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Mapping Human-Wildlife Interfaces for Zoonotic Pathogens Spillover Surveillance in the District des Montagnes, Côte D'Ivoire

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Abstract

Background/Objectives: In Côte d'Ivoire, existing disease surveillance systems seldom cover human-wildlife interfaces despite the potential for pathogen spillovers that are likely to occur in these areas. Therefore, it is imperative to map these interfaces to assist government and stakeholders in establishing coordinated and multisectoral disease surveillance and risk monitoring. This study aimed to develop an interactive map of human-wildlife interfaces in the District des Montagnes. **Methods:** Using GIS technology and approaches. We collected data from government institutions to develop five indices of interactions between humans and wildlife that characterize the level of human infiltration of protected areas and classified forests, the extent of roadways, human settlements, population density in the vicinity of protected areas, and the number of wild meat sales and consumption points. We further spatialized the five indices to create maps that were merged in a multicriteria spatial analysis to produce a synthesis map of human-wildlife interfaces. **Results:** The departments of Man and Danané showed the highest level of interactions between humans, wildlife, and the environment. In addition, various classified forests, parks, and reserves face anthropogenic pressure resulting in high levels of interactions between humans and wildlife. **Conclusions**: The interactive map of human-wildlife interfaces produced will serve as a decision-making tool to enhance disease surveillance systems and promote the One Health approach in Côte d'Ivoire.

Keywords

Mapping, Human-Wildlife Interfaces, Zoonotic Disease, Disease Surveillance, Côte d'Ivoire

1. Introduction

Côte d'Ivoire, located in West Africa, is a country renowned for its rich biodiversity and diverse ecosystems, ranging from tropical forests to savannahs. This ecological diversity represents as many human-wildlife interfaces, facilitating the emergence and spread of zoonotic diseases (zoonoses). Zoonoses, defined as diseases or infections naturally transmissible from vertebrate animals to humans and vice versa, account for around 60% of emerging infectious diseases in humans [1]. They can spread between animals and humans. Zoonoses can have an impact on both human and animal health, leading to reduced productivity and even death, as was the case with COVID-19 [2]. This was also the case with Avian influenza (or bird flu), which led to a panzootic in the early 2000s [3]-[5]. Further, the Ebola virus epidemics that occurred in Central and West Africa have often had an animal origin. Monitoring zoonoses is therefore a national and regional priority.

In 2017, Côte d'Ivoire conducted a zoonotic disease prioritization exercise, using the One Health Zoonotic Disease Prioritization (OHZDP) tool developed by the CDC (Center for Disease Control and Prevention). The exercise identified five groups of priority zoonoses for the country [6]. These are diseases due to Mycobacterium species; Brucella species; Rabies virus; viruses of hemorrhagic fevers; Arboviruses and respiratory viruses such as highly pathogenic Avian Influenza virus, Coronaviruses (SARS CoV and MERS CoV). For these priority diseases, Côte d'Ivoire has put in place several surveillance systems, notably for rabies, which is monitored using the "One Health" approach [7] [8]. The "One Health" approach is an integrative framework that recognizes the interconnectedness of human, animal and environmental health. It emphasizes collaborative efforts across multiple sectors to address complex health challenges, particularly those at the interface between humans, animals and the environment [9]. In Côte d'Ivoire, the government's interest in public, veterinary and environmental health has led to the creation of the national "One Health" platform and a Technical Working Group (TWG) on surveillance. Despite efforts from the government of Côte d'Ivoire, human-wildlife interfaces are seldom covered by existing surveillance systems. The District des Montagnes, shares borders with Guinea and Liberia which experienced major epidemics caused by Ebola and Lassa viruses. The District des Montagnes remains vulnerable due to its geographical proximity to endemic areas and cross-border mobility, underscoring the need for continuous disease surveillance. Further, zoonosis surveillance in Côte d'Ivoire faces several challenges, including weak multi-sectoral coordination of human, animal and environmental health, the lack of wildlife surveillance, particularly at human-animal-environment interfaces, and insufficient use of Geographic Information Systems (GIS).

The aim of this study was to identify areas at high risk of zoonotic pathogen transmission at human-animal-environment interfaces to support disease surveillance activities.

2. Materials and Methods

2.1. Study Area

The area covered by this study is the District des Montagnes located in western Côte d'Ivoire (**Figure 1**), with the city of Man as its capital. The district has a population of about 3,027,023 [10] and is divided into three regions: Tonkpi, Guémon and Cavally. It is bordered to the north by Guinea and the Woroba District, to the east and south by the Sassandra-Marahoué district and the Bas-Sassandra district; and to the west by Liberia. This district is home to the largest number of parks, reserves and classified forests in Côte d'Ivoire: Parc national du Mont Sangbé, Parc national du Mont Péko, Parc national de Taï, Réserve naturelle intégrale du Mont Nimba, Réserve de faune du N'Zo, Forêt classée du Scio, Forêt classée de Goin-Débé and Forêt classée du Cavally. This large number of protected areas with great ecological variability is synonymous with wildlife diversity, and, therefore, a breeding ground for zoonotic pathogens spillover.

2.2. Data collection

We conducted this descriptive cross-sectional study from October 1, 2023 to September 30, 2024. The following government ministries and agencies provided the data used to map human-wildlife interfaces: *Société de Développement des Forêts* (SODEFOR), *Office Ivoirienne des Parcs et Réserves* (OIPR), *Ministère des Eaux et Forêts* (MINEF), *Institut Nationale de la Statistique* (INS), *Bureau National d'Etudes Techniques et du Développement/Centre de l'Information Géographique et du Numérique* (BNETD/CIGN), *Comité National de Télédétection et de l'Information Géographique* (CNTIG), *Centre Universitaire de Recherche et d'Application en Télédétection* (CURAT), *Institut National d'Hygiène Publique* (INHP), and *Ministère du Tourisme et des Loisirs*.

We collected the data on the district physical features (hydrography and topography), land use, agricultural operations, and forest formations and administrative entities (district, regions, departments, sub-prefectures, district capital city, regional capital city, department capital city, sub-prefecture capital city, villages, and camps). These data were all in digital vector format, and were, therefore, retrieved on a USB key. We further collected data from national parks,

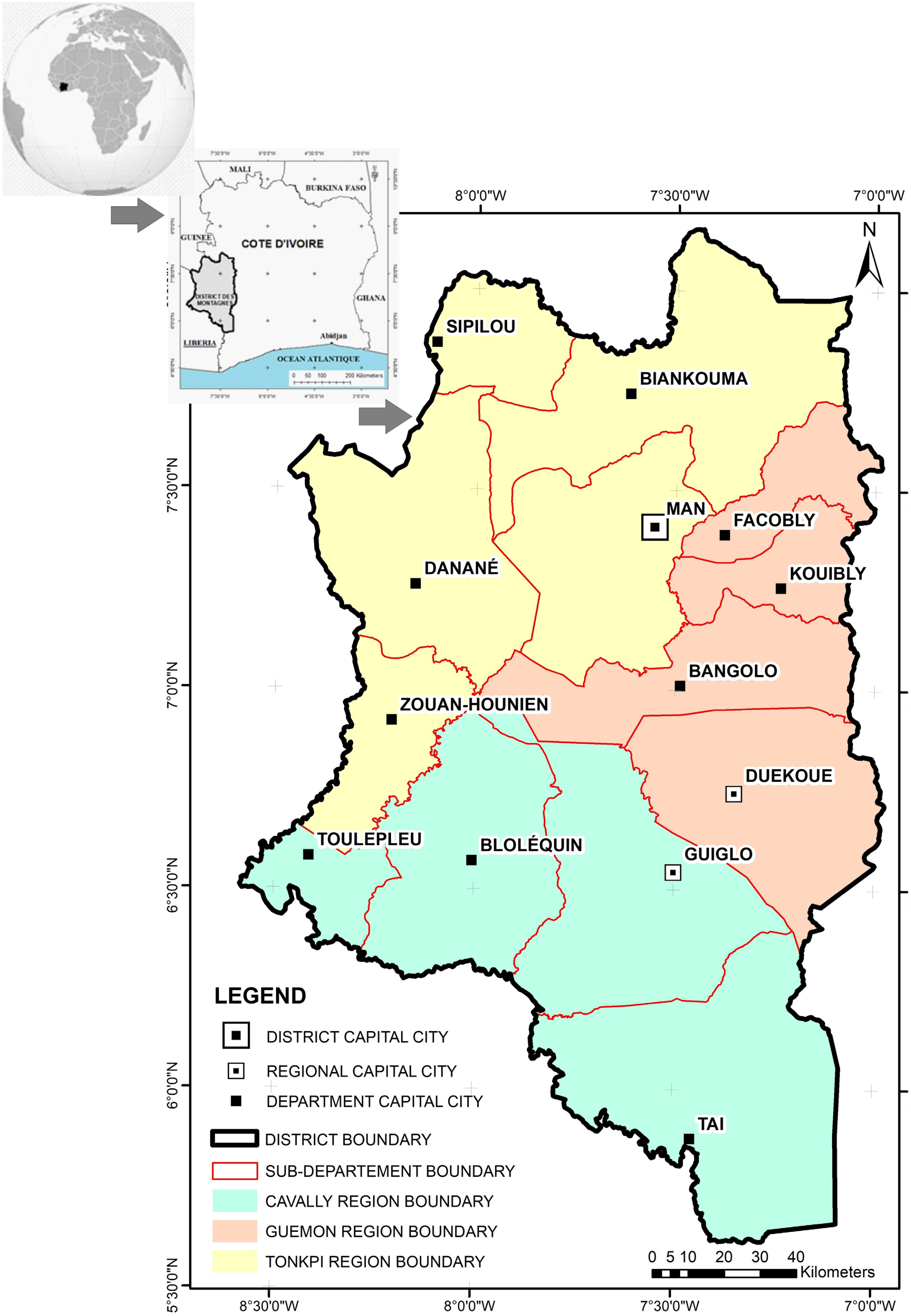

Figure 1. Map of the study area.

