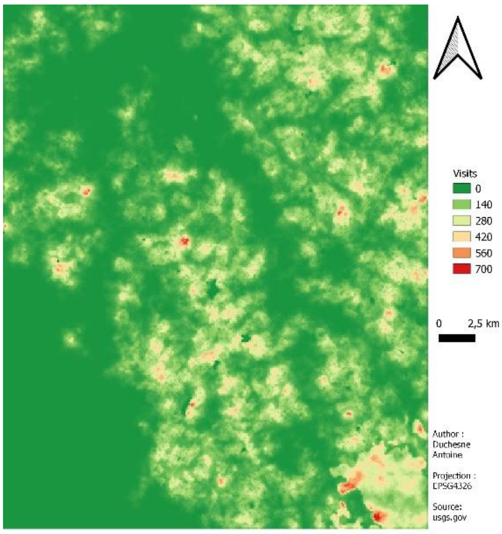


Bird 305

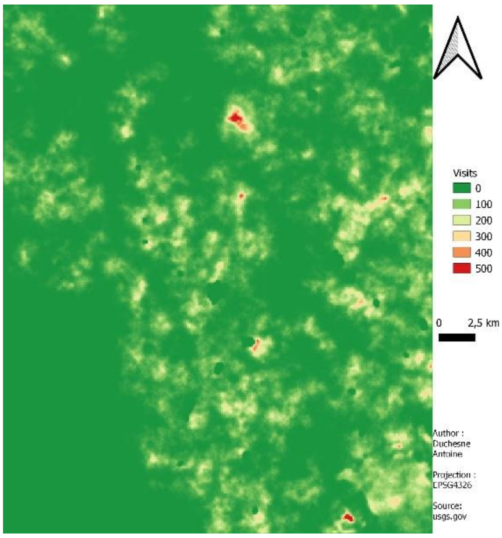


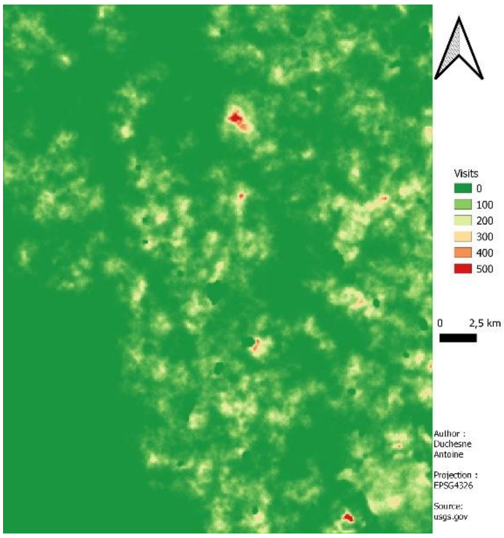
Bird 306



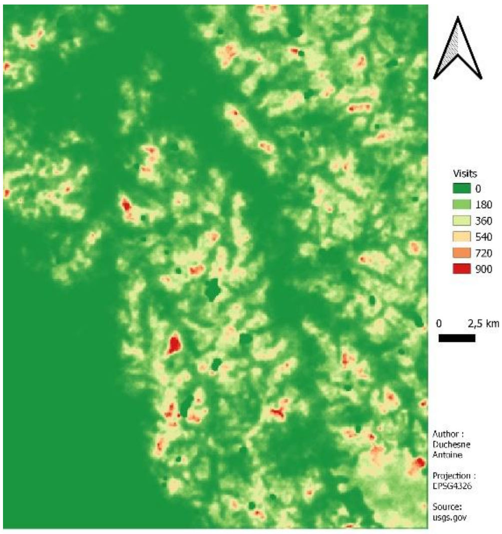


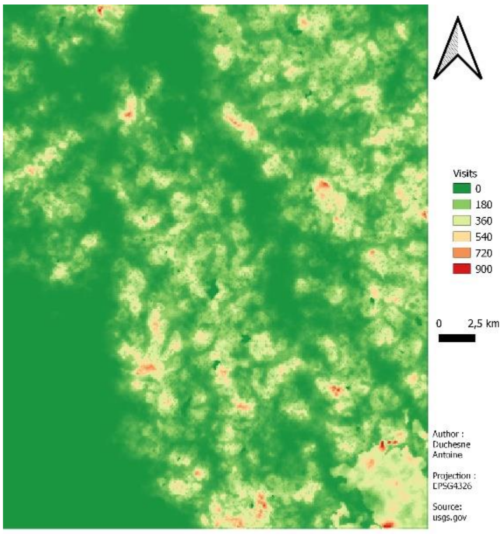
Bird 307



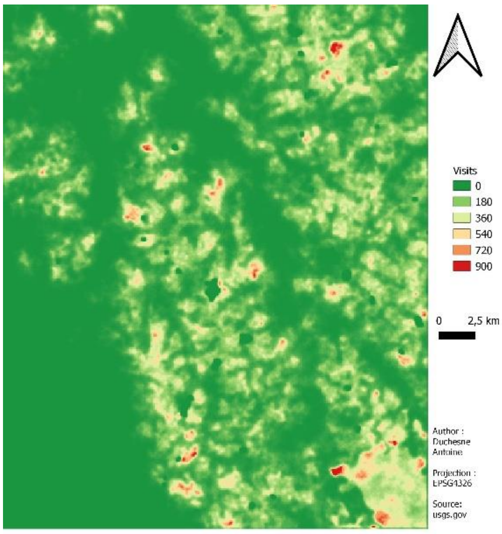


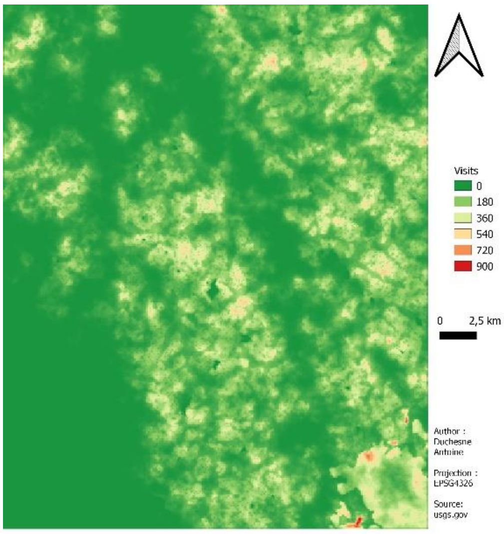
Bird 308



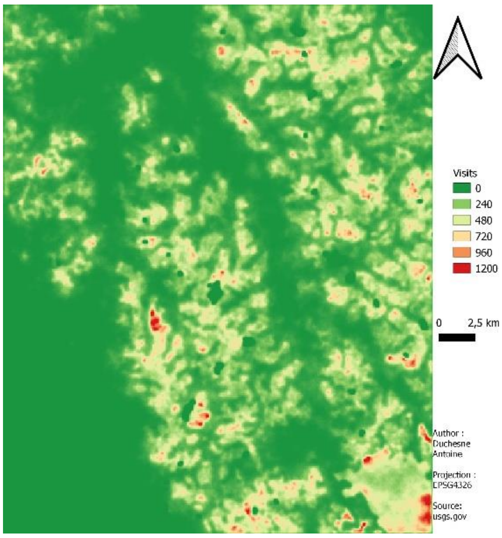


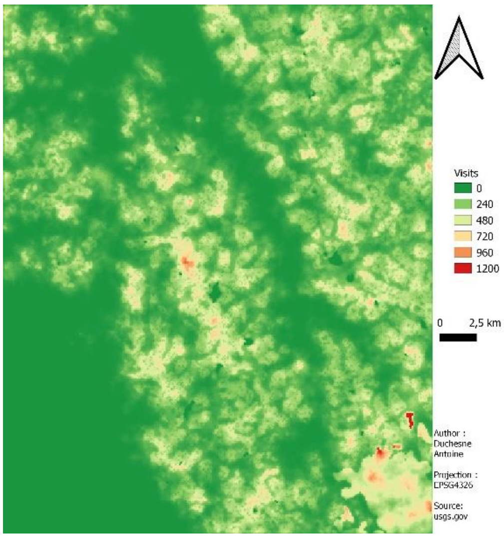
Bird 309



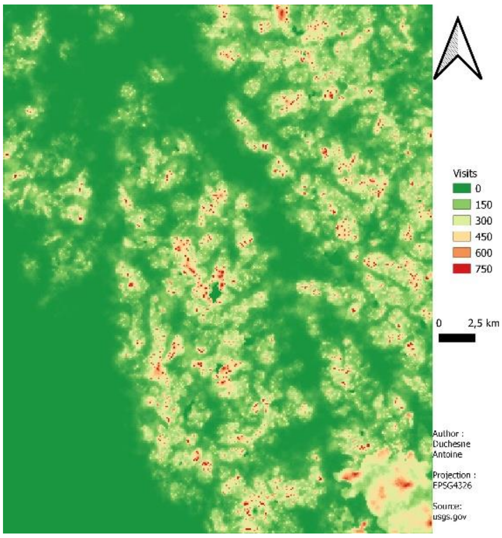


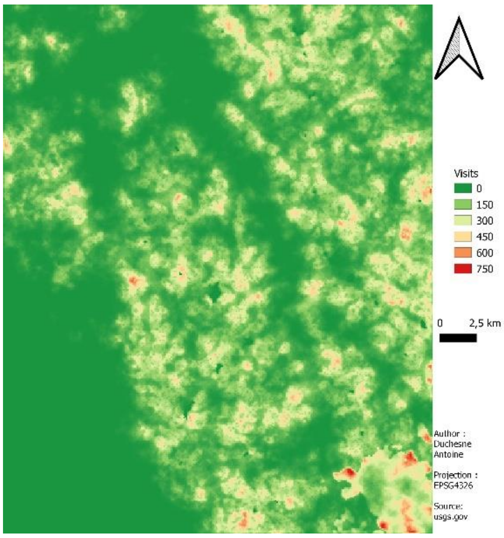
Bird 310



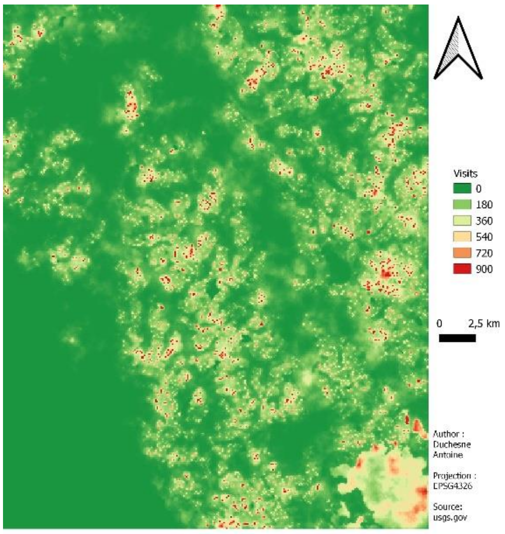


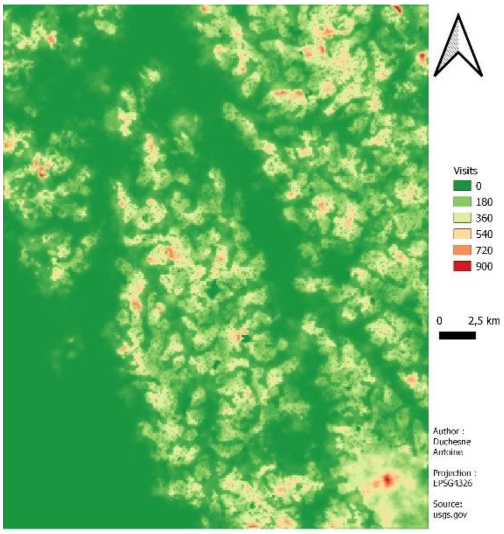
Bird 311



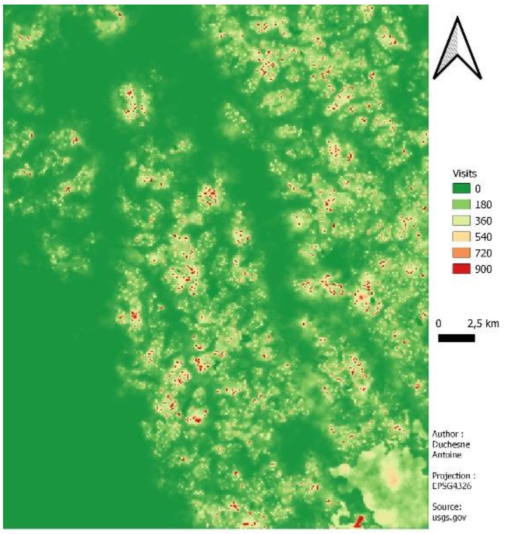


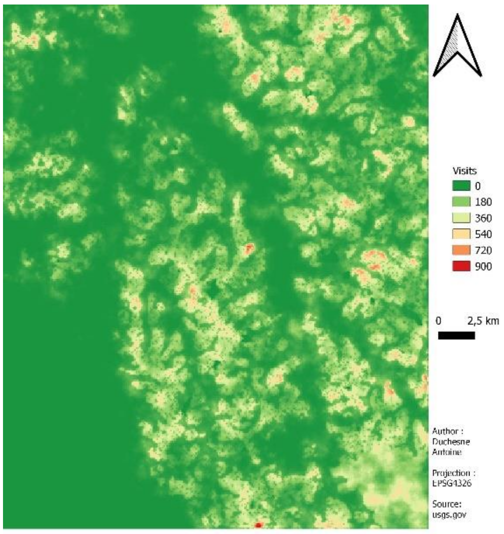
Bird 312





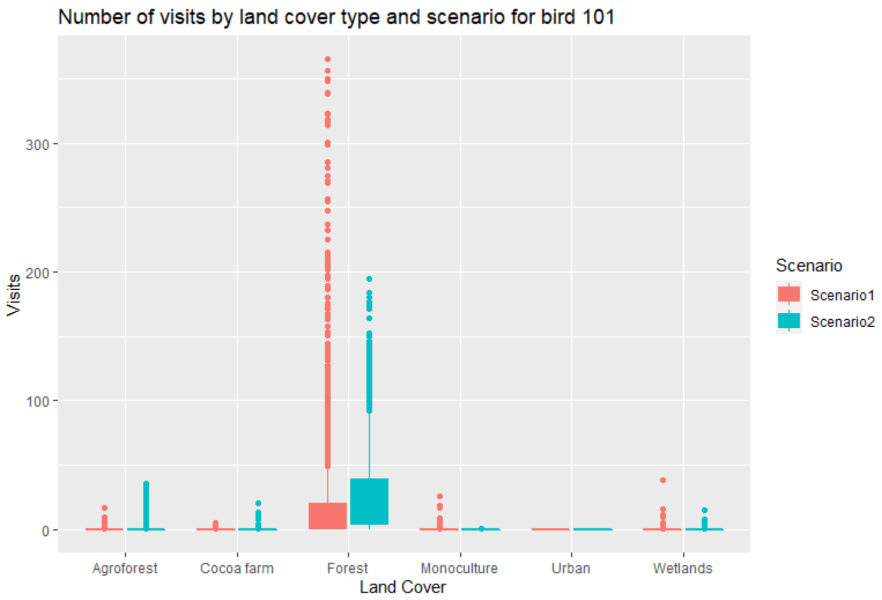
Bird 313



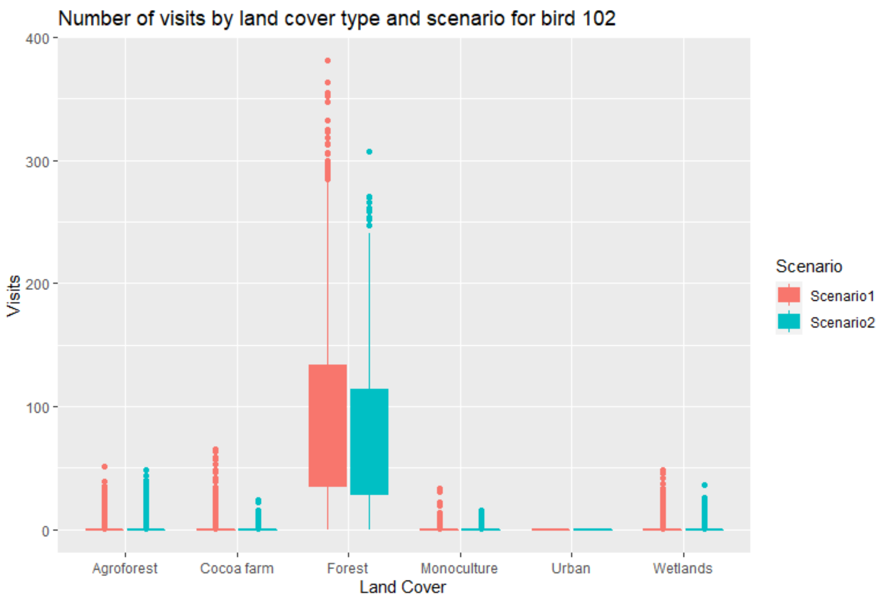


APPENDIX 3 - NUMBER OF VISITS PER LAND USE: BOXPLOTS

