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A Conceptual Approach to Modeling the Geospatial Impact of Typical Urban Threats on the Habitat Quality of River Corridors

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Abstract: While for most of a landscape, urbanization leads to a significant habitat loss, rivers in urban areas are usually maintained or developed for their drainage function. Rivers are often the most important biophysical and ecological connection of cities with their surrounding ecosystems, although usually heavily altered due to urban impacts. For the conservation of urban rivers as ecological corridors, it is important to assess the impact of typical urban threats on habitat quality. In this study, we used the InVEST (Integrated Valuation of Environmental Services and Trade-offs) habitat quality model to assess the individual and combined impacts of built-up areas, first- and second-order road and water pollution from urban drainage, and wastewater discharge on habitat quality within a 200 m wide river corridor. The Pochote River in León, Nicaragua, was used as a case study. Our results show the spatial distribution and magnitude of the individual threat impacts, as well as the respective contribution of each threat to the overall impact of urbanization on the habitat quality within the river corridor. While close to the city center, all threats almost equally contributed to severe habitat degradation, while further downstream, an individual threat influence became more distinct with only water pollution having a consistent negative impact. We concluded that the InVEST habitat quality model can be used to assess the impact of typical urban threats on habitat quality in river corridors at a high spatial resolution. The results can help to improve urban planning and development to improve habitat conservation along urban rivers.

Keywords: spatial modeling; urbanization; threats; river corridor; habitat quality; biodiversity conservation; remote sensing; InVEST; Nicaragua

1. Introduction

The recently published Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) report on biodiversity and ecosystem services documented a hitherto unprecedented decline of nature along with an accelerating rate of species going extinct. According to the report, 75% of the earth's land surface has been significantly altered, 66% of the ocean area is experiencing increasing cumulative impacts, and over 85% of wetlands have been lost due to human activity. Unless action is taken to reduce the current drivers of biodiversity loss, it is suggested that around 1 million species will face extinction (around 25% of species are threatened), and many of those within decades [1]. The global rate of species extinction is already at least tens to hundreds of times higher than it has averaged over the past 10 million years and without action, this rate will further accelerate. Such acceleration will have devastating consequences for people across the world [2].

The five greatest drivers of biodiversity loss are changes in land and sea use, direct exploitation of organisms, climate change, pollution, and invasion of alien species. Out of these drivers, changes in land and sea use has had the greatest impact on biodiversity loss, directly leading to both habitat loss and fragmentation. Land-use change has had the largest relative negative impact on terrestrial and freshwater ecosystems since 1970, followed by their direct exploitation, in particular overexploitation, of animals, plants, and other organisms, mainly via harvesting, logging, hunting, and fishing. While agricultural expansion is the most widespread form of land-use change, with over one-third of the terrestrial land surface being used for cropping or animal husbandry, within land-use change, urban areas have more than doubled since 1992. This has come mostly at the expense of forests, wetlands, and grasslands. In freshwater ecosystems, a series of combined threats involving land-use change, including water extraction, exploitation, pollution, climate change, and invasive species, are prevalent. Man-made infrastructures, such as the expansions of road networks, built-up areas, hydroelectric dams, and oil and gas pipelines can come with high environmental and social costs, including deforestation, habitat fragmentation, and biodiversity loss [1].

Rivers remain the most important biophysical and ecological connection of cities to their surrounding ecosystems (connectivity function as an ecological corridor), although this is often altered due to urban impacts. This makes rivers in urban areas a very important ecological feature and habitat for maintaining biodiversity. While for most of a landscape, urbanization leads to a complete land-use change, rivers in urban areas are usually maintained for their drainage function. Since there is a significant need to drain excess stormwater and to discharge wastewater from urban areas, rivers are used as receiving water bodies due to their topography [3]. However, when rivers are excessively used for stormwater and wastewater drainage (especially when the drained waters are not or not sufficiently treated), other functions of a river corridor (e.g., recreational and ecological functions) are lost [4,5]. It is important to create awareness regarding the potential of rivers to provide ecosystem services before they are completely lost.

The threat to biodiversity, despite its importance for maintaining habitat quality, has motivated specific habitat quality model development. These numerical models both estimate habitat quality based on land-use/land-cover characteristics and the impacts of threats [6–9]. Both habitat quality and the impact of threats provide crucial information for making correct habitat and biodiversity conservation decisions [10]. For the assessment of habitats, a large number of remote-sensing-based tools and methods, with specific strengths and limitations, have been developed [8].