classified forests and reserves on the level of infiltration of protected areas by human activities. The *Institut National d'hygiène Publique* (INHP) and the Ministry of Tourism provided data on points of sale and consumption of wild meat in the District des Montagnes.

2.3. Data Analysis and Processing

We entered the data collected into an Excel spreadsheet and later exported them to ArcGIS software to produce the maps. We created thematic vector layers in ArcGIS software followed by the development of indices to characterize and spatialize various data and information collected.

2.3.1. Creation of Thematic Vector Layers in ArcGIS Software

We projected vector data (point-line-polygon) in digital format into a single reference frame (UTM-WGS 84, zone 29) to form the spatial database for human-wildlife-environment interfaces. We further spatialized data (point-line-polygon) collected from various government entities [8] using the same projection.

2.3.2. Development of Indices to Characterize and Spatialize Human-Wildlife Interactions

We developed two groups of indices. The term "index" refers to a rating used to assess the quality or intensity of human-wildlife and environment interactions [11]. The first group of indices described sites of direct (physical) contact between humans and wildlife. These were: points of wild meat consumption (households, restaurants and hotels), sales, hunting, trapping, and touristic wildlife observation. The second group of indices characterized the environmental and socio-economic factors that materialize contacts between humans and wildlife. The factors were: the extent of inhabited areas in the vicinity of sites with high concentrations of wildlife; the level of population densities per square kilometer in areas hosting protected areas (classified forests, national parks and reserves), as wildlife is the primary source of animal protein for rural populations; the number of human settlements that have infiltrated sites with high concentrations of wildlife where the population engages in farming, hunting, trapping, and animal carcasses collection; the extent of existing roadways facilitating access into areas with high concentrations of wildlife. We developed the following five indices to characterize Human-wildlife interactions:

- Index 1: sale and consumption of wild meat;
- Index 2: length of roadways within a 5 km radius of classified forests, parks and reserves;
- Index 3: number of localities within a 5 km radius of classified forests, parks and reserves;
- Index 4: level of infiltration of classified forests parks and reserves;
- Index 5: sub-prefectural population density within a 5 km radius of classified forests, parks and reserves.

We further prioritized and spatialized the indices developed which are proxies to characterize the level of interactions between humans and wildlife [8].

2.3.3. Hierarchization and Spatialization of Indices of Human-Wildlife Interactions

Index 1: Sale and consumption of wild meat

This index was generated by summing up all the sites where wild meat is sold or consumed (hotels, and restaurants) in the various departments of the District des Montagnes. The sum of the data from the Ministry of Tourism and Leisure, the National Institute of Public Health and the Google platform yielded values ranging from 11 to 82 points of sale or consumption of bush meat. The classification hierarchy was based on the tercile method (division into three equal groups in terms of numbers). Each group contains the same number of observations (12 values/4 per group) (Table 1). Table 1 shows the hierarchization based on the tercile method for wild meat Sale and consumption.

Table 1. Hierarchization based on the tercile method for wild meat sale and consumption.

Classes	Range	values
Low	1 - 4	11, 11, 12, 13
Medium	5 - 8	17, 17, 30, 30
High	9 - 12	31, 31, 44, 82

We used hierarchization of the values derived from the summation to create three classes of indices coded as follows.

1. High index corresponding to Code 3 (number of points of sale or consumption greater or equals to 40);
2. Medium index corresponding to Code 2 (number of points of sale or consumption between 15 and 40);
3. Low index corresponding to Code 1 (number of points of sale or consumption less than or equals to 15).

Index 2: Length of roads within a 5 km radius of classified forests, parks and reserves

We developed this index by summing up the lengths of all roadways in meters within a 5 km radius of classified forests, parks and reserves. To determine road lengths using GIS tools, buffer zones of 5 km were created around classified forests, national parks and reserves. This operation resulted in road lengths ranging from 119,434 to 325,407 meters.

The lengths of all roadways within these zones were computed. The classification into three interaction classes was approached using terciles (division into three equal groups) (Table 2). This approach was based on 28 values for classification into three groups. Table 2 shows the hierarchization based on the tercile method for road length.

Table 2. Hierarchization based on the tercile method for road length.

Classes	Range	values
Low	71.08 - 150.00	9
Medium	167.06 - 280.72	9
High	299.79 - 691.80	10

These classes are adjusted as follows:

1. High index corresponding to Code 30 (roadways with total length greater than or equals 300,000 m;
2. Medium index corresponding to Code 20 (roadways with total length between 150,000 and 300,000 m;
3. Low index corresponding to Code 10 (roadways with total length less than or equals 150,000 m.

Index 3: Number of agglomerations within a 5 km radius of classified forests, parks and reserves

We generated this index by determining and then summing up the number of localities within a 5 km radius of classified forests, parks and reserves. A three-class hierarchy was established using the standard deviation classification method. This method was based on the mean of 100.15 and the standard deviation of 150.02 of the data on localities to determine the three classes.

Calculation of the mean: 100.12 + 150.02 = 250.22.

Calculation of low values: 100.12 - 140.22 = −40.1. Adjusted to 0 because negative values are meaningless.

Calculation of high values: >250.

These classes are adjusted as follows:

1. High index corresponding to Code 300 (number of localities greater or equals to 250;
2. Medium index corresponding to Code 200 (number of localities between 100 and 250;
3. Low index corresponding to Code 100 (number of localities less than or equals to 100).

Index 4: Level of infiltration of classified forests, parks and reserves

We generated this index by assessing the level of infiltration of classified forests, national parks and reserves. The hierarchy of infiltration classes is based on survey forms completed by protected area managers rather than satellite images. Thus, interactions between humans and wildlife are low if forests (areas with high concentrations of wildlife) have a low level of human infiltration (0% - 25%). This interaction becomes moderate when human infiltration of forests (sites with high concentrations of wildlife) increases to 25% - 50%. Finally, interaction between humans and wildlife reaches its peak when human infiltration exceeds 50%. We further classified the levels of the infiltration into three classes of indices coded as follows:

1. High index corresponding to Code 3000 (infiltration levels between 50% and

75%;
2. Medium index corresponding to Code 2000 (infiltration levels between 25% and 50%;
3. Low index corresponding to Code 1000 (infiltration levels between 0% and 25% or 75% and 100%.

Index 5: Sub-prefectural population density within a 5 km radius of classified forests, parks and reserves.

This index was generated by assessing the population density of sub-prefectures within a 5 km radius of classified forests, parks and reserves. We further classified population density values into three classes of indices coded as follows:

1. High index corresponding to Code 30,000 (population density greater than or equals to 200 inhabitants per square kilometer;
2. Medium index corresponding to Code 20,000 (population density between 100 and 200 inhabitants per square kilometer;
3. Low index corresponding to Code 10,000 (population density less than or equals to 100 inhabitants per square kilometer.

We used each index to create thematic maps which were combined or merged to form a synthesis map such that Index 1, Index 2, Index 3, Index 4 and Index 5 had their classes labeled Low, Medium and High coded respectively by units (1, 2, 3), tens (10, 20, 30), hundreds (100, 200, 300), thousands (1000, 2000, 3000) and tens of thousands (10000, 20000, 30000). Furthermore, the combination of the five index maps using "Map Algebra on ArcGIS" operation resulted in a new map which we reclassified according to the values of codes to produce the final map of human-wildlife interfaces.

2.4. Ethical considerations

The study did not require approval from the Ethics Committee since all data used are of public interest and were collected from authorized government entities at central and regional level. No human or animal subjects were used.