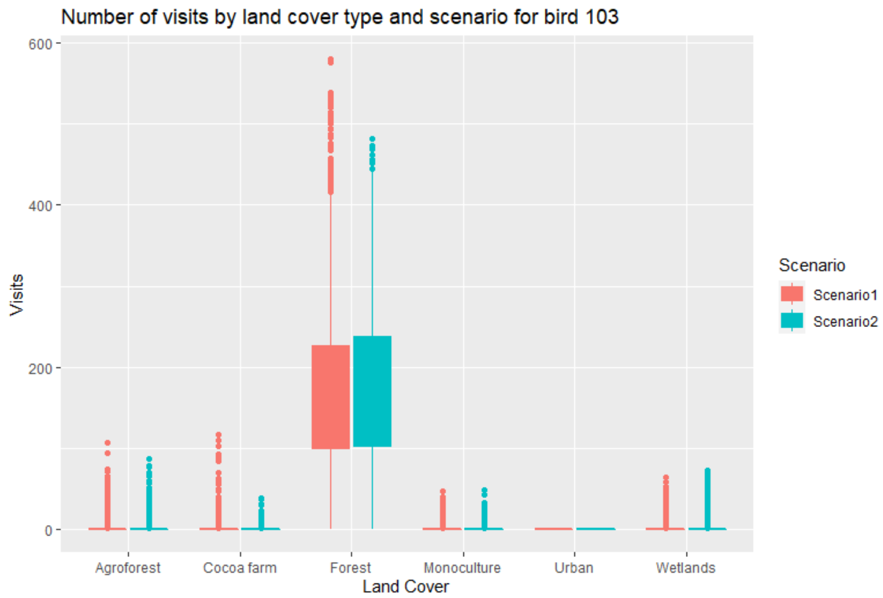
The number of visits for each land cover is here represented thanks to a graph. Beneath the graph, there is the results of each Anova II and their p-values.



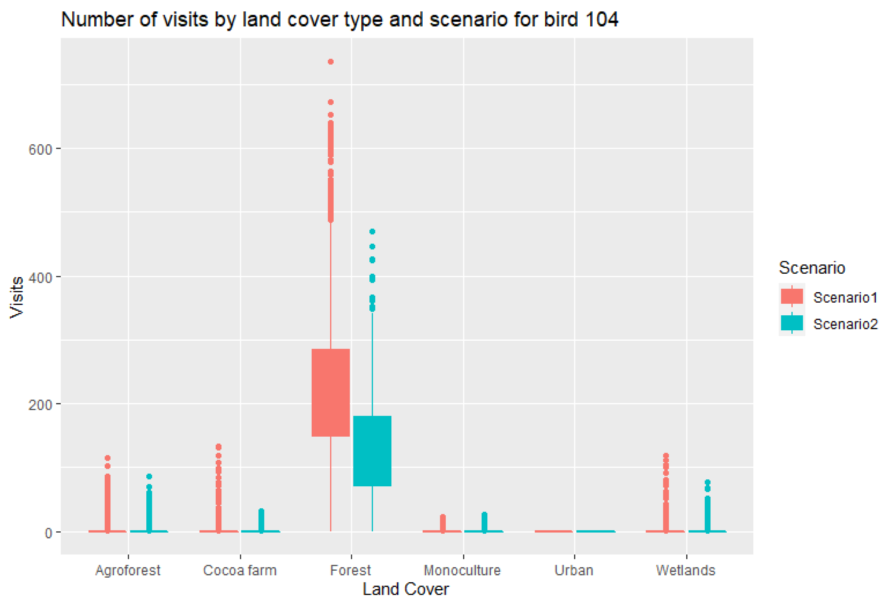

```
Response: Sim101
                     Sum Sq     Df  F value    Pr(>F)
LandCover           3499087      5 20207.71 < 2.2e-16 ***
Scenario               2757      1    79.62 < 2.2e-16 ***
LandCover:Scenario    89701      5   518.04 < 2.2e-16 ***
Residuals           7942598 229348
```



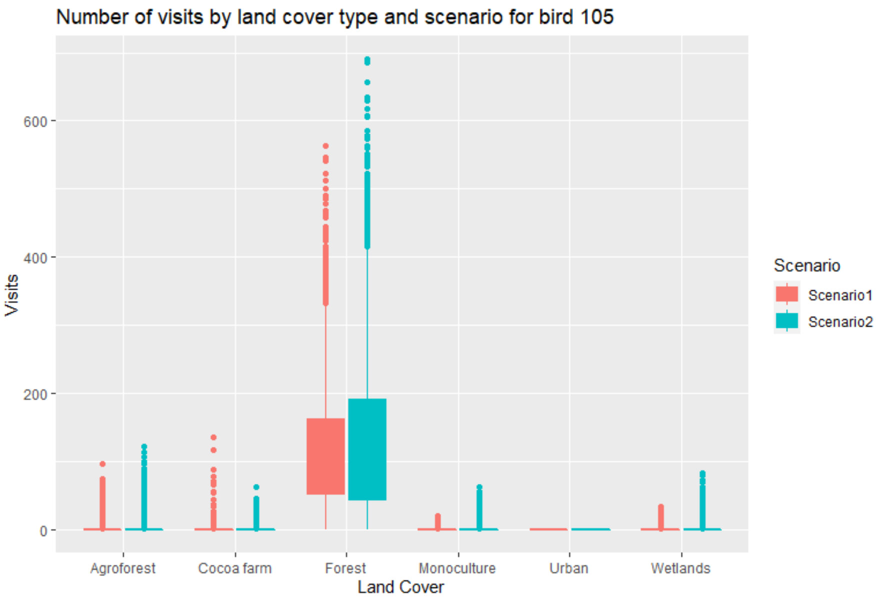

```
Response: Sim102
                      Sum Sq     Df   F value    Pr(>F)
LandCover           41987031      5 79587.829 < 2.2e-16 ***
Scenario                8033      1    76.138 < 2.2e-16 ***
LandCover:Scenario    231588      5   438.982 < 2.2e-16 ***
Residuals           24198779 229348
```