However, the costs for data and software remains a challenge [8]. The open-source software suite InVEST (Integrated Valuation of Environmental Services and Trade-offs) [11], provides a habitat quality assessment model that integrates readily available spatial data on land use and land cover (LULC), anthropogenic threats to biodiversity, and expert knowledge to assess changes in habitat quality as a proxy for biodiversity [11]. It has been applied to terrestrial ecosystems [12,13] and large river basins [14], among others, but not yet for urban river corridors and specific threats of urban areas. Such a small-scale application (<10 km^2) of the InVEST model in an urban context, including specific habitat threats such as water contamination due to untreated wastewater discharge, is novel. Hence, the purpose of this work was to analyze the applicability of the InVEST Habitat Quality Model to urban river ecosystems and specific threats related to urbanization. By applying the model to a case study of an urban river corridor of the City of León in Nicaragua, the individual impact of each threat and the impact of all threats together were analyzed, as well as their influence on the habitat quality. The main aim of this study was to provide guidance on how the habitat quality of urban river corridors in developing countries can be assessed by including typical urban threats to derive recommendations for habitat protection and the control of habitat degradation.

2. Methods

2.1. Study Area

A 200 m wide corridor along the Pochote River in the north of the city of León in Nicaragua represents the study area. With around 180,000 inhabitants, Nicaragua's second-largest city is located about 93 km northwest of the country's capital Managua [15]. The Pochote River flows in a southwest direction along the city boundary for about 6 km, for a few kilometers after leaving the city limits, where it confluents after 14.2 km of flow length with the Chiquito River, another river of the city of León, forming a common river basin that leads to the Pacific Ocean. Its drainage area is 61.42 km^2. The study area has a tropical savannah climate with a rainy season from May to October and a pronounced dry season from November to April. The average monthly precipitation in the rainy season ranges from 300 to 500 mm, whereas during the dry season, there is almost no rainfall. The average daily temperature lies between 27 to 29 °C, with the lowest values found between December and February [16].

An overview of the study area is given in Figure 1. The source area of the Pochote River located inside the city is composed of three river branches, each approximately 1 km in length. Although it is located in an urbanized area, access to the river is limited due to the canyon-like topography. The three branches merge along the mid-course of the river into a single stream channel, which then meanders and forms floodplains when flowing downstream in a western direction (Figure 1). The distinct hydromorphological characteristics of the source area and the mid- and lower-course of the river resulted in different ecological conditions, as well as influenced different formal and informal settlement patterns along the river corridor. As illustrated in Figure 1, the settlement diversity along the river shores ranges from historical formally and densely urbanized regions (1) to informal urban–rural transitional regions (2) and recent formal rural settlements (3). While the formal settlements are intentionally developed by the municipality, the informal settlements are not. In a formal settlement development, gradual infrastructure development is intended. Thus, buildings and streets are arranged for a later implementation of a water supply, a drainage network, and wastewater treatment. In informal settlements, buildings and streets often develop spontaneously without infrastructural planning. In the downstream section (4) in Figure 1, the river is far less impacted by urban development and the land cover within the river corridor is less disturbed. A highly fragmented landscape exists due to this settlement and ecological diversity. Amongst the drivers of habitual fragmentation in this region are the inefficient operation of the local wastewater treatment plants and sewerage system, direct wastewater discharge from households along the shore, hydraulic stress due to stormwater runoff from sealed surfaces, deforestation of riparian areas, and uncontrolled garbage burning and disposal [17]. In the north area of the river corridor, intensive industrial agriculture (mostly peanut cultivation north of the middle river course and sugar cane west and north of the lower river course) is practiced, which causes additional environmental problems. In some parts, this agricultural land use invades the river corridor (see Figure 1).

However, the river water and numerous natural wells close to the river are regularly used by residents, especially those in more rural settlements along the river, in their daily lives (e.g., for household duties and livestock needs; [17]). The natural wells deliver significant amounts of clean water to the river even during the dry season from November to April, when the main river is fed only by wastewater from households. The contribution from natural wells leads to an important dilution of wastewater, and together with the natural morphology of the river, this results in a continuous improvement of the water quality downstream [4].