3. Results

3.1. Spatial Distribution of Human-Wildlife Interactions in Relation to Wild Meat Sales and Consumption Points at Prefectural Level (Index 1)

Data from the Ministry of Tourism and Leisure (MT), the National Institute of Public Hygiene (INHP) and the Google (GOO) platform yielded the number of wild meat sales or consumption points ranging from 11 to 82 at prefectural level. Index 1, characterizing the spatial distribution of wild meat sales and consumption points is shown in Figure 2. Based on the Index 1 distribution, the departments of Man and Danané have the highest levels of human-wildlife interactions (Figure 2). The central zone of the District des Montagnes including the departments of Bangolo, Zouan-Hounien, Blolequin and Toulepleu, had the lowest levels of human-wildlife interactions. The northern and southern parts of the District des Montagnes had medium levels of human-wildlife interaction.

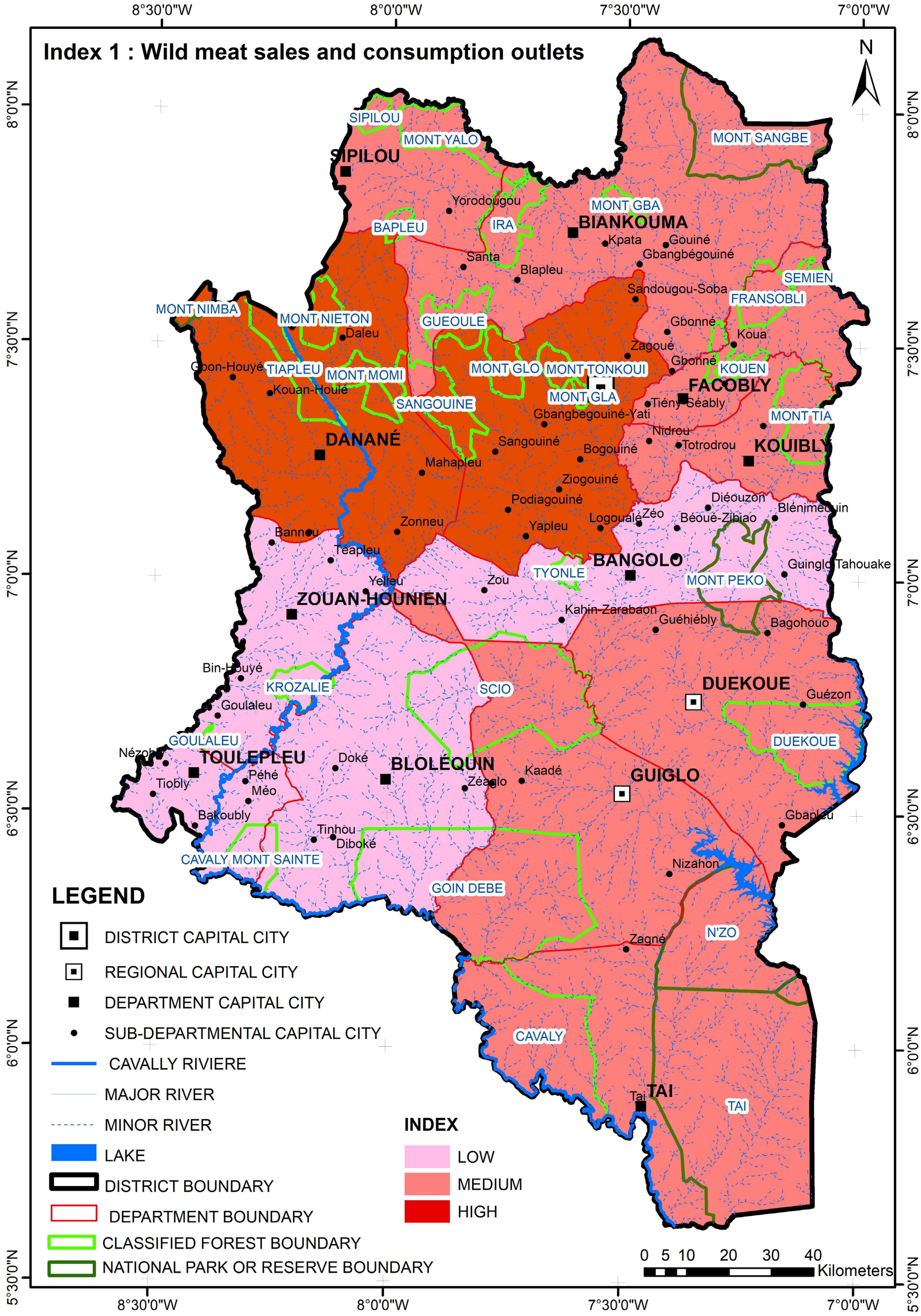

Figure 2. Map of the intensity of human-wildlife interactions based on sales and consumption points of wild meat in the District des Montagnes.

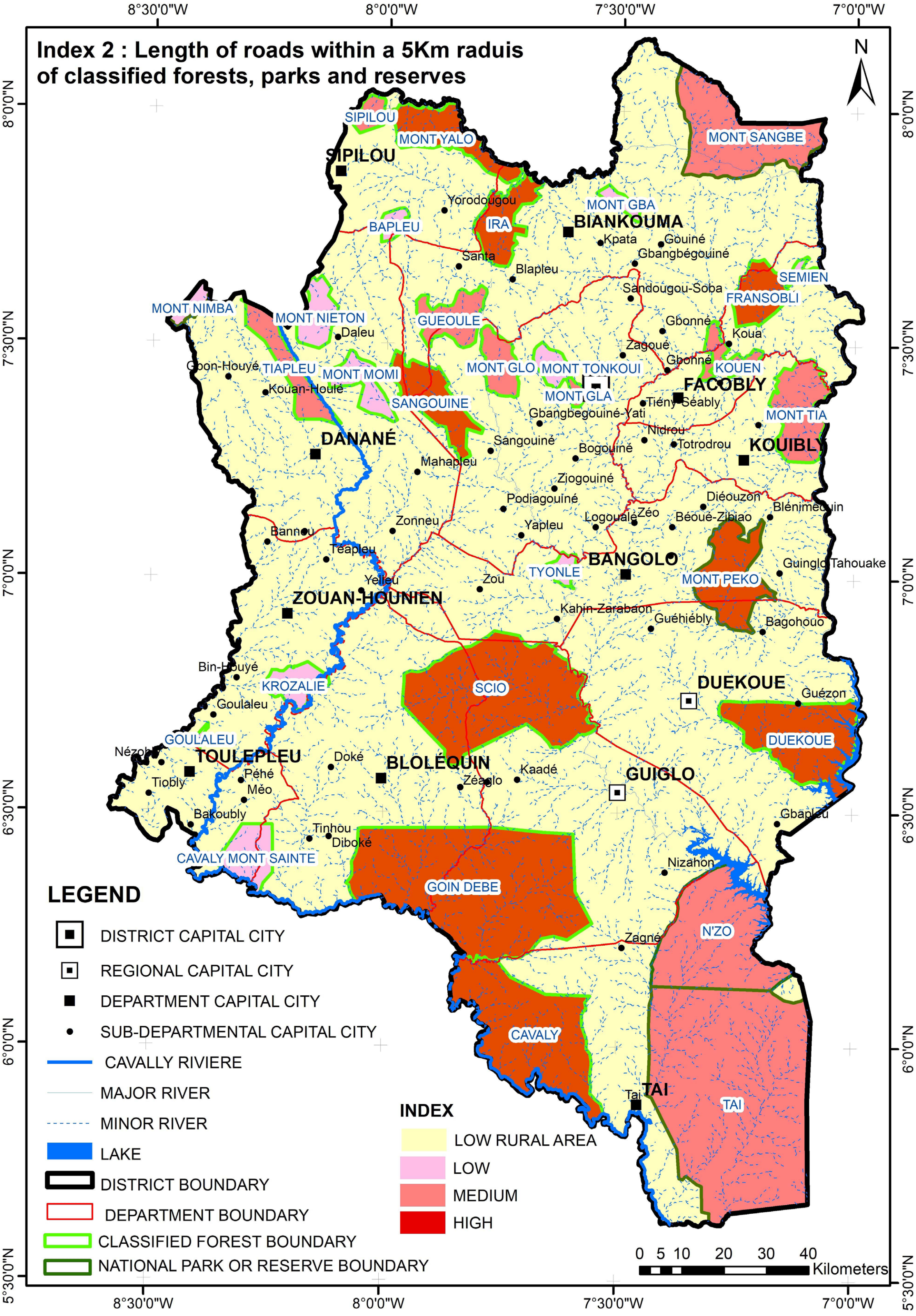

Figure 3. Map of the human-wildlife interactions based on the extent of roadways surrounding classified forests, parks and reserves in the District des Montagnes.