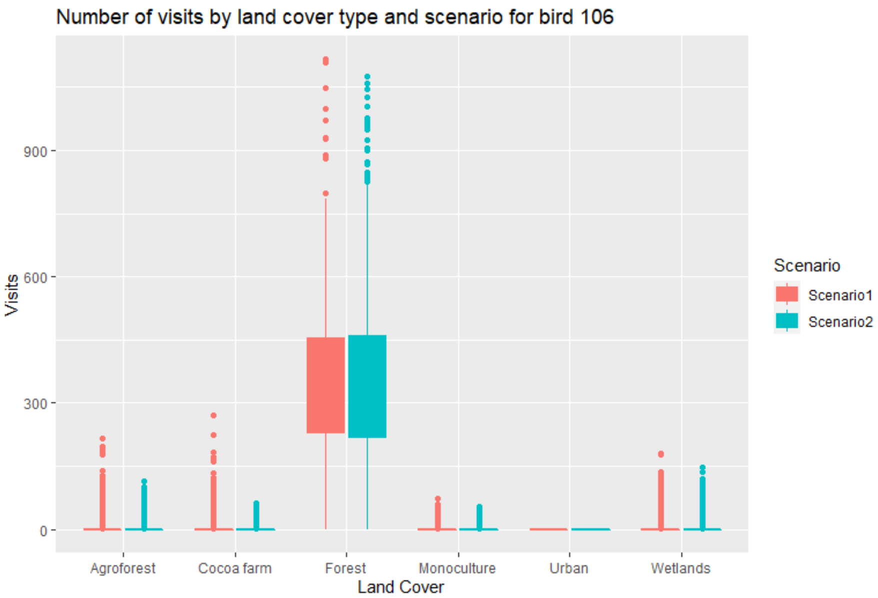

```
Response: Sim103
                      Sum Sq     Df    F value Pr(>F)
LandCover          184035721      5 1.4418e+05 <2e-16 ***
Scenario                 220      1 8.6020e-01 0.3537
LandCover:Scenario     21531      5 1.6868e+01 <2e-16 ***
Residuals           58549969 229348
```



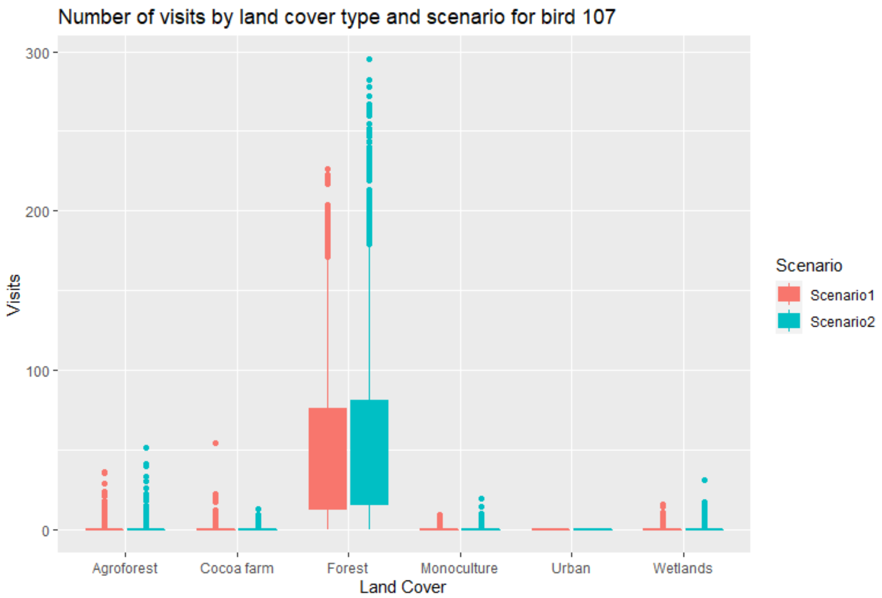

```
Response: Sim104
                      Sum Sq     Df  F value    Pr(>F)
LandCover          196825207      5 153683.6 < 2.2e-16 ***
Scenario              433021      1   1690.5 < 2.2e-16 ***
LandCover:Scenario  14214996      5  11099.2 < 2.2e-16 ***
Residuals           58745981 229348
```



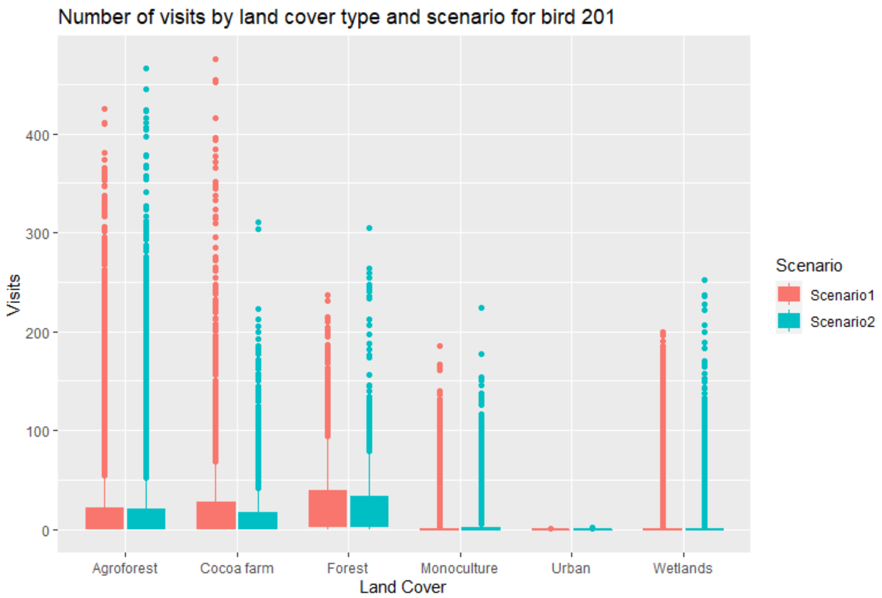

```
Response: Sim105
                     Sum Sq     Df   F value    Pr(>F)    
LandCover          97138251      5 59327.474 < 2.2e-16 ***
Scenario              14885      1    45.456 1.565e-11 ***
LandCover:Scenario   301597      5   184.202 < 2.2e-16 ***
Residuals          75103360 229348
```



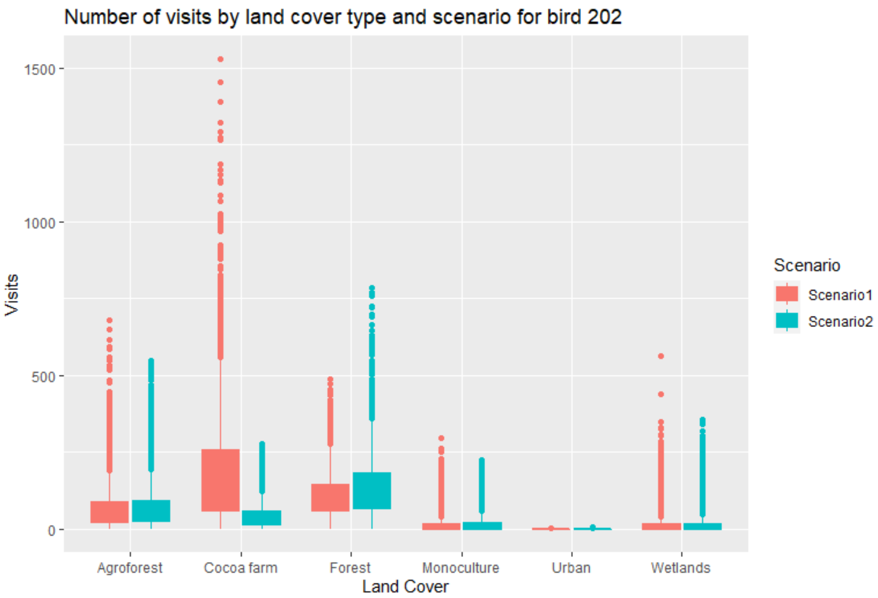

```
Response: Sim106
                      Sum Sq     Df    F value Pr(>F)    
LandCover          768410874      5 1.9997e+05 <2e-16 ***
Scenario                 633      1 8.2310e-01 0.3643    
LandCover:Scenario      4112      5 1.0701e+00 0.3746    
Residuals          176256785 229348
```



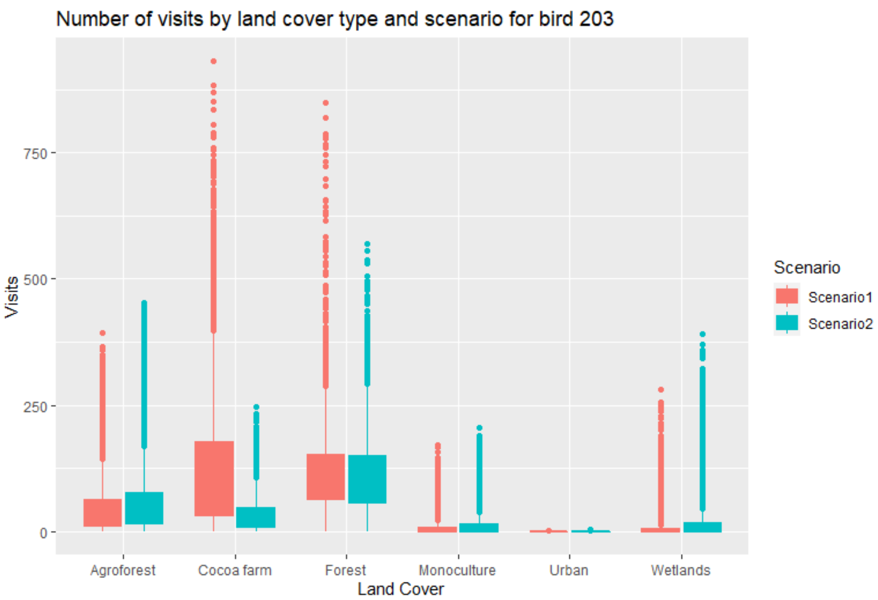

```
Response: Sim107
                      Sum Sq     Df   F value    Pr(>F)
LandCover           17474323      5 52256.572 < 2.2e-16 ***
Scenario                1416      1    21.169 4.207e-06 ***
LandCover:Scenario     45335      5   135.572 < 2.2e-16 ***
Residuals           15338553 229348
```



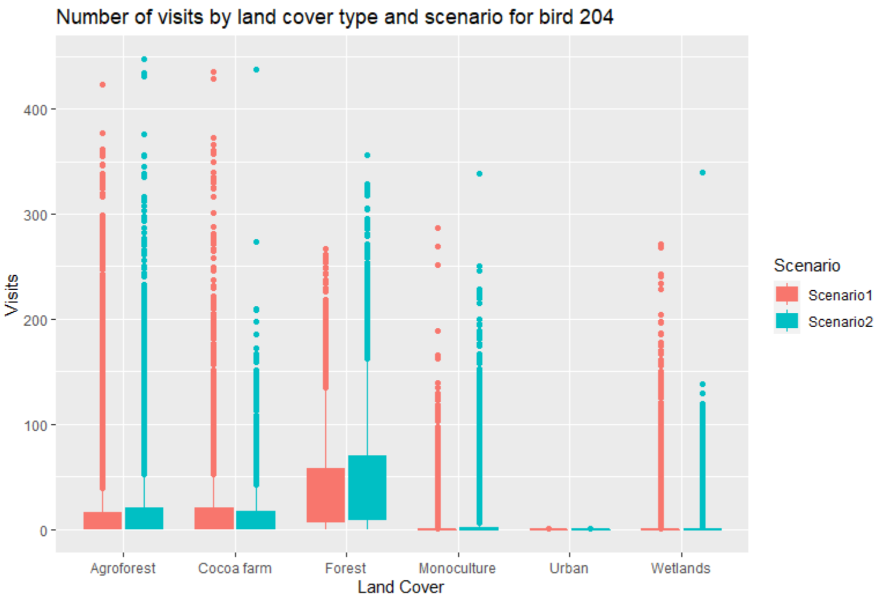

```
Response: Sim201
                       Sum Sq     Df  F value    Pr(>F)
LandCover            13716629      5 5267.499 < 2.2e-16 ***
Scenario                22247      1   42.716 6.341e-11 ***
LandCover:Scenario     283349      5  108.812 < 2.2e-16 ***
Residuals           119444964 229348
```