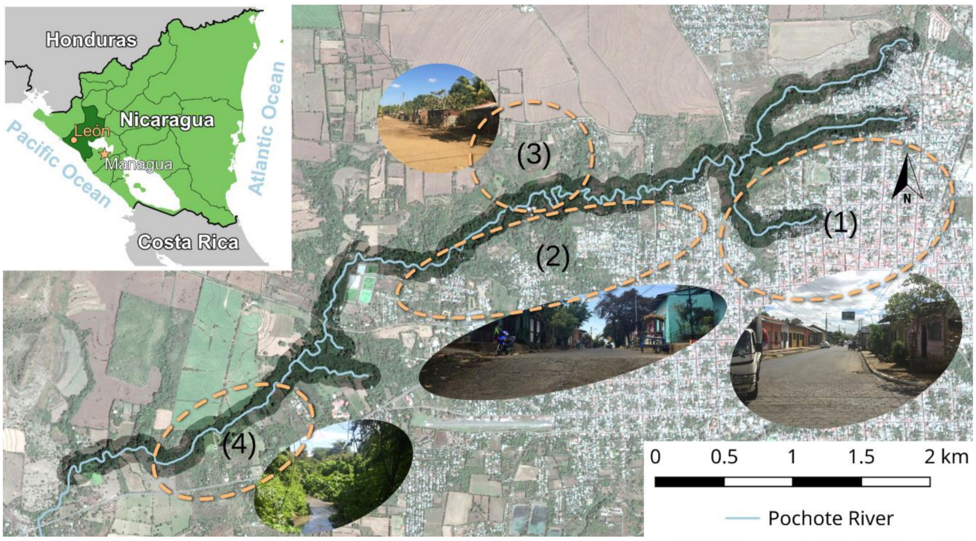

Figure 1. Overview of the study area: Pochote River and City of León [4], areas indicated with dashed lines and corresponding photographs (1)–(4) illustrate landscape characteristics in the surroundings of the river corridor: (1) historical formally and densely urbanized regions, (2) informal urban–rural transitional regions, (3) recent formal rural settlements, and (4) a less disturbed downstream section of the river corridor.

2.2. Methods

By modeling ecosystem services, the ecological values of nature to humans can be quantified and mapped [18]. The modeling program InVEST was used in this study to model the habitat degradation due to three urban threats (built-up areas, road networks, and water pollution) and the change in the distribution of habitat qualities resulting from these threats. As a geospatial tool, it was developed by Stanford University and Minnesota University, the World Wide Fund, and the Natural Conservancy [19] to support policymaking. The program models habitat quality using a standalone application that evaluates the impact of land-use change and anthropogenic threats on ecosystem services, such as biodiversity [9]. According to the model developers, habitat quality is described based on a concept introduced by Hall et al. [20] as the ability of an ecosystem to provide conditions appropriate for individual and population persistence. In the model, habitat quality is considered a continuous variable, ranging from low to high, based on the resources available for survival, reproduction, and population persistence [20]. High-quality habitats are defined as those that are intact with ecological structures and functions to effectively support the mentioned conditions of persistence. InVEST models the habitat quality as a proxy for biodiversity by estimating the extent of habitat and vegetation types and their state of degradation across a landscape [18]. The model assumes that high-quality habitats have a better chance to maintain their biodiversity [21]. The software assumes that the habitat quality decreases with the proximity and intensity of anthropogenic land use and that the decrease varies according to the type of land use [9]. As a general rule, the degradation of habitat quality occurs when the intensity of nearby land-use increases [22–24]. Habitat quality is considered to be a function of habitat suitability and four threat parameters [18]. For this study, InVEST was used to estimate the habitat quality of the Pochote River for the current land-use/land-cover (LULC) and threat situation based on field data and remotely sensed information on the LULC. Model inputs were assumed to not be specific to any particular species, but rather applied to biodiversity generally.

2.2.1. Land Use and Land Cover

The program uses raster maps, where each cell in the raster is assigned to a LULC type (e.g., forest, grassland, and cropland; LULC types can be unmanaged (natural) or managed (unnatural)). The classification can be at any level of detail. A LULC raster map representing the current land use and land cover is deployed for exploring the current condition of the habitats. A scenario LULC raster map can be used to investigate a future development or a scenario with alternative environmental conditions [18].

2.2.2. Habitat Suitability

The user must define which LULC types are suitable habitats for the conservation of biodiversity. An accurate way to estimate habitat quality is to determine the relationship between the survival of species and the habitat [25]. A suitability score, which ranges between 0 and 1, reflects the suitability of a habitat for sustaining biodiversity. A score of less than 1 indicates habitats with lower suitability and where species have lower chances of survival [18].