3.2. Spatial Distribution of Human-Wildlife Interactions Based on the Length of Roads within a 5 km Radius of Classified Forests, Parks and Reserves (Index 2)

Index 2 showed human pressure on areas with a high concentration of wildlife, based on the extent in length of roadways within a 5 km radius of classified forests, parks and reserves. The lengths of all roads within this area were counted. This operation yielded road lengths ranging from 119,434 to 325,407 meters. Taking Index 2 into account, the largest classified forests and national parks, in terms of surface, located in the southern part of the District des Montagnes were surrounded by extensive roadways indicating a high level of anthropogenic pressure that could facilitate human-wildlife interactions (**Figure 3**).

3.3. Spatial Distribution of Human-Wildlife Interactions in Relation to the Number of Localities Around Classified Forests, Parks and Reserves (Index 3)

Index 3 characterized human pressure on areas with a high concentration of wildlife as captured by the number of agglomerations within a 5 km radius of classified forests, parks and reserves (**Figure 4**). All localities within this area were counted. This operation resulted in a number of localities ranging from 45 to 504 around the sites of interest. Considering Index 3, the classified forests, parks and reserves located in the central zone of the District des Montagnes faced the highest level of anthropogenic pressure that could enhance human-wildlife interactions.

3.4. Spatial Distribution of Human-Wildlife Interactions in Relation to the Level of Human Infiltration of Classified Forests, Parks and Reserves (Index 4)

Index 4 materialized human pressure on areas with high concentrations of wildlife based on the extent of anthropogenic infiltration of classified forests, parks and reserves. This index indicated values ranging from 0% to 100% infiltration. Taking Index 4 into account, the classified forests on the western edge of the District des Montagnes faced the highest level of human infiltration that facilitated human-wildlife interactions. Classified forests, parks and reserves located in the heart of the District des Montagnes showed a level of human infiltration between 75% and 100% and had low human-wildlife interactions as they have been almost entirely transformed into agricultural land mostly for cocoa plantations (**Figure 5**).

3.5. Spatial Distribution of Human-Wildlife Interactions in Relation to Sub-Prefectural Population Density (Index 5)

Index 5 showed human pressure on areas of high wildlife concentration, based on sub-prefectural population density within a 5 km radius of classified forests, parks and reserves. These data from the 2021 census indicated population densities ranging from 15 to 394 inhabitants per square kilometer. With respect to the sub-prefectural population density, classified forests, particularly those located in the central zone of the District des Montagnes had the highest population density

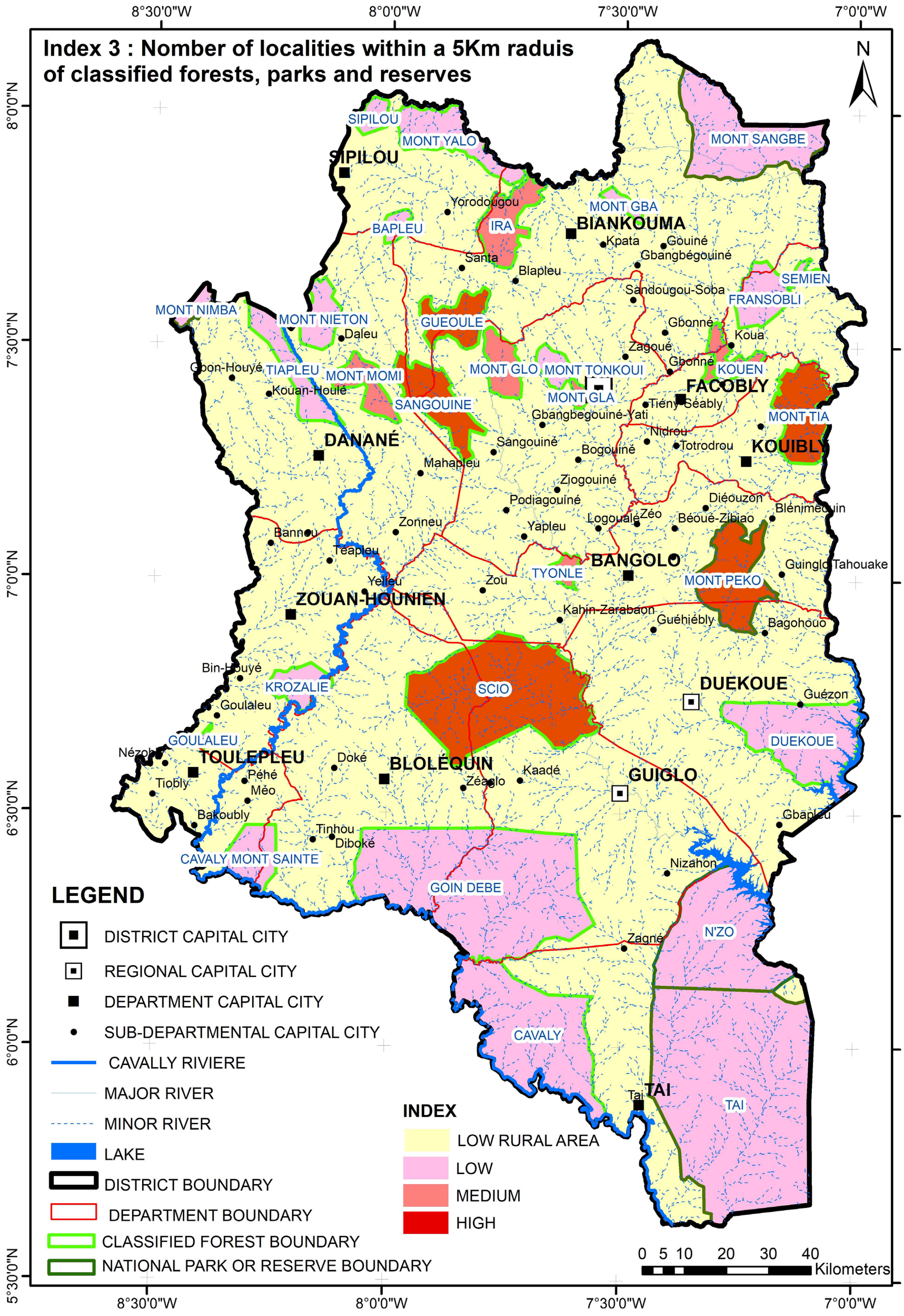

Figure 4. Map of the human-wildlife interactions based on the number of agglomerations around classified forests, parks and reserves in the District des Montagnes.

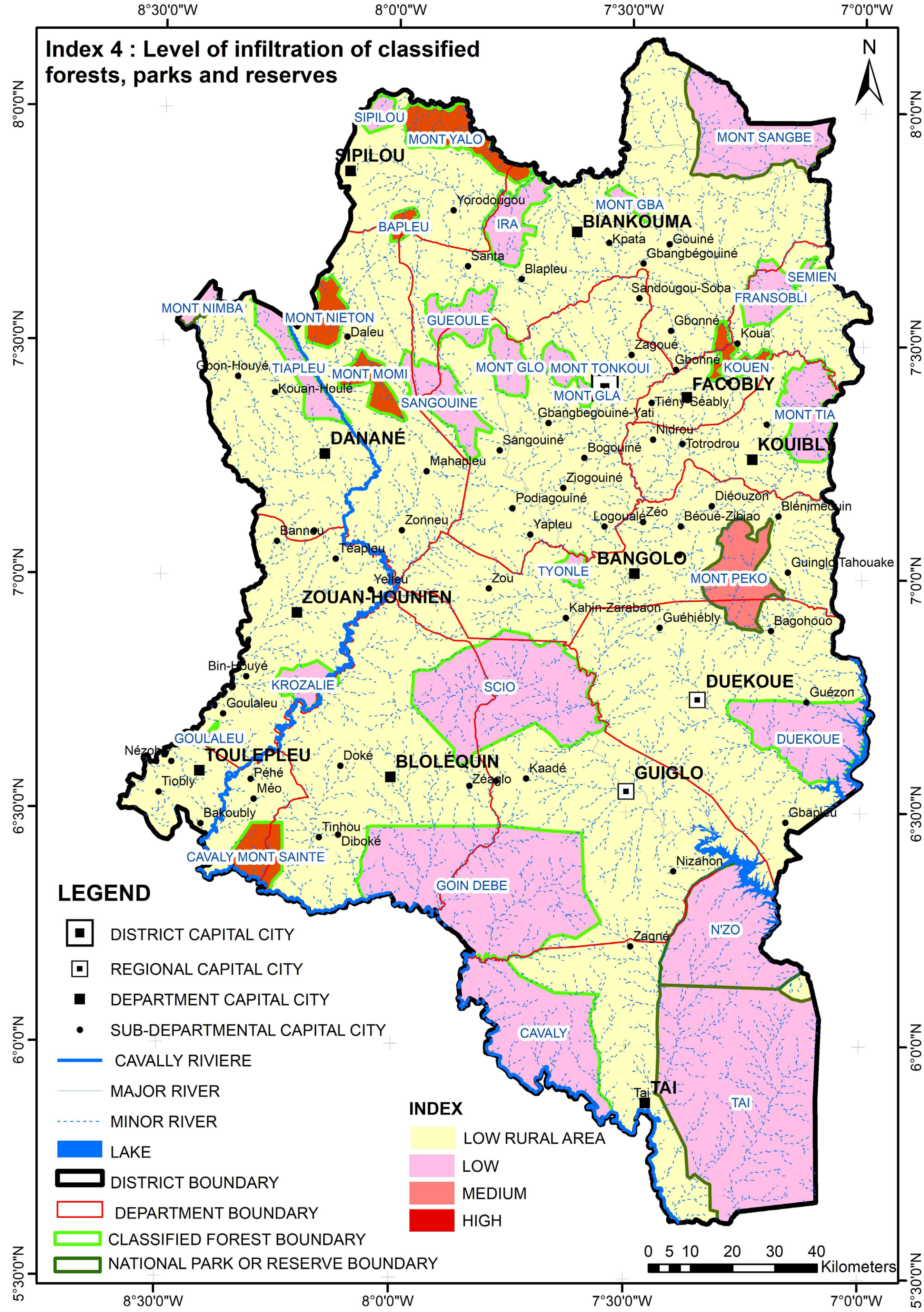

Figure 5. Map of the human-wildlife interactions based on the level of human infiltration of classified forests, parks and reserves in the District des Montagnes.