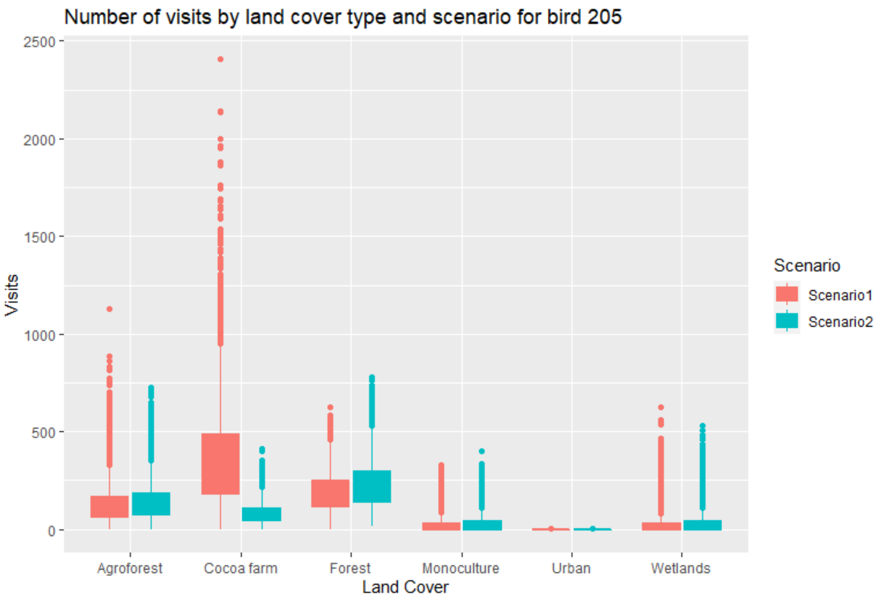

```
Response: Sim202
                     Sum Sq     Df   F value    Pr(>F)
LandCover         243308974      5 19389.557 < 2.2e-16 ***
Scenario             179753      1    71.623 < 2.2e-16 ***
LandCover:Scenario  53893258      5  4294.812 < 2.2e-16 ***
Residuals         575592599 229348
---
```



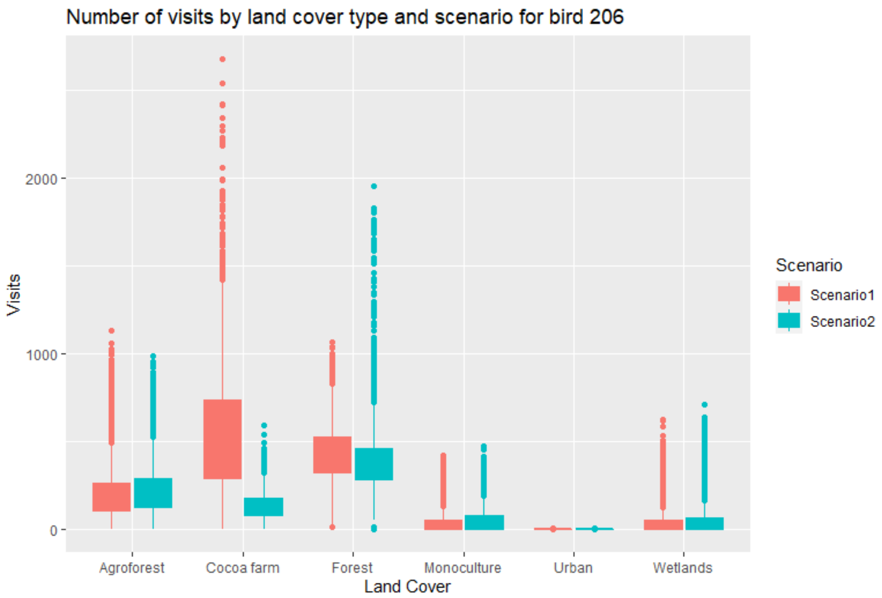

```
Response: Sim203
                     Sum Sq     Df  F value    Pr(>F)
LandCover         160996485      5 17399.24 < 2.2e-16 ***
Scenario             422467      1   228.28 < 2.2e-16 ***
LandCover:Scenario  25685716      5  2775.91 < 2.2e-16 ***
Residuals         424434976 229348
```



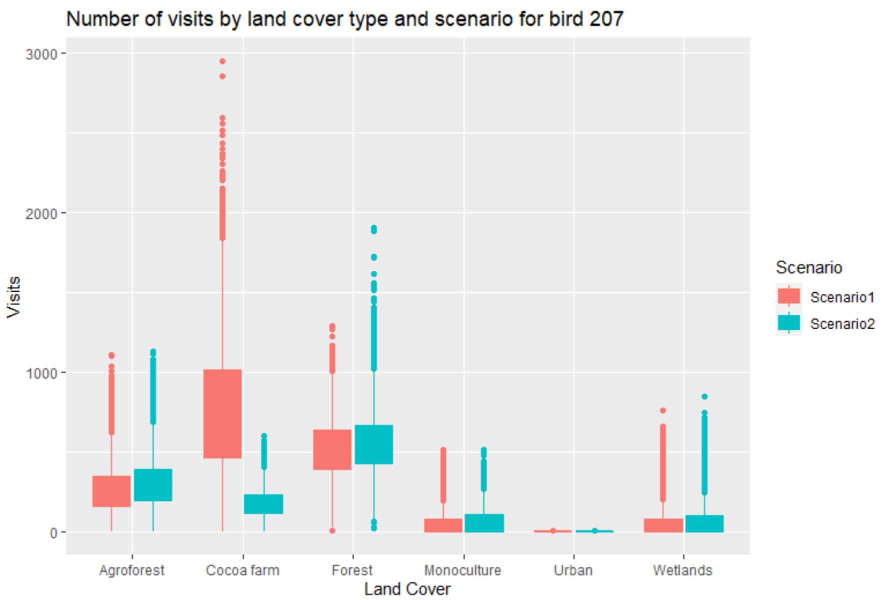

```
Response: Sim204
                      Sum Sq     Df  F value    Pr(>F)    
LandCover           17656964      5 7506.533 < 2.2e-16 ***
Scenario              247171      1  525.401 < 2.2e-16 ***
LandCover:Scenario    224195      5   95.312 < 2.2e-16 ***
Residuals          107895074 229348                       
```



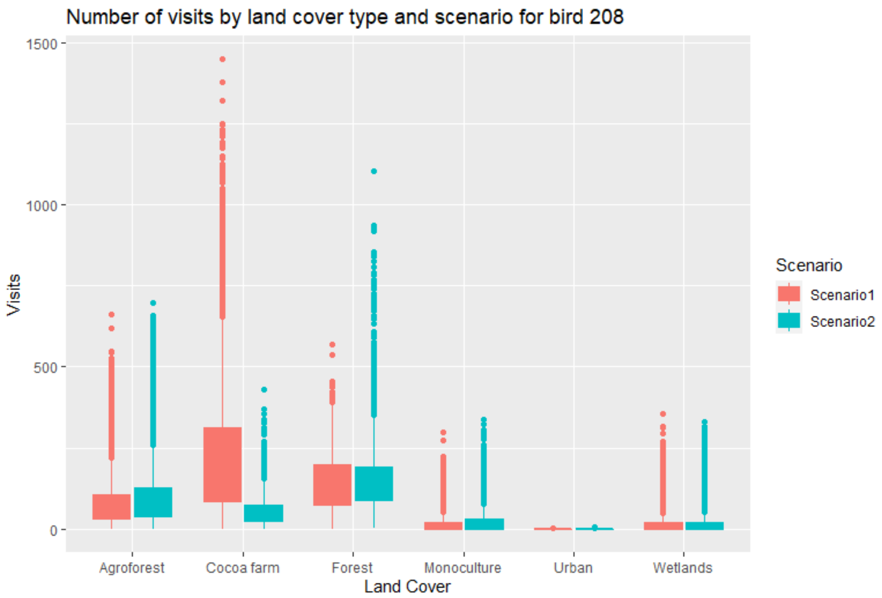

```
Response: Sim205
                       Sum Sq     Df  F value    Pr(>F)    
LandCover           917497329      5 33117.34 < 2.2e-16 ***
Scenario              1146118      1   206.85 < 2.2e-16 ***
LandCover:Scenario  211769916      5  7643.90 < 2.2e-16 ***
Residuals          1270791585 229348                       
```



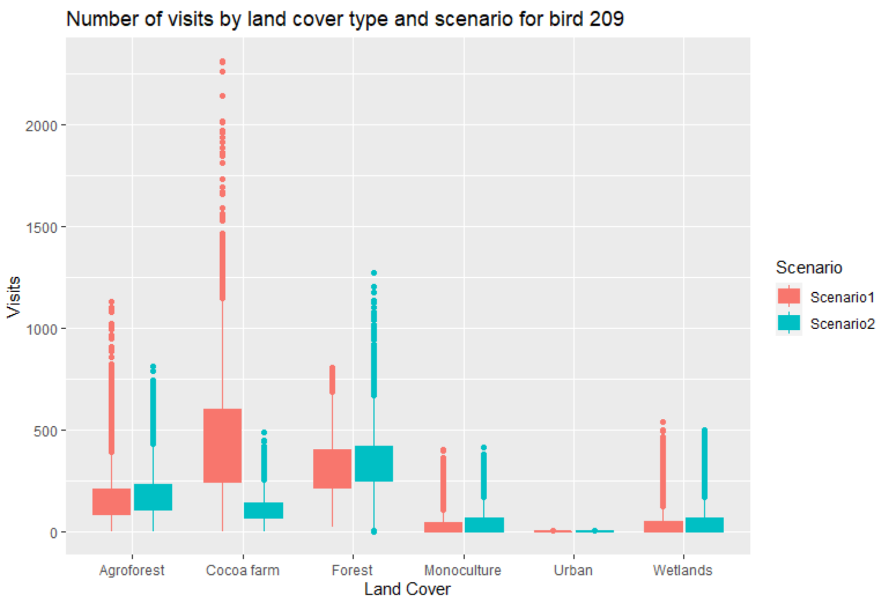

```
Response: Sim206
                      Sum Sq     Df   F value    Pr(>F)
LandCover         2434121124      5 45309.739 < 2.2e-16 ***
Scenario              675154      1    62.838 2.254e-15 ***
LandCover:Scenario  459903450     5  8560.833 < 2.2e-16 ***
Residuals         2464197882 229348
```