2.2.3. Threat Parameters

Anthropogenically modified land uses that cause fragmentation and degradation in the neighboring habitats are considered threats [21]. The sources of each threat must be mapped on a raster grid map. For this case study, each value of a cell indicates either the presence or absence of a threat. The presence or absence is binarily expressed, where a 1 indicates a cell with a threat and 0 indicates a cell without a threat. Four threat parameters that are summarized in an input Comma-separated values (CSV)-table are taken into consideration:

1. The weight of each threat indicates its relative impact. The weight can have any value between 0 and 1. A weighting score of 1 in a raster map cell causes represents twice as much degradation as a weight score of 0.5 [13].
2. The distance and impact of each threat over space. The impact of a threat depends on how quickly it decreases over space. For this case study, an exponential function described this decay, which is an indicative pattern seen in ecology [13]. The impact of a threat r from the threat source raster cell y on a habitat in the raster cell x is given by i_{xy}. The linear distance between cells x and y is d_{xy} and the maximum distance of threat r's reach is $d_{r,max}$. The program computes the impact of each threat over space with the following exponential equation [18]:

$$i_{rxy} = e^{-\frac{2.99}{d_{r,max}} d_{xy}} . \tag{1}$$

3. The level of accessibility in each habitat cell x. The greater the physical, social, or legal protection the cell has, the less it is affected by threats. Difficult terrain or formal protection are factors that decrease the accessibility [13]. For this case study, the accessibility score was binary, where 1 indicates full accessibility and 0 indicates full protection without any access.
4. The relative sensitivity of each habitat type to each threat. The model assumes that the more sensitive a habitat is to a threat, the more it will be affected by it. For example, a forest may suffer more from the proximity of agriculture than of settlements [13]. The sensitivity score for each raster cell ranges between 0 and 1, where 1 indicates the highest sensitivity score [18].

The program computes the total threat level, also named the degradation score, in habitat cell x with the habitat type j using the following equation:

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \frac{W_r}{\sum_{r=1}^{R} W_r} \times r_y \times i_{rxy} \times \beta_x \times S_{jr}, \tag{2}$$

where:

D_{xj}: total threat level
r: threat
y: indexes all cells on threat r's raster
Y_r: set of grid cells on threat r's raster

W_r: weight of each threat
i_{rxy}: impact of each threat
β_x: level of accessibility in grid cell x
S_{jr}: sensitivity score of habitat j to threat r [18].

2.2.4. Habitat Quality

The habitat quality of raster cells is a function of the habitat suitability and the degradation score. The habitat quality for each raster cell x is computed by the program using the following equation:

$$Q_{xj} = H_j \left(1 - \frac{D_{xj}^z}{D_{xj}^z + k^z} \right), \tag{3}$$

where:

Q_{xj}: quality of habitat in cell x of habitat type j
H_j: habitat suitability score of the LULC type j
D_{xj}^z: total threat level
z and k: scaling parameters.

The parameter z is set by the program. The k constant, namely the half-saturation constant, is set by the user. In general, it is set to half of the resulting degradation score after the first run. By default, k is set to 0.5. The model must then be run a second time. Q_{xj} increases with H_j and decreases with D_{xj}. When Q_{xj} = 1, the quality of the habitat in grid cell x is at its maximum (see the InVEST user's guide for more information) [18]. Q_{xj} can only be 0 if H_j is 0, not as a result of threat impacts. In the absence of impacts from threats, Q_{xj} = H_j.

2.2.5. Calculation of Habitat Degradation Due to Threats

The habitat degradation due to the considered urban threats (built-up area, the network of first- and second-order roads, and different degrees of river water pollution) in this study within the river corridor, described as habitat degradation R, was calculated based on the habitat suitability (i.e., the theoretical habitat suitability potential of the land cover in the absence of threats) and the modeled habitat quality, as follows:

$$R = H - Q \text{ i.e., } R_r = H - Q_r \tag{4}$$

where:

R: habitat degradation due to the impact of all threats
H: habitat suitability
Q: habitat quality as a result of all threat impacts
R_r: habitat degradation due to the impact of threat r
Q_r: habitat quality as a result of threat r.