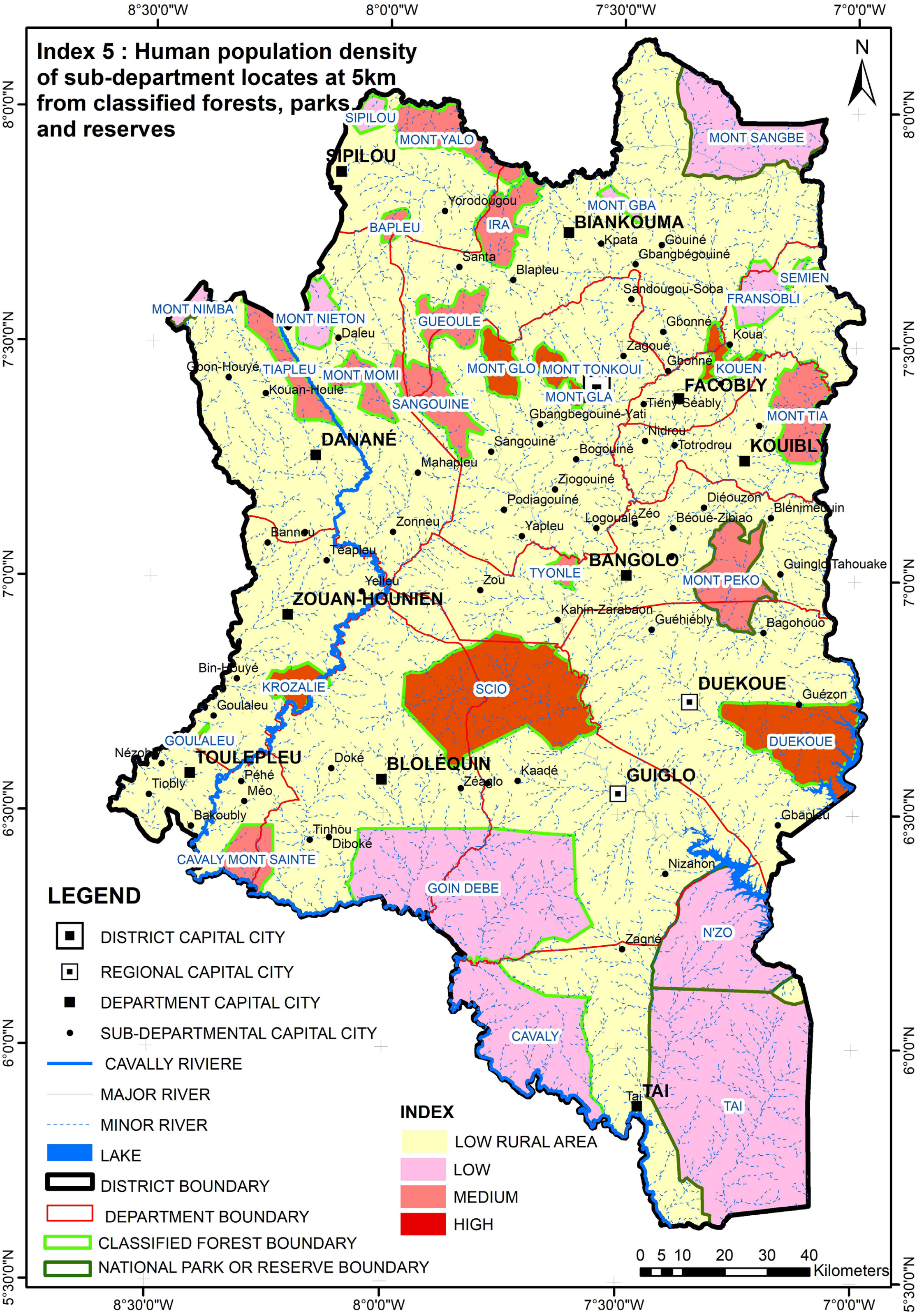

Figure 6. Map of human-wildlife interactions as related to sub-prefectural population density in the District des Montagnes.

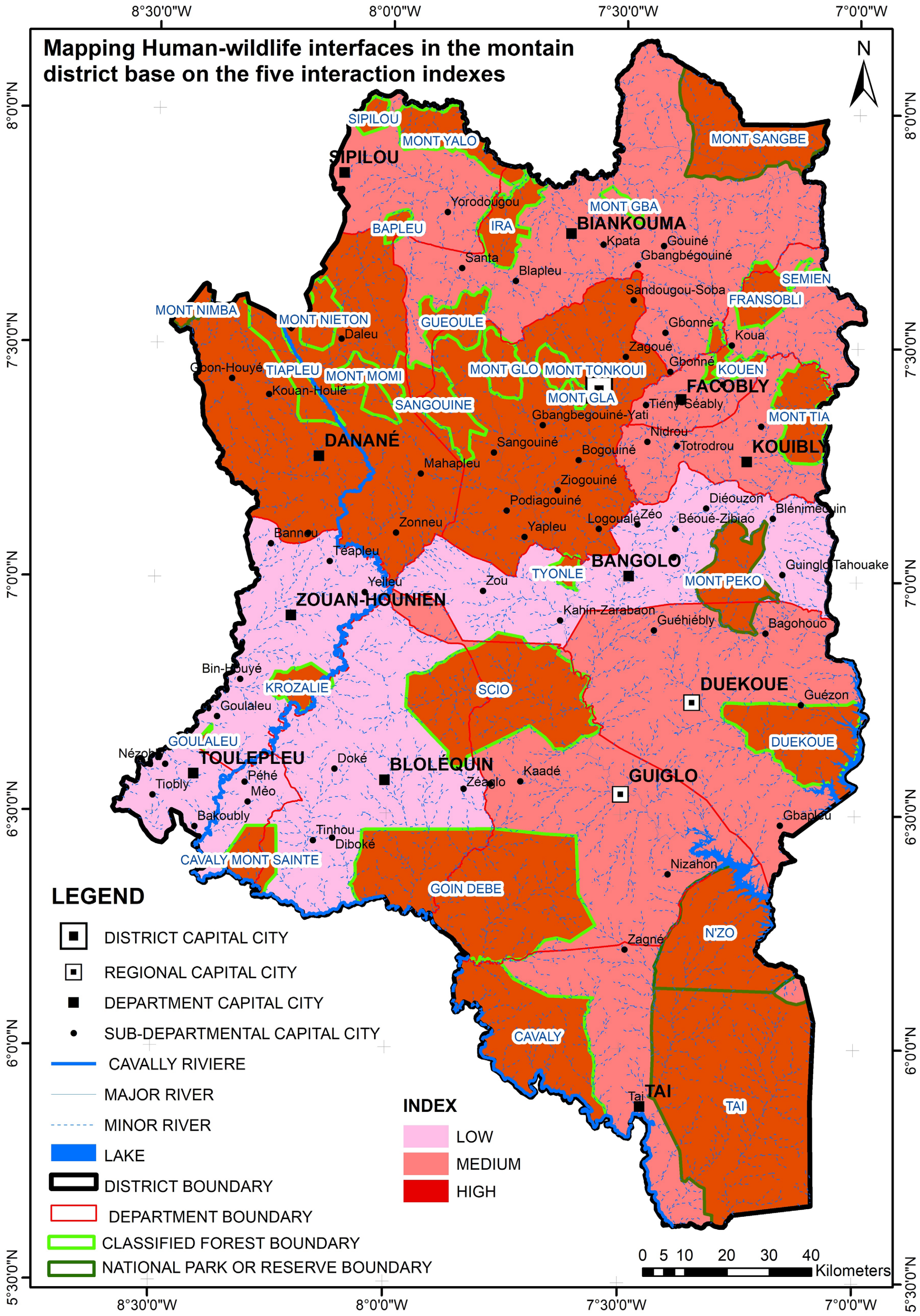

Figure 7. Synthesis map of human-wildlife interfaces with high levels of potential spillovers in the District des Montagnes.

pressure leading to high levels of human-wildlife interactions (**Figure 6**).