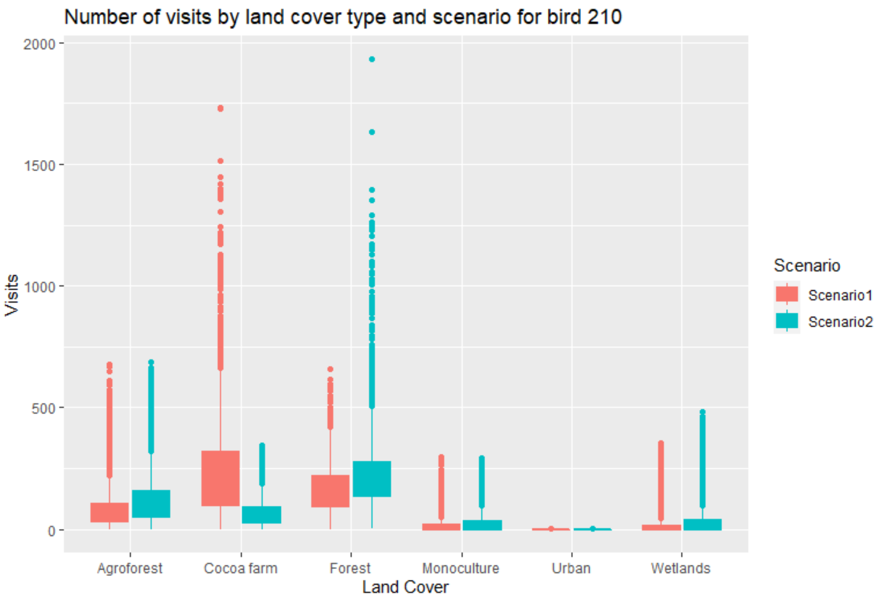

```
Response: Sim207
                      Sum Sq     Df   F value    Pr(>F)
LandCover         4495833140      5 59518.226 < 2.2e-16 ***
Scenario              299230      1    19.807 8.572e-06 ***
LandCover:Scenario  907232450     5 12010.425 < 2.2e-16 ***
Residuals         3464855724 229348
```



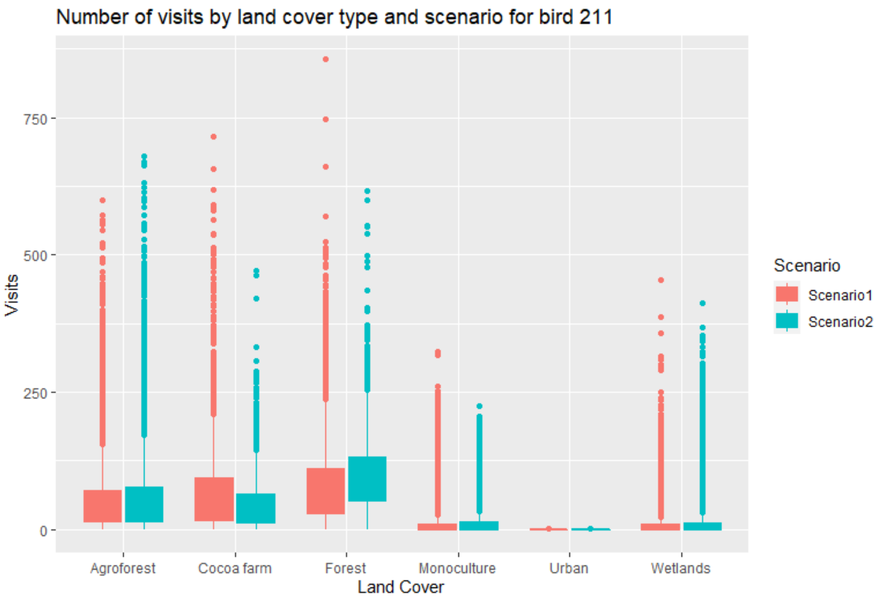

```
Response: Sim208
                      Sum Sq     Df   F value Pr(>F)
LandCover          386463153      5 22634.8757 <2e-16 ***
Scenario                 133      1     0.0391 0.8433
LandCover:Scenario  81224269      5  4757.2484 <2e-16 ***
Residuals          783167995 229348
```



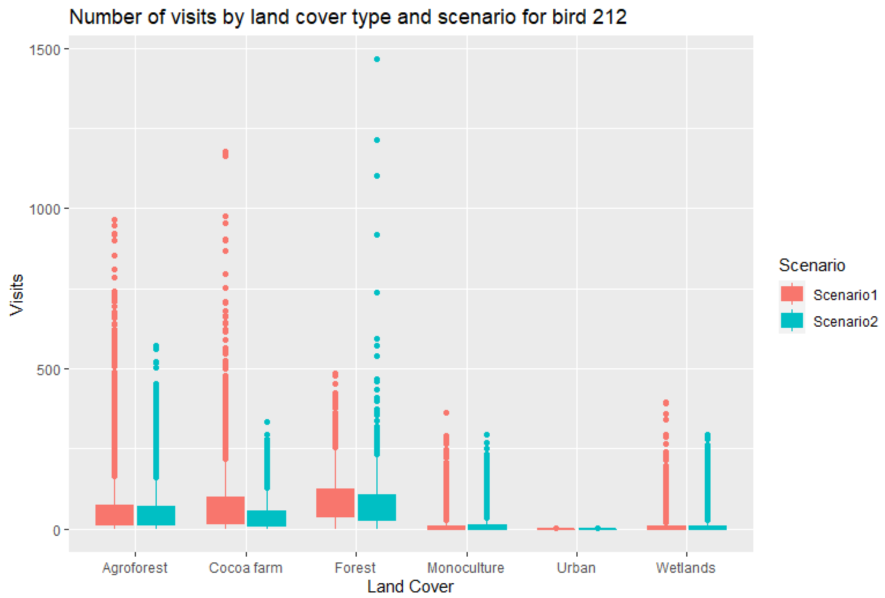

```
Response: Sim209
                       Sum Sq     Df   F value Pr(>F)
LandCover          1576863750      5 44769.1156 <2e-16 ***
Scenario                 1960      1     0.2782 0.5979
LandCover:Scenario  316046959      5  8972.9647 <2e-16 ***
Residuals          1615625157 229348
```



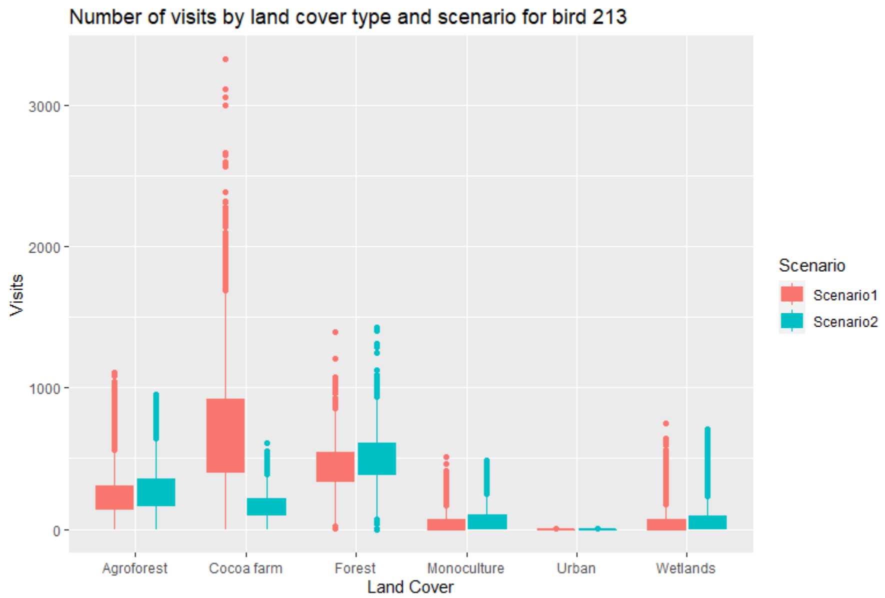

```
Response: Sim210
                     Sum Sq     Df  F value    Pr(>F)    
LandCover         516629614      5  25884.0 < 2.2e-16 ***
Scenario            9178132      1   2299.2 < 2.2e-16 ***
LandCover:Scenario 94206093      5   4719.9 < 2.2e-16 ***
Residuals         915529820 229348                       
```



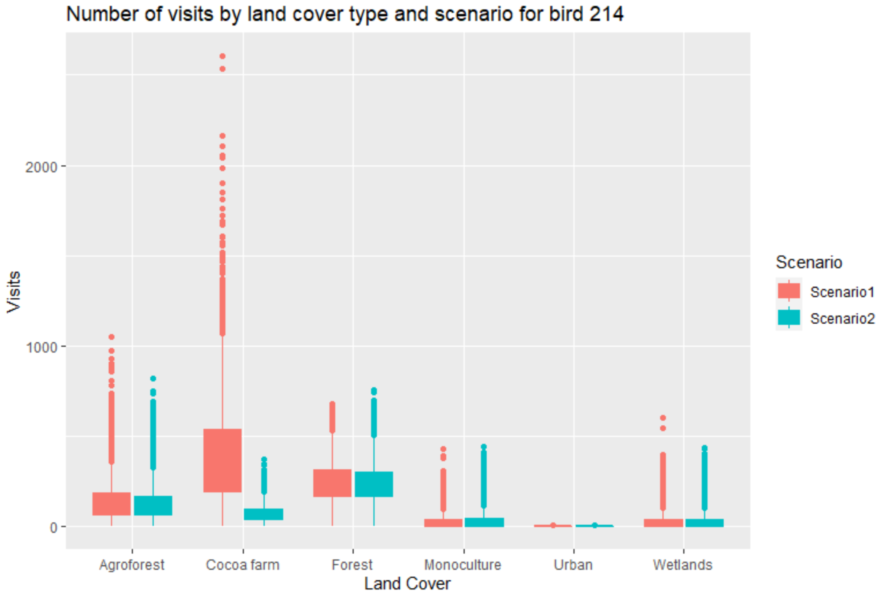

```
Response: Sim211
                     Sum Sq     Df  F value    Pr(>F)    
LandCover         128346055      5 15258.56 < 2.2e-16 ***
Scenario             207684      1   123.45 < 2.2e-16 ***
LandCover:Scenario  1784189      5   212.12 < 2.2e-16 ***
Residuals         385828162 229348                       
```



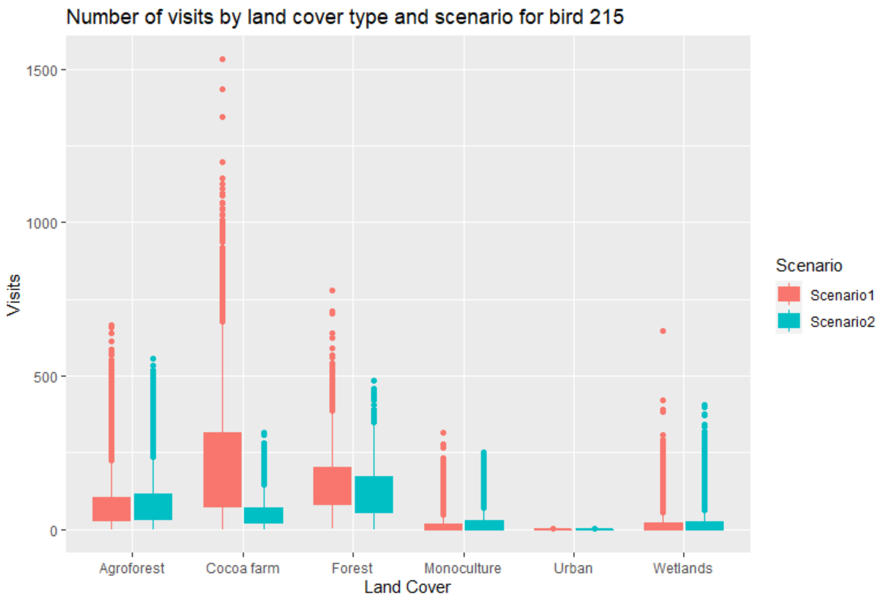

```
Response: Sim212
                     Sum Sq     Df   F value    Pr(>F)
LandCover         125061051      5 13818.286 < 2.2e-16 ***
Scenario             126803      1    70.054 < 2.2e-16 ***
LandCover:Scenario  3308343      5   365.546 < 2.2e-16 ***
Residuals         415138345 229348
```