This calculation of the habitat degradation is done for each threat individually, as well as for the combination of all threats. Following this procedure enables one to assess the relative habitat degradation from each threat along the river corridor to better interpret the impact resulting from the application of all threats and to be able to identify specific impact sources of the urban river environment. The habitat degradation impact analysis of the individual and combined threats on habitat quality represents a main outcome of this work as it is the basis for the discussion regarding whether and to what degree the InVEST model is able to reasonably model the impact of typical urban threats on the habitat quality of river corridors.

2.3. Material Used and Model Parameterization

The evaluation of the habitat quality for the current case study was based on data from previous research from the Research Group SEE-URBAN-WATER [17]. For this case study, the model required six types of entry data:

1. Current raster LULC map: A GeoTIFF-file raster dataset with a LULC class code for each cell.
2. CSV-table with threat data: The CSV-table contains information on the threat's weight, the maximum distance in kilometers, and information on whether the decay is linear or exponential. For this study, an exponential decay was used.
3. Threat raster maps: GeoTIFF-files of the spatial distribution of each threat. Each raster cell contains a value that indicates its presence or absence. The types of threats vary between the current situation and the scenario; therefore, they have their own set of threat raster maps.
4. CSV-table with habitat suitability and sensitivity scores: The LULC types, their suitability scores, and the sensitivity of each habitat type to each threat are listed in a CSV-table [18].
5. Constant k: The value of the parameter k in Equation (3) is set to the half of the highest grid cell degradation score on the landscape. When running the model, a habitat quality and a habitat degradation raster map is created. The model has to be run once where k is set to 0.5. The model is then run a second time with the new k constant.

The projection of all GIS maps used is EPSG: 3857, WGS 84/Pseudo Mercator. The projection unit is meters. A vector layer of the study area's land cover provided by SEE-URBAN-WATER was used for the LULC classification. It categorizes the land cover into three different types: high vegetation, low vegetation, and built-up areas. The LULC vector layer was transformed into a raster layer using the geoinformation software QGIS [26]. The size of each pixel in the LULC map and each threat map was 10×10 m. Each pixel was assigned with a number from 1 to 3, which stood for one of the three LULC classes (high vegetation, low vegetation, and built-up areas, respectively). Table 1 contains an overview of the LULC classification.

Table 1. Land-use and land-cover classification of the study area.

Land Cover	Description
High vegetation	Unmanaged land dominated by trees
Low vegetation	Managed land with bushes, grassland, and degraded forests
Built-up area	Buildings of all kinds (mainly residential houses) considered as non-habitats for wildlife

Model Parameterization

The parameterization of threats was also based on available GIS layers from the SEE-URBAN-WATER project [17], which were all converted into raster layers to be run in the InVEST software (Natural Capital project, Stanford University, Stanford, CA, USA). Each raster cell contained a value that indicated either the presence of a threat, with a value of 1, or its absence, a value of 0. Three different threats that are supposed to have negative impacts on the riparian habitats of the Pochote River were considered: built-up areas, roads, and the polluted river itself (Figure 2). Settlements and roads have negative impacts on the habitats, including habitat loss, fragmentation, and increased human activities, which result in reduced wildlife populations [13]. The impacts on the environment of different types of roads differ in terms of their distance from the habitat, intensity of substance pollution and noise pollution, and in their fragmenting effect [27]. Two types of roads were considered in this study, which were distinguished as first- and second-order roads. First-order roads were assigned a higher threat impact than second-order roads.