3.6. Final Map of the Human-Wildlife Interfaces in the District Des Montagnes Based on the Five Interaction Indices

By merging the spatial distribution of the above five indices, we produced the synthesis map shown in **Figure 7**. This combined map of human-wildlife interactions defines the interfaces where humans and wildlife interact with a potential of pathogens spillover in the District des Montagnes. The combined map particularly showed interfaces located in the departments of Man and Danané as areas of intense human-wildlife interactions (**Figure 7**).

4. Discussion

4.1. Sale and Consumption of Wild Meat

Wild meat consumption is a common practice in many parts of the world, particularly in Southeast Asia and sub-Saharan Africa. In Côte d'Ivoire, the District des Montagnes is home to a large number of natural wildlife reserves. High levels of human-wildlife interactions can be explained by the geographical and ecological context. Man, and Danané, located in the District des Montagnes, are towns surrounded by forests and protected areas that are home to significant biodiversity. They are close to the Mont Sangbé National Park and not far from the Mont Nimba Strict Nature Reserve, a UNESCO World Heritage Site. This proximity to rich natural ecosystems creates a context conducive to human-wildlife interactions. These interactions can occur during the consumption and trade of wild meat. The consumption and trade of wild meat raise significant concerns regarding public health, animal welfare, and environmental conservation [12]. Regarding population health, wild meat consumption can pose significant risks to human health. According to one study, handling and consuming wild meat can expose humans to various zoonotic pathogens, including viruses, bacteria, and parasites [13]. A notable example is the emergence of the Ebola virus, some outbreaks of which have been linked to the handling and consumption of wild meat, including from bats and primates [14]. The wild meat trade can facilitate the transmission of emerging zoonotic diseases, thus representing a potential threat to global public health [15]. Animal health and the environment are also negatively impacted by the sale and consumption of wild meat because of the increase in the demand for wild meat [16]. Furthermore, the loss of certain key species due to hunting can have cascading effects throughout the ecosystem. For example, the decline in large herbivores can alter vegetation structure and affect carbon storage in tropical forests [17]. The sale and consumption of wild meat presents complex challenges at the intersection of public health, wildlife conservation, and environmental management. The high human-wildlife interactions in the departments of Man and Danané may also be explained by the fact that these departments have experienced urban expansion over the past two decades, resulting in a reduction and fragmentation of surrounding natural habitats. According to a study, the departments of

Man and Danané have experienced a significant decrease in their forest cover, mainly due to urbanization and agriculture [18]. Habitat loss increasingly drives wildlife to move into urban and peri-urban areas, resulting in more frequent human-wildlife interactions. Our findings align with previous studies [19]; [20] that have explored the mechanisms of cross-species pathogen transmission at urban-forest interfaces, as well as the relationships between bushmeat hunting, deforestation, and the emergence of zoonotic diseases, particularly in urban areas adjacent to forested regions. These studies respectively examined the mechanisms of pathogen transmission between species, for urban-forest interfaces and the links between wild meat hunting, deforestation and the emergence of zoonoses, particularly for urban areas close to forests.

4.2. Length of Roadways within a 5 km Radius of Classified Forests, Parks, and Reserves

The presence and extent of road networks near protected areas can have significant effects on various aspects of ecosystem and human health. The proximity of roads to protected areas can influence public health in several ways. Roads facilitate human access to natural habitats and related resources extraction, increasing human-wildlife interactions. This increased interaction can promote the transmission of zoonotic diseases [21]. For example, road construction in the Brazilian Amazon has been associated with an increase in human malaria cases [22]. The presence of roads near protected areas can significantly affect the health and behavior of wildlife. Roads fragment natural habitats, creating barriers that can disrupt animal movements, their access to resources, and their genetic diversity [23]. This fragmentation can lead to increased stress and a decline in animal populations. The proximity of roads increases the risk of collisions between vehicles and animals. These collisions can have significant impacts on animal populations, particularly for species with low reproductive rates [24]. Noise and light associated with road traffic can disrupt animals' natural behaviors. For example, a study showed that anthropogenic noise can affect the acoustic communication of birds, influencing their reproduction and survival [25]. Roads near protected areas can have profound effects on the ecological integrity of ecosystems. A Study demonstrated that roads act as "backbones" of deforestation, facilitating access to previously untouched areas [26]. Within a 5 km radius, this effect can be particularly pronounced, leading to significant habitat loss and degradation. Roads are sources of various pollutants, including heavy metals and hydrocarbons. A study made by Trombulak and Frissell showed that these pollutants can leach into adjacent soils and streams, affecting water quality and the health of aquatic ecosystems [27]. Roads can facilitate the spread of invasive species. According to Lippe and Kowarik, vehicles can transport seeds of exotic species over long distances, threatening the ecological integrity of protected areas [28]. The length of roads within a 5km radius of protected forests, parks, and reserves can have significant and interconnected impacts on public, animal, and environmental health. These effects underscore the importance of careful planning of road infrastructure near protected areas. Mapping them could help develop integrated management approaches, including the establishment of wildlife crossings, speed limits, the use of noise-reducing road surfaces, and the creation of buffer zones between roads and sensitive habitats. Furthermore, this mapping will support ongoing monitoring and rigorous environmental impact assessments, essential for understanding and managing the long-term effects of road networks on the health of ecosystems and human populations near protected areas.

4.3. Number of Agglomerations within a 5 km Radius of Classified Forests, Parks, and Reserves

The proximity and density of human settlements around protected areas can have significant effects on various aspects of ecosystem and human health. High human population density near natural habitats increases human-wildlife interactions, which can promote the transmission of zoonotic diseases. Approximately 60% of emerging diseases are of zoonotic origin, and proximity to wildlife is a significant risk factor [1]. For example, a study highlighted that land-use changes, including the establishment of communities near forests, can increase the risk of diseases such as malaria and leishmaniasis. Increased human presence can induce chronic stress in wildlife [21]. According to Zbyryt *et al.*, 2018, even seemingly benign human activities can increase stress levels in animals, affecting their health and behavior [29]. This human presence can increase human-wildlife conflicts. Woodroffe showed that these conflicts can lead to injuries or deaths of wildlife, as well as economic losses for local communities [30]. Proximity to human settlements can facilitate disease transmission from domestic animals to wildlife. For example, Craft studied how proximity to villages affects the transmission of canine distemper from domestic dogs to lions in the Serengeti. Increasing the number of localities around protected areas can lead to increased habitat fragmentation and degradation [31]. According to Haddad, habitat fragmentation can reduce biodiversity by up to 75% and disrupt essential ecosystem functions [10]. A greater number of localities can put increased pressure on natural resources in protected areas. Golden showed how local communities' reliance on wild meat can affect wildlife in protected areas in Madagascar [32]. Mapping these habitation areas near protected areas will support ongoing disease surveillance, monitoring and interdisciplinary research essential for understanding and managing the complex interactions between human habitats and protected ecosystems, in order to promote the health and well-being of both human populations and natural systems. Increased human-wildlife contact due to infiltration increases the risk of zoonotic disease transmission.

4.4. Level of Infiltration of Classified Forests, Parks, and Reserves

Human infiltration into protected areas can have significant public health consequences. For example, a study showed that hunting and wild meat consumption in Central Africa, often linked to illegal infiltration, have been linked to the emergence of diseases such as HIV and Ebola [33]. Infiltration into forest ecosystems can expose human populations to new disease vectors. Patz pointed out that land-use changes, including infiltration into forests, can increase exposure to vectors such as mosquitoes that carry malaria or dengue fever [21]. Infiltration can lead to the uncontrolled use of natural resources, including medicinal plants. According to Shanley and Luz, this unregulated exploitation can pose public health risks due to the inappropriate use or contamination of these resources [34]. Human infiltration can facilitate the transmission of diseases from humans or domestic animals to wildlife. For example, a study documented the transmission of bovine tuberculosis from domestic animals to lions in Kruger National Park in South Africa, a problem exacerbated by illegal livestock infiltration [35]. Infiltration is often associated with poaching, which can have direct impacts on the health of animal populations. Ripple *et al.* (2016) highlighted how intensive poaching not only threatens the survival of many species but also disrupts the ecological balance of ecosystems [36]. The level of infiltration of classified forests, parks, and reserves can have significant impacts on public health and the environment. Mapping these infiltrated areas will therefore enable the strengthening of disease surveillance and law enforcement, the involvement of local communities in resource management, environmental education, and the implementation of policies that promote sustainable livelihoods for populations living near or within protected areas.