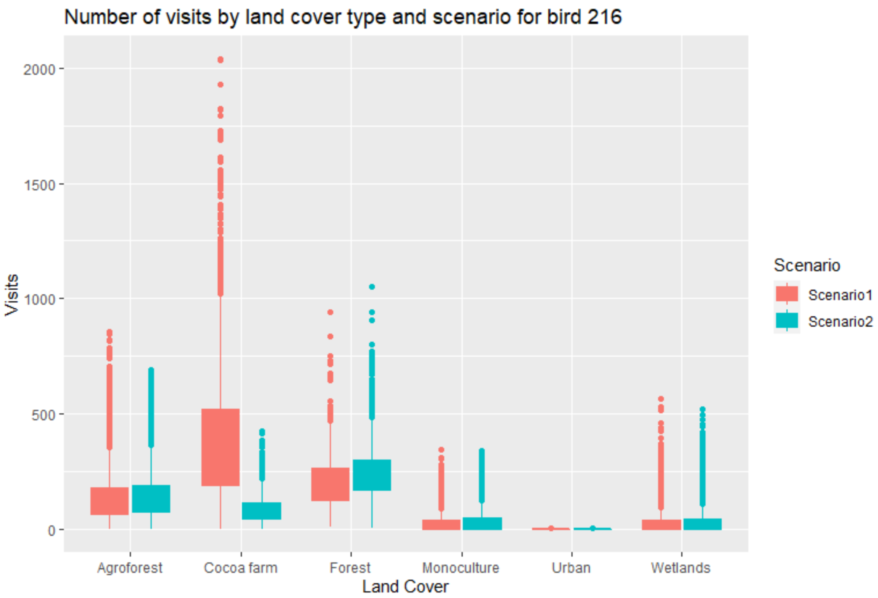

```
Response: Sim213
                      Sum Sq     Df    F value    Pr(>F)
LandCover         3630710709      5 54921.1577 < 2.2e-16 ***
Scenario              105102      1     7.9493  0.004811 **
LandCover:Scenario 768380973      5 11623.1713 < 2.2e-16 ***
Residuals         3032333162 229348
```



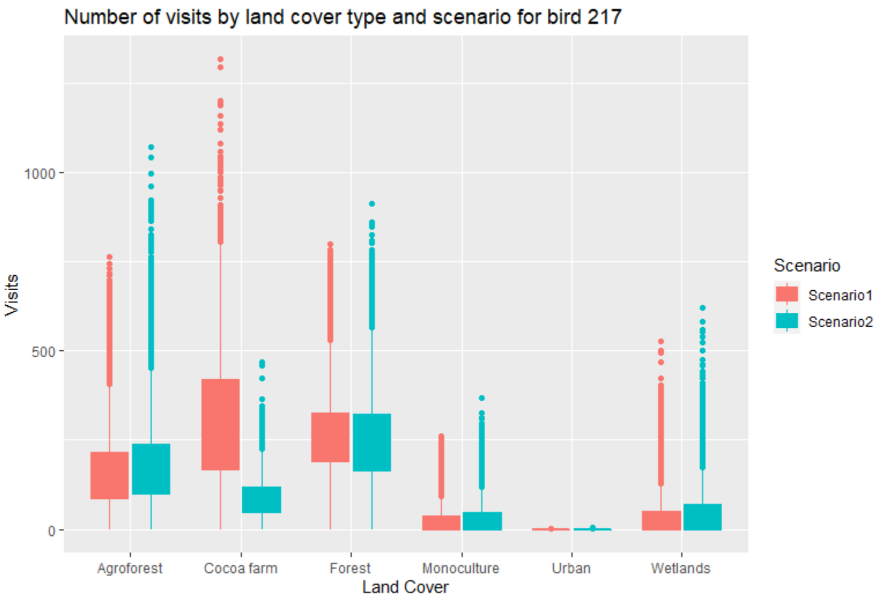

```
Response: Sim214
                        Sum Sq     Df  F value    Pr(>F)    
LandCover            953302714      5  34420.6 < 2.2e-16 ***
Scenario              12702146      1   2293.2 < 2.2e-16 ***
LandCover:Scenario   243648562      5   8797.3 < 2.2e-16 ***
Residuals           1270391216 229348
```



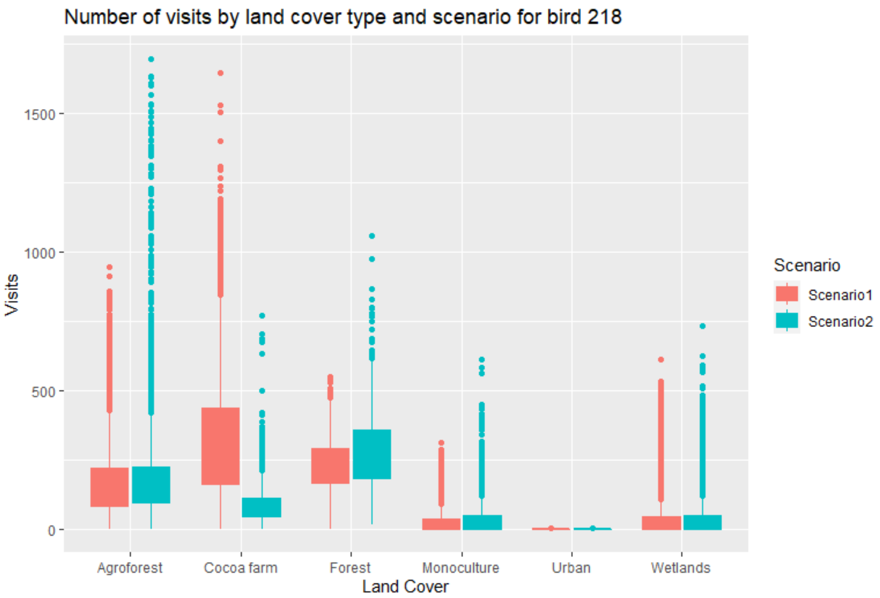

```
Response: Sim215
                       Sum Sq     Df  F value    Pr(>F)    
LandCover           339417156      5 22058.32 < 2.2e-16 ***
Scenario               403898      1   131.24 < 2.2e-16 ***
LandCover:Scenario   76346270      5  4961.65 < 2.2e-16 ***
Residuals           705807507 229348
```



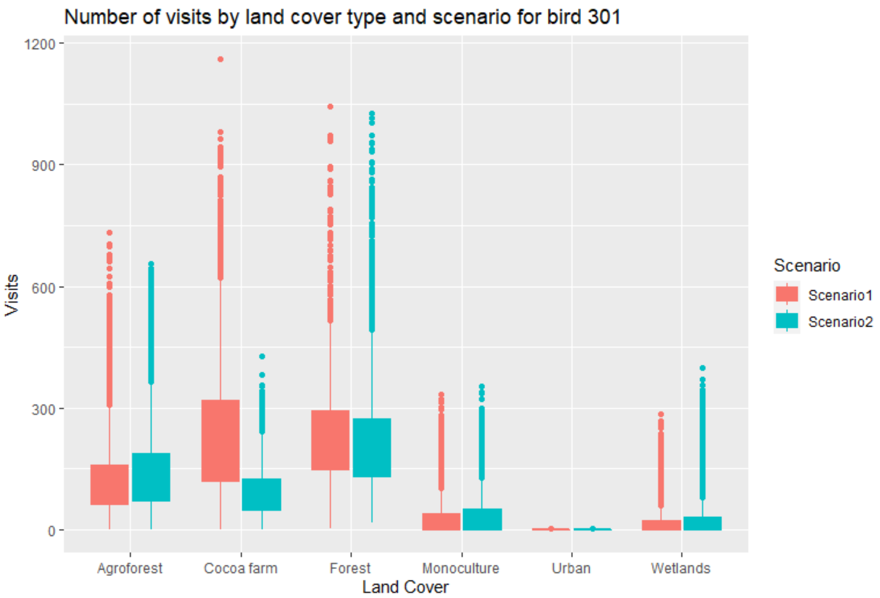

```
Response: Sim216
                      Sum Sq     Df  F value    Pr(>F)    
LandCover          980221526      5 34444.12 < 2.2e-16 ***
Scenario             1366194      1   240.03 < 2.2e-16 ***
LandCover:Scenario 232070529      5  8154.75 < 2.2e-16 ***
Residuals         1305371435 229348                       
```



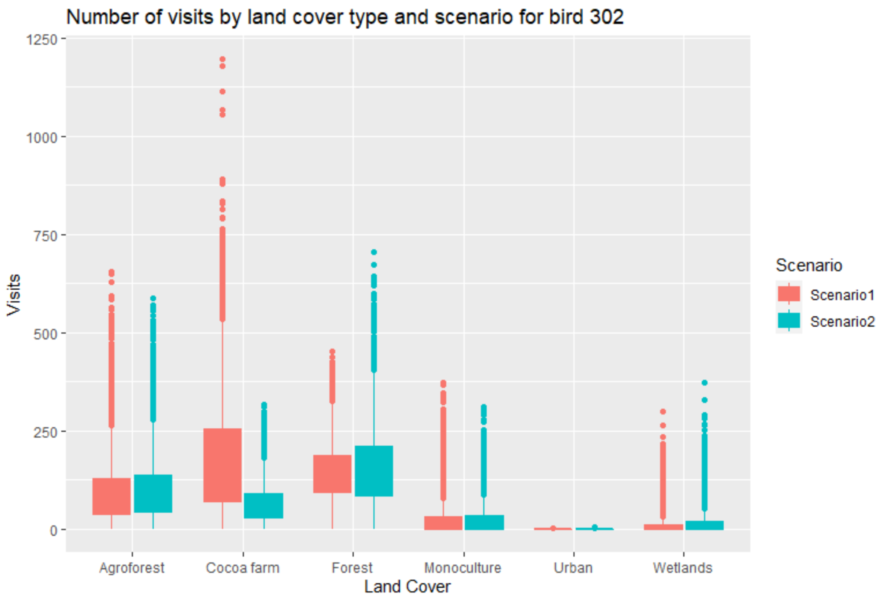

```
Response: Sim217
                      Sum Sq     Df  F value    Pr(>F)    
LandCover         1262500308      5 40760.75 < 2.2e-16 ***
Scenario              126307      1    20.39 6.321e-06 ***
LandCover:Scenario 132535167      5  4279.00 < 2.2e-16 ***
Residuals         1420738913 229348                       
```