4.5. Sub-Prefectural Population Density within a 5 km Radius of Classified Forests, Parks and Reserves

Similar to the concentration of localities within a 5 km radius of areas with a high presence of wildlife, taking into account the sub-prefectural population density indicates that classified forests, particularly those located in the central area of the district, are those with the highest levels of human-wildlife interaction. The central part of the mountain district is home to cosmopolitan cities such as Duekoué, the regional capital, Bangolo and Zouan-Houenien, departmental capitals, and several cities (Guézon, Zéaglo, Kaadé, Gbapleu, etc.), sub-prefectural capitals. The central part of the District des Montagnes is also home to many classified forests, notably those of Duekoué, Scio, and Krozalie. Although classified, these forests have an infiltration rate of between 75% and 100%. However, when sub-prefectural populations settle and concentrate within a 5 km radius of forests in general, or even classified forests or specific parks and reserves, daily activities such as collecting firewood, small-scale agriculture, livestock grazing, and hunting gradually develop and lead populations to regularly come into contact with wild reservoirs and arthropod vectors. These repeated contacts, even in small doses, increase the likelihood of exposure and can increase the number of susceptible hosts interacting with wildlife. This increases the risk of a spread event occurring and persisting [37]. Plowright and colleagues formalized how exposure frequency, pathogen excretion dynamics in reservoir hosts, and susceptibility of receptor hosts jointly determine the probability of spread. In addition to direct contact, vector-borne transmission routes are sensitive to population growth and land use concentrated near protected areas. Peri-urban and peri-forest environments often create mosaics of water reservoirs and irrigated fields that promote vector reproduction and increase encounters between humans and vectors. Studies mapping the risks of mosquito-borne diseases show that human-created microhabitats in forest fringe areas increase vector abundance and bite rates [38]. At the same time, domestic animals raised in peripheral areas serve as intermediate hosts: pigs, goats, and domestic poultry, which reach high densities near villages, often contribute to amplifying or maintaining viruses [38]. It should also be noted that population density within a 5 km radius of parks and reserves influences not only contact rates but also the ecological composition of wildlife. Fragmentation caused by roads, smallholder clearing, and resource extraction reduces the habitat of specialized predators and large vertebrates, while favoring reservoir species and synanthropic rodents. This resulting reshaping of wildlife often increases the relative abundance of hosts, which in turn increases the prevalence of pathogens [38]. Empirical analyses of Ebola epidemics and other viral outbreaks have linked recent forest loss and fragmentation near human settlements to an increased likelihood of epidemics highlighting how densely populated forest edges transform ecological networks into landscapes more conducive to pathogens [39] [40]. The Nipah virus outbreaks in Bangladesh provided an instructive example of how activities carried out in close proximity to bat roosts and fragmented forest plots have facilitated the spread of the virus [40]. Luby and his colleagues showed how date palm sap collection and domestic animal husbandry near bat feeding sites led to repeated infections in humans and pigs, amplified by the density and lack of regulation of human settlements. In West and Central Africa, spatial analyses have demonstrated associations between recent local deforestation near human communities and the emergence of the Ebola virus, highlighting the interaction between demographic encroachment and habitat change [40]. In the Americas, hantavirus pulmonary syndrome has been attributed to rural dwellings on the edge of forests, where rodent population density, favored by anthropogenic landscape features, has increased human exposure [41]. Despite these results, which will certainly contribute to the development of monitoring plans, there are some limitations that should be noted. The different spatial scales of data collection can be considered a limitation of this study. For example, data on wildlife sales and consumption sites were collected at the prefectural level, while data on population densities are at a sub-prefectural scale. Although data on forest infiltration levels were estimated by managers of the various areas and are therefore relatively up-to-date, the data on national vegetation cover available at the time of this study are old (2016) and should be updated.

5. Conclusion

The present study mapped key human-wildlife interfaces with the potential of pathogens spillovers. It particularly highlighted that Man and Danané are the departments with the highest human-wildlife interactions. It also revealed the influence of roads, population density around parks and reserves, and the degree of forest infiltration on human-wildlife interactions. In addition to these elements, the study highlighted the importance of GIS approaches in locating human-wildlife interfaces in the District des Montagnes. Mapping wild meat consumption and sales areas, road lengths, the number of settlements around classified forests, parks and reserves, and infiltration levels could help to better identify these areas and take appropriate measures. In addition, this mapping will assist in ongoing monitoring and rigorous environmental impact assessments, which are essential for understanding and managing the long-term effects of road networks on the health of ecosystems and human populations near protected areas. The results of this study will also help the human, animal and environmental sectors target their health activities such as health education and communication as well as disease surveillance. The government will prioritize education, information sharing and participatory surveillance programs to target populations located in areas with high animal and human interactions such as Danané and Man. Local government will use the results of this study to monitor town expansions driven by various anthropogenic activities leading to encroachment of protected areas. Areas with important roadways that facilitate animal and forest products flow could be identified and serve as key disease control points.

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Author Contributions

The study was conceptualized by MAM and SND, the methodology was designed by SND, DHN, and MAM and then validated by KD, the software used and data analysis were performed by BEK and DHN. The article was written by MAM and AMYE and then reviewed by all authors. GL was responsible for project administration. All authors have read and agree to the publication of this manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Jones, K.E., Patel, N.G., Levy, M.A., Storeygard, A., Balk, D., Gittleman, J.L., *et al.* (2008) Global Trends in Emerging Infectious Diseases. *Nature*, **451**, 990-993. https://doi.org/10.1038/nature06536

[2] Mahase, E. (2020) Coronavirus: COVID-19 Has Killed More People than SARS and MERS Combined, Despite Lower Case Fatality Rate. *BMJ*, **368**, m641. https://doi.org/10.1136/bmj.m641

[3] Hatta, M., Gao, P., Halfmann, P. and Kawaoka, Y. (2001) Molecular Basis for High Virulence of Hong Kong H5N1 Influenza a Viruses. *Science*, **293**, 1840-1842. https://doi.org/10.1126/science.1062882

[4] Webster, R.G. (1998) Influenza: An Emerging Disease. *Emerging Infectious Diseases*, **4**, 436-441. https://doi.org/10.3201/eid0403.980325

[5] Monne, I., Fusaro, A., Nelson, M.I., Bonfanti, L., Mulatti, P., Hughes, J., *et al.* (2014) Emergence of a Highly Pathogenic Avian Influenza Virus from a Low-Pathogenic Progenitor. *Journal of Virology*, **88**, 4375-4388. https://doi.org/10.1128/jvi.03181-13

[6] Varela, K., Goryoka, G., Suwandono, A., Mahero, M., Valeri, L., Pelican, K., *et al.* (2022) One Health Zoonotic Disease Prioritization and Systems Mapping: An Integration of Two One Health Tools. *Zoonoses and Public Health*, **70**, 146-159. https://doi.org/10.1111/zph.13015

[7] Mamadou, Y., Vessaly, K., Aristide, Z., Lendzele, S., Ouattara, D. and Lydie, A. (2025) Prevalence and Risk Factors of Rabies in Côte d'ivoire from 2020 to 2023. *Open Veterinary Journal*, **3**, Article No. 1488. https://doi.org/10.5455/ovj.2025.v15.i3.38

[8] Siam, Z.S., Hasan, R.T., Anik, S.S., Noor, F., Adnan, M.S.G., Rahman, R.M., *et al.* (2022) National-Scale Flood Risk Assessment Using GIS and Remote Sensing-Based Hybridized Deep Neural Network and Fuzzy Analytic Hierarchy Process Models: A Case of Bangladesh. *Geocarto International*, **37**, 12119-12148. https://doi.org/10.1080/10106049.2022.2063411

[9] Pitt, S.J. and Gunn, A. (2024) The One Health Concept. *British Journal of Biomedical Science*, **81**, Article No. 12366. https://doi.org/10.3389/bjbs.2024.12366

[10] Haddad, N.M., Brudvig, L.A., Clobert, J., Davies, K.F., Gonzalez, A., Holt, R.D., *et al.* (2015) Habitat Fragmentation and Its Lasting Impact on Earth's Ecosystems. *Science Advances*, **1**, e1500052. https://doi.org/10.1126/sciadv.1500052

[11] Pérez-Fernández, O. and Michel, G.R. (2025) Spatial Accessibility to Healthcare Facilities: GIS-Based Public-Private Comparative Analysis Using Floating Catchment Methods. *ISPRS International Journal of Geo-Information*, **14**, Article 253. https://doi.org/10.3390/ijgi14070253

[12] Marchiori, E., Bono, L., Voltan, L., Dotto, G., Tessarin, C. and Marcer, F. (2024) Gastrointestinal Parasites in Non-Human Primates in Zoological Gardens in Northern Italy. *Animals*, **14**, Article 2607. https://doi.org/10.3390/ani14172607

[13] Tumelty, L., Fa, J.E., Coad, L., Friant, S., Mbane, J., Kamogne, C.T., *et al.* (2023) A Systematic Mapping Review of Links between Handling Wild Meat and Zoonotic Diseases. *One Health*, **17**, Article 100637. https://doi.org/10.1016/j.onehlt.2023.100637

[14] Naa, C. Lokko, M. and Lokko F.O. (2025) Epidemiology of Human Ebola virus Disease Outbreak in Sub-Saharan Africa. https://www.researchgate.net/publication/389295665

[15] Mahanta, K. and Sulabh, S. (2025) Zoonotic Spillovers: How Climate Change, Habitat Destruction, and Bushmeat Trade Might Amplify Bat-Driven Viral Disease Risks.