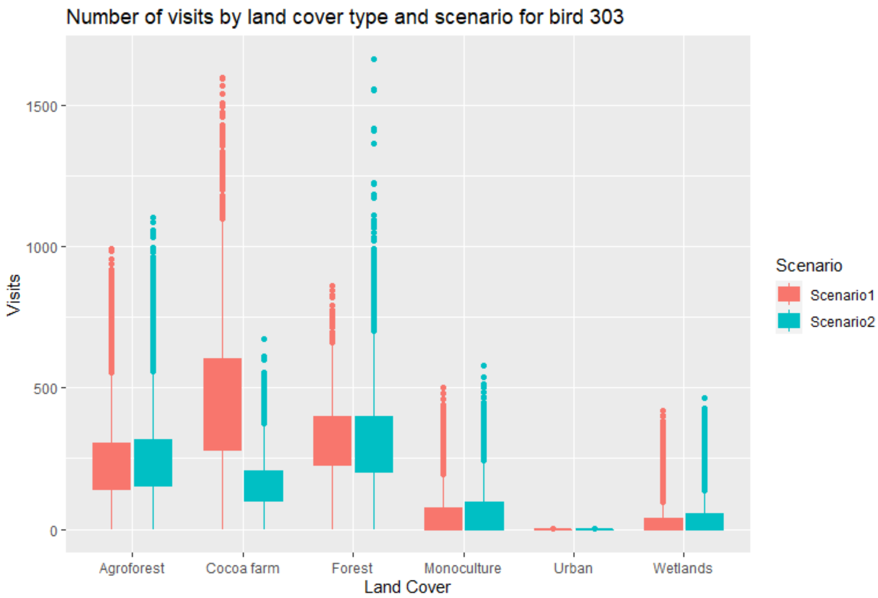

```
Response: Sim218
                       Sum Sq     Df   F value    Pr(>F)
LandCover          1248298947      5 37040.047 < 2.2e-16 ***
Scenario               502515      1    74.554 < 2.2e-16 ***
LandCover:Scenario  144477282      5  4286.990 < 2.2e-16 ***
Residuals          1545866657 229348
```



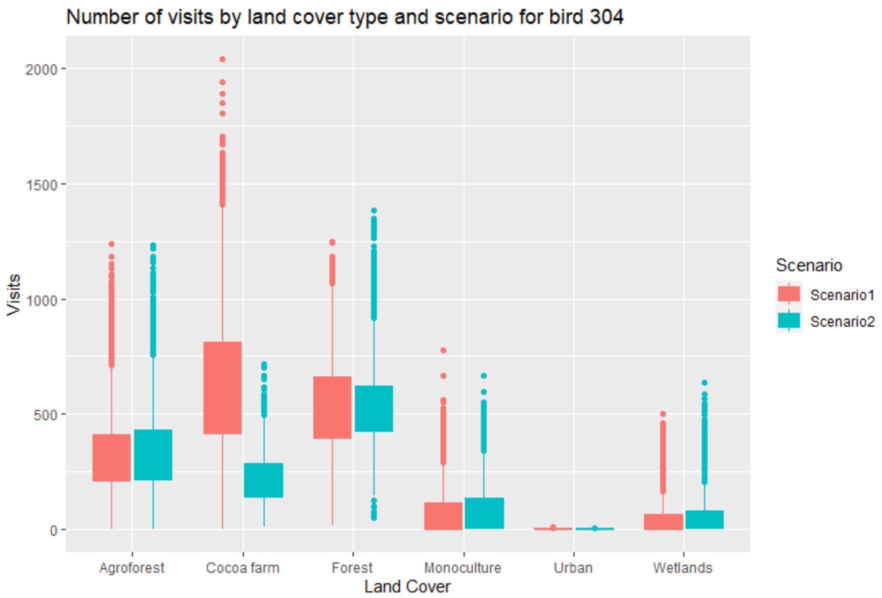

```
Response: Sim301
                      Sum Sq     Df  F value    Pr(>F)
LandCover          792428277      5 36836.08 < 2.2e-16 ***
Scenario              987712      1   229.57 < 2.2e-16 ***
LandCover:Scenario  60997169      5  2835.46 < 2.2e-16 ***
Residuals          986760071 229348
```



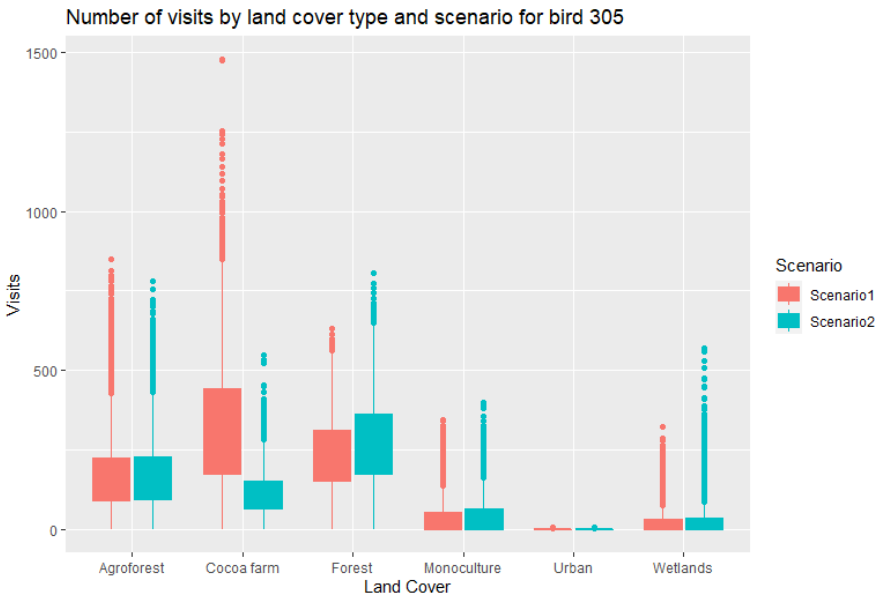

```
Response: Sim302
                      Sum Sq     Df    F value Pr(>F)
LandCover          418197974      5 26356.2857 <2e-16 ***
Scenario                6598      1     2.0791 0.1493
LandCover:Scenario  36776303      5  2317.7701 <2e-16 ***
Residuals          727817797 229348
```



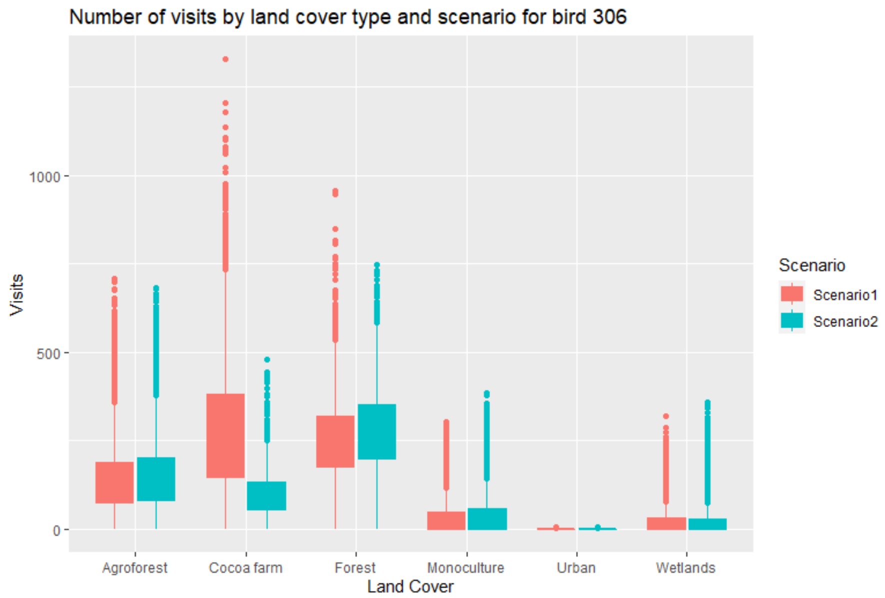

```
Response: Sim303
                       Sum Sq     Df   F value    Pr(>F)
LandCover          2461088452      5 51216.831 < 2.2e-16 ***
Scenario               489974      1    50.983 9.343e-13 ***
LandCover:Scenario  230886481      5  4804.896 < 2.2e-16 ***
Residuals          2204141494 229348
```



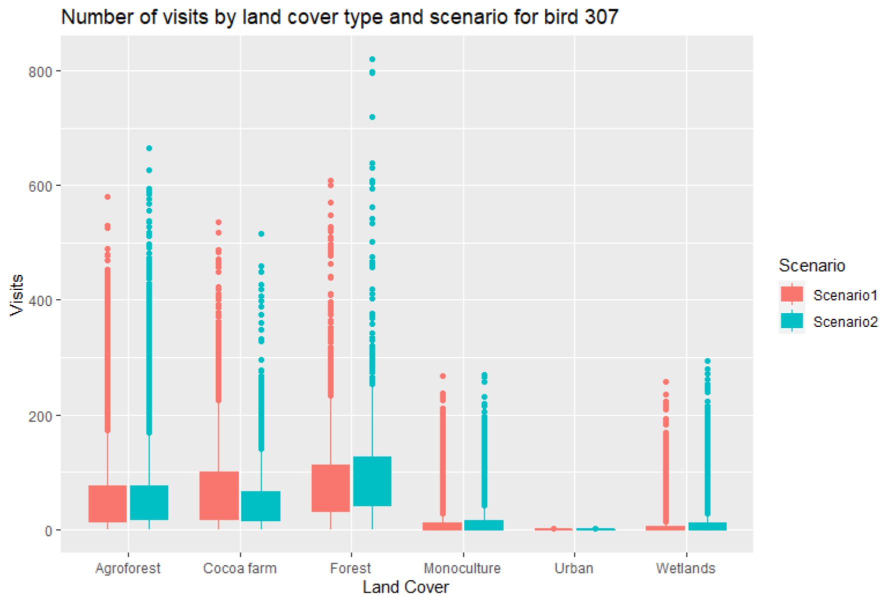

```
Response: Sim304
                       Sum Sq     Df  F value    Pr(>F)    
LandCover          4865107503      5 65755.75 < 2.2e-16 ***
Scenario              2851337      1   192.69 < 2.2e-16 ***
LandCover:Scenario  438337532      5  5924.48 < 2.2e-16 ***
Residuals          3393779826 229348                       
```



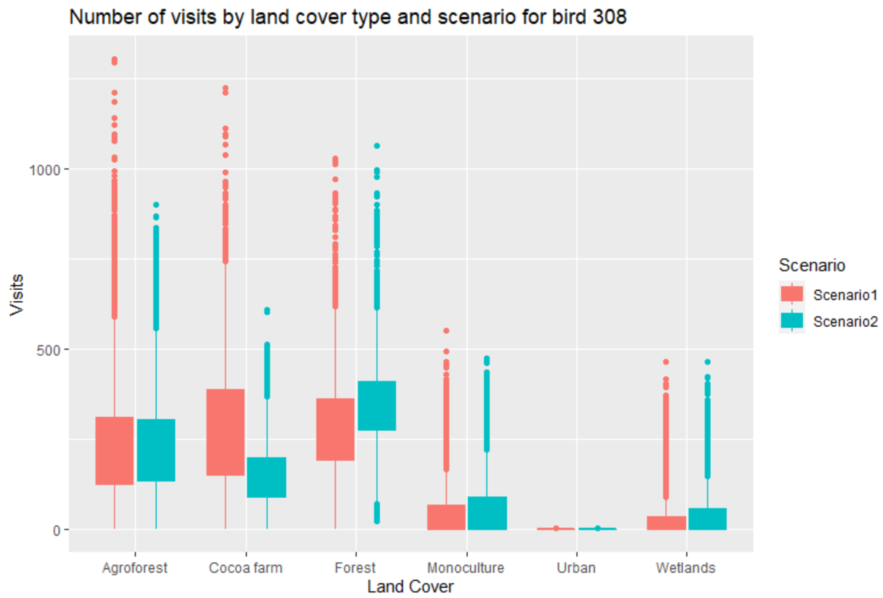

```
Response: Sim305
                       Sum Sq     Df  F value    Pr(>F)    
LandCover          1273732705      5 43711.61 < 2.2e-16 ***
Scenario               624472      1   107.15 < 2.2e-16 ***
LandCover:Scenario  117581984      5  4035.15 < 2.2e-16 ***
Residuals          1336615493 229348                       
```