European Journal of Wildlife Research, **71**, 1-20. https://doi.org/10.1007/s10344-025-01951-2

[16] Ingram, D.J., Froese, G.Z.L., Carroll, D., Bürkner, P.C., Maisels, F., Abugiche, A.S., *et al.* (2025) Regional Patterns of Wild Animal Hunting in African Tropical Forests. *Nature Sustainability*, **8**, 202-214. https://doi.org/10.1038/s41893-024-01494-5

[17] Brodie, J.F., Bello, C., Emer, C., Galetti, M., Luskin, M.S., Osuri, A., *et al.* (2025) Defaunation Impacts on the Carbon Balance of Tropical Forests. *Conservation Biology*, **39**, e14414. https://doi.org/10.1111/cobi.14414

[18] Cuny, P., Plancheron, F., Bio, A., Kouakou, E. and Morneau, F. (2023) La forêt et la faune de Côte d'Ivoire dans une situation alarmante—Synthèse des résultats de l'Inventaire forestier et faunique national. *Bois & Forets des Tropiques*, **355**, 47-72. https://doi.org/10.19182/bft2023.355.a36939

[19] Borremans, B., Faust, C., Manlove, K.R., Sokolow, S.H. and Lloyd-Smith, J.O. (2019) Cross-species Pathogen Spillover across Ecosystem Boundaries: Mechanisms and Theory. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **374**, Article 20180344. https://doi.org/10.1098/rstb.2018.0344

[20] Murphy, K.J., Byrne, A.W., Marples, N., O'Hagan, M.J.H., Kelly, D.J., Quinn, D., *et al.* (2025) Wildlife Response to Land-Use Change Forces Encounters between Zoonotic Disease Hosts and Farms in Agricultural Landscapes. *Agriculture, Ecosystems & Environment*, **386**, Article 109561. https://doi.org/10.1016/j.agee.2025.109561

[21] Patz, J.A., Daszak, P., Tabor, G.M., Aguirre, A.A., Pearl, M., Epstein, J., *et al.* (2004) Unhealthy Landscapes: Policy Recommendations on Land Use Change and Infectious Disease Emergence. *Environmental Health Perspectives*, **112**, 1092-1098. https://doi.org/10.1289/ehp.6877

[22] Esposito, M.M., Turku, S., Lehrfield, L. and Shoman, A. (2023) The Impact of Human Activities on Zoonotic Infection Transmissions. *Animals*, **13**, Article 1646. https://doi.org/10.3390/ani13101646

[23] Duquette, C.A., Loss, S.R. and Hovick, T.J. (2021) A Meta-Analysis of the Influence of Anthropogenic Noise on Terrestrial Wildlife Communication Strategies. *Journal of Applied Ecology*, **58**, 1112-1121. https://doi.org/10.1111/1365-2664.13880

[24] Berkhout, B.W., Budria, A., Thieltges, D.W. and Slabbekoorn, H. (2023) Anthropogenic Noise Pollution and Wildlife Diseases. *Trends in Parasitology*, **39**, 181-190. https://doi.org/10.1016/j.pt.2022.12.002

[25] Kight, C.R. and Swaddle, J.P. (2011) How and Why Environmental Noise Impacts Animals: An Integrative, Mechanistic Review. *Ecology Letters*, **14**, 1052-1061. https://doi.org/10.1111/j.1461-0248.2011.01664.x

[26] Laurance, W.F., Goosem, M. and Laurance, S.G.W. (2009) Impacts of Roads and Linear Clearings on Tropical Forests. *Trends in Ecology & Evolution*, **24**, 659-669. https://doi.org/10.1016/j.tree.2009.06.009

[27] Trombulak, S.C. and Frissell, C.A. (2000) Review of Ecological Effects of Roads on Terrestrial and Aquatic Communities. *Conservation Biology*, **14**, 18-30. https://doi.org/10.1046/j.1523-1739.2000.99084.x

[28] von der Lippe, M. and Kowarik, I. (2007) Long-Distance Dispersal of Plants by Vehicles as a Driver of Plant Invasions. *Conservation Biology*, **21**, 986-996. https://doi.org/10.1111/j.1523-1739.2007.00722.x

[29] Zbyryt, A., Bubnicki, J.W., Kuijper, D.P.J., Dehnhard, M., Churski, M. and Schmidt, K. (2018) Do Wild Ungulates Experience Higher Stress with Humans than with Large Carnivores? *Behavioral Ecology*, **29**, 19-30. https://doi.org/10.1093/beheco/arx142

[30] Woodroffe, R., Thirgood, S. and Rabinowitz, A. (2005) People and Wildlife, Conflict or Co-Existence? Cambridge University Press.

[31] Carignano Torres, P., Morsello, C., Orellana, J.D.Y., Almeida, O., de Moraes, A., Chacón-Montalván, E.A., *et al.* (2022) Wildmeat Consumption and Child Health in Amazonia. *Scientific Reports*, **12**, 1-14. https://doi.org/10.1038/s41598-022-09260-3

[32] Golden, C.D., Fernald, L.C.H., Brashares, J.S., Rasolofoniaina, B.J.R. and Kremen, C. (2011) Benefits of Wildlife Consumption to Child Nutrition in a Biodiversity Hotspot. *Proceedings of the National Academy of Sciences*, **108**, 19653-19656. https://doi.org/10.1073/pnas.1112586108

[33] Wolfe, N.D., Daszak, P., Kilpatrick, A.M. and Burke, D.S. (2005) Bushmeat Hunting, Deforestation, and Prediction of Zoonotic Disease. *Emerging Infectious Diseases*, **11**, 1822-1827. https://doi.org/10.3201/eid1112.040789

[34] Brandão, D.O., Barata, L.E.S. and Nobre, C.A. (2022) The Effects of Environmental Changes on Plant Species and Forest Dependent Communities in the Amazon Region. *Forests*, **13**, Article 466. https://doi.org/10.3390/f13030466

[35] Woodroffe, R., Donnelly, C.A., Cox, D.R., Bourne, F.J., Cheeseman, C.L., Delahay, R.J., *et al.* (2006) Effects of Culling on Badger *Meles meles* Spatial Organization: Implications for the Control of Bovine Tuberculosis. *Journal of Applied Ecology*, **43**, 1-10. https://doi.org/10.1111/j.1365-2664.2005.01144.x

[36] Ripple, W.J., Abernethy, K., Betts, M.G., Chapron, G., Dirzo, R., Galetti, M., *et al.* (2016) Bushmeat Hunting and Extinction Risk to the World's Mammals. *Royal Society Open Science*, **3**, Article 160498. https://doi.org/10.1098/rsos.160498

[37] Plowright, R.K., Parrish, C.R., McCallum, H., Hudson, P.J., Ko, A.I., Graham, A.L., *et al.* (2017) Pathways to Zoonotic Spillover. *Nature Reviews Microbiology*, **15**, 502-510. https://doi.org/10.1038/nrmicro.2017.45

[38] Keesing, F., Belden, L.K., Daszak, P., Dobson, A., Harvell, C.D., Holt, R.D., *et al.* (2010) Impacts of Biodiversity on the Emergence and Transmission of Infectious Diseases. *Nature*, **468**, 647-652. https://doi.org/10.1038/nature09575

[39] Olivero, J., Fa, J.E., Real, R., Márquez, A.L., Farfán, M.A., Vargas, J.M., *et al.* (2017) Recent Loss of Closed Forests Is Associated with Ebola Virus Disease Outbreaks. *Scientific Reports*, **7**, Article No. 14291. https://doi.org/10.1038/s41598-017-14727-9

[40] Rulli, M.C., Santini, M., Hayman, D.T.S. and D'odorico, P. (2017) The Nexus between Forest Fragmentation in Africa and Ebola Virus Disease Outbreaks. *Scientific Reports*, **7**, Article No. 41613. https://doi.org/10.1038/srep41613

[41] Luby, S.P., Gurley, E.S. and Hossain, M.J. (2009) Transmission of Human Infection with Nipah Virus. *Clinical Infectious Diseases*, **49**, 1743-1748. https://doi.org/10.1086/647951