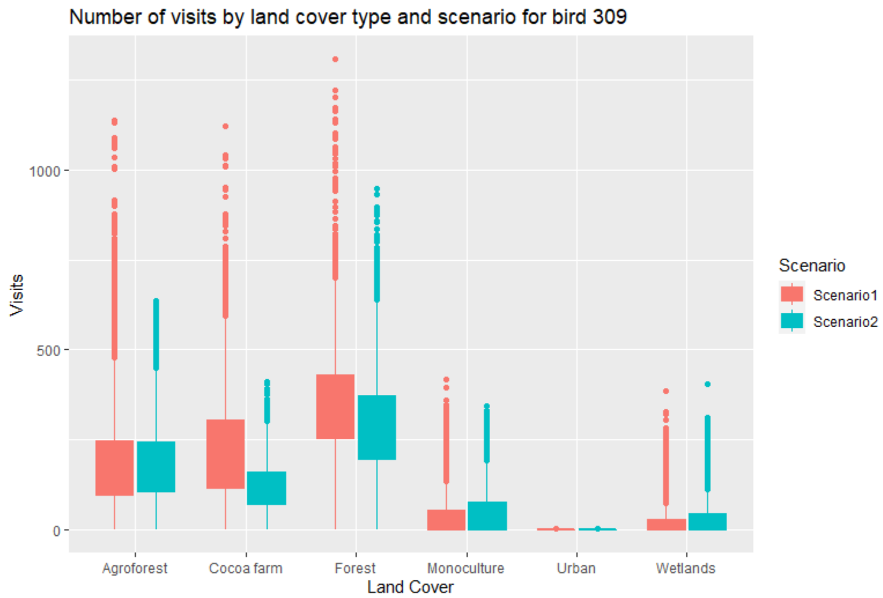

```
Response: Sim306
                        Sum Sq     Df  F value    Pr(>F)    
LandCover           1049695825      5 43707.32 < 2.2e-16 ***
Scenario                207836      1    43.27  4.78e-11 ***
LandCover:Scenario    87398679      5  3639.11 < 2.2e-16 ***
Residuals           1101626173 229348
```



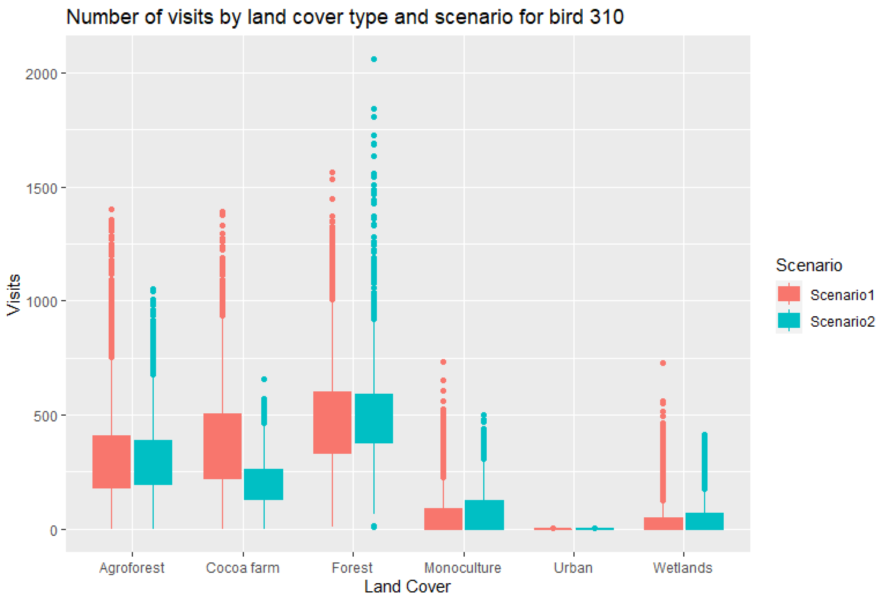

```
Response: Sim307
                      Sum Sq     Df   F value    Pr(>F)    
LandCover          134105563      5 16664.874 < 2.2e-16 ***
Scenario              123657      1    76.832 < 2.2e-16 ***
LandCover:Scenario   1715328      5   213.158 < 2.2e-16 ***
Residuals          369121817 229348
```



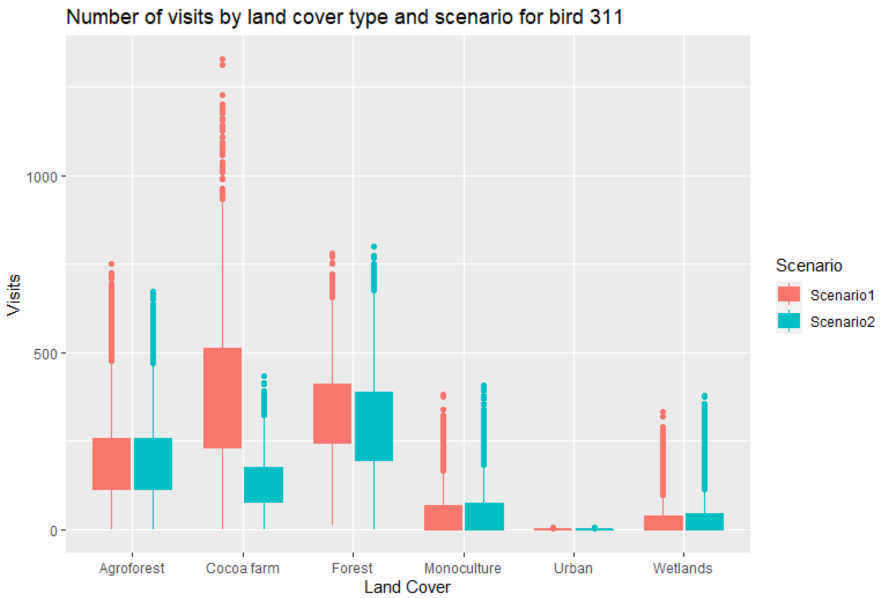

```
Response: Sim308
                        Sum Sq     Df   F value    Pr(>F)    
LandCover           2079824356      5 46117.588 < 2.2e-16 ***
Scenario                689299      1    76.422 < 2.2e-16 ***
LandCover:Scenario    54921607      5  1217.820 < 2.2e-16 ***
Residuals           2068640530 229348                        
```



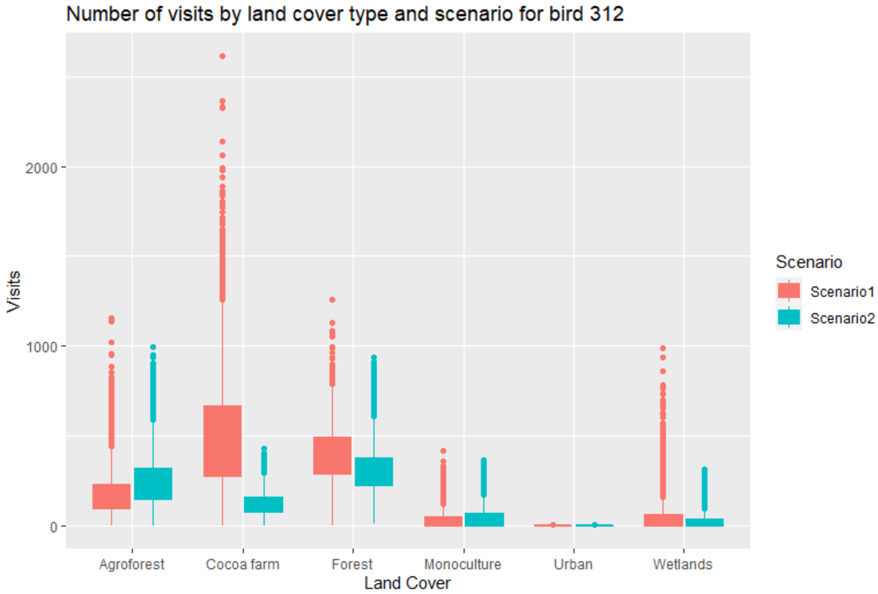

```
Response: Sim309
                        Sum Sq     Df    F value Pr(>F)    
LandCover           1491915926      5 45650.5960 <2e-16 ***
Scenario                   645      1     0.0987 0.7534    
LandCover:Scenario    37186758      5  1137.8642 <2e-16 ***
Residuals           1499073236 229348                      
```



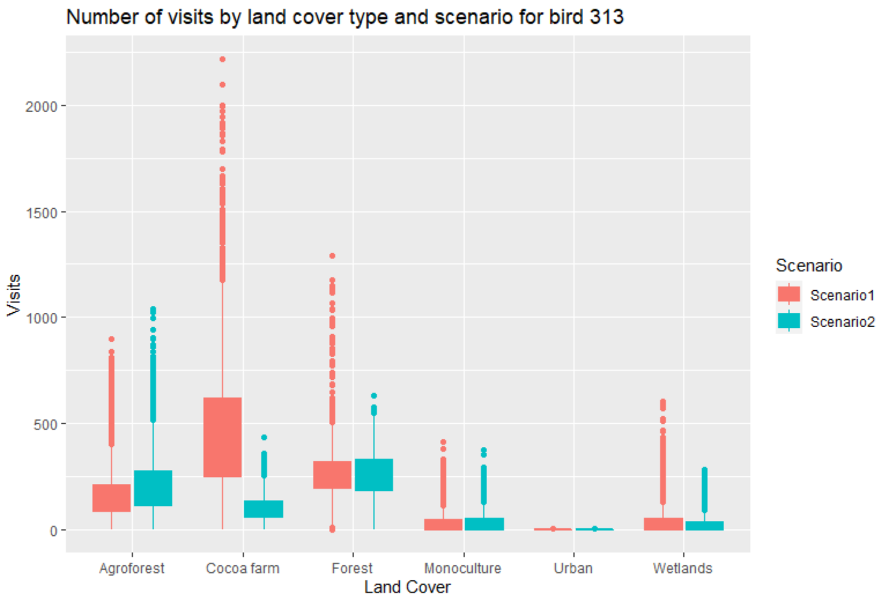

```
Response: Sim310
                       Sum Sq     Df   F value    Pr(>F)    
LandCover          3955485270      5 60466.848 < 2.2e-16 ***
Scenario               167887      1    12.832 0.0003408 ***
LandCover:Scenario   90814954      5  1388.273 < 2.2e-16 ***
Residuals          3000595089 229348                        
```




```
Response: Sim311
                       Sum Sq     Df  F value    Pr(>F)    
LandCover          1738325306      5 53860.61 < 2.2e-16 ***
Scenario              5562029      1   861.67 < 2.2e-16 ***
LandCover:Scenario  158442944      5  4909.23 < 2.2e-16 ***
Residuals          1480419270 229348                       
```




```
Response: Sim312
                        Sum Sq     Df   F value    Pr(>F)
LandCover           2313137272      5 50618.726 < 2.2e-16 ***
Scenario                376657      1    41.212 1.368e-10 ***
LandCover:Scenario   480095613      5 10506.004 < 2.2e-16 ***
Residuals           2096115192 229348
```




```
Response: Sim313
                        Sum Sq     Df   F value    Pr(>F)
LandCover           1681032471      5 44927.668 < 2.2e-16 ***
Scenario                212421      1    28.386 9.947e-08 ***
LandCover:Scenario   369642036      5  9879.140 < 2.2e-16 ***
Residuals           1716276193 229348
```

CV

Bachelier en sciences géographiques à l'UNamur

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