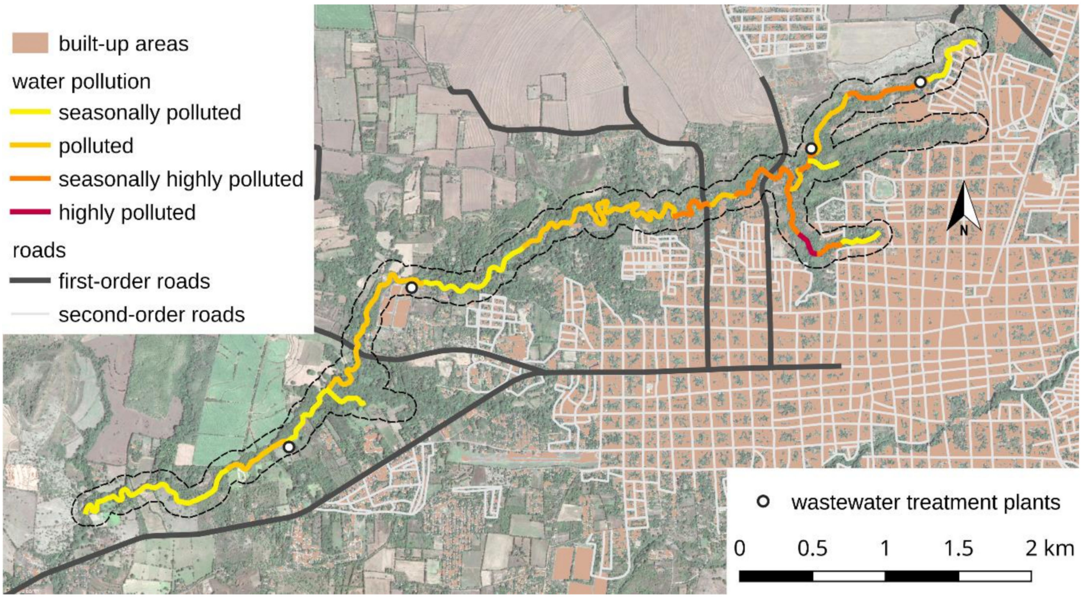

Figure 2. Map showing the three threats (built-up areas, water pollution, and roads) resulting from urbanization that were considered in this study.

Previous georeferenced photo documentation indicates that the source of the river pollution consists mostly of domestic wastewater discharges, solid waste, and stormwater runoff from roads [17]. The negative impact of the pollution on the river, which originates from both poorly performing wastewater treatment plants and illegal direct wastewater discharges, also negatively impacts on riparian habitats. According to a previous study from Beißler and Hack [4], water pollution can be categorized into four different degrees of pollution: seasonally polluted, polluted, seasonally highly polluted, and highly polluted (see Figure 2 for the spatial distribution of water pollution per 100 m river sections and Table for the threat parameterization).

The threat parameters for LULC and roads, indicated in Table 2, were based on the study of Sharma et al. [13] and Seiler [27]. They base their habitat assumptions on studies about general ecology and environmental degradation. For this study, it was assumed that their data was suitable for the Pochote River as well. The study area of the Pochote River is relatively small, and it is located close to the city. Therefore, it is most likely that most of the habitats are structurally modified and more used to urban disturbances than isolated ecosystems. Taking these conditions into account, the distances of impact were adapted to obtain a distribution of habitat qualities ranging from low to high. It was assumed that roads were only being used for transportation and not for entering riparian areas by foot. The distance of impact of both road types was set to 200 m [27]. It was assumed that the river polluted the surrounding ground when flooding occurs. The maximum distance of the impact of the polluted river was set to 10 m. The distance of impact of the built-up area was also set to 200 m. The habitat sensitivity and suitability scores from the study of Sharma et al. [13] were also used for this case study. High vegetation, such as forests, are more sensitive to threats compared to low vegetation because they are assumed to have a more intact biodiversity [13]. All LULC classes are considered less sensitive to the pollution of the river compared to the other threats because the pollution does not cause a direct habitat loss, which is what occurs in the case of settlements and roads. In general, high vegetation is considered a suitable habitat (habitat suitability score = 1), that was assumed to be mostly intact, undisturbed, original vegetation that provided sufficient breeding, forage, and shelter functions to maintain a high level of biodiversity. Low vegetation was considered a semi-suitable habitat (habitat suitability score = 0.6), that was assumed to be disturbed, secondary land cover providing moderate breeding, forage, and shelter functions to maintain a medium level of biodiversity. Built-up areas were considered non-habitats for wildlife (habitat suitability score = 0). Table 2 contains an overview of the threat parameters, habitat suitability, and sensitivity scores.

Table 2. Threat parameters, habitat suitability, and sensitivity used in this study.

Threats	Max. Effective Distance (km)	Weight (–)	Decay over Space	LULC Classes		
				High Vegetation	**Low Vegetation**	**Built-Up Area**
				Habitat Suitability Score (–)		
				1	**0.6**	**0**
				Sensitivity Score of Habitats to Threats (–)		
Built-up area	0.2	1	exp.	0.8	0.7	0
First-order road	0.2	0.8	exp.	0.8	0.7	0
Second-order road	0.2	0.7	exp.	0.6	0.5	0
Water pollution—seasonally polluted	0.01	0.1	exp.	0.6	0.4	0
Water pollution—polluted	0.01	0.3	exp.	0.6	0.4	0
Water pollution—seasonally highly polluted	0.01	0.7	exp.	0.6	0.4	0
Water pollution—highly polluted	0.01	0.9	exp.	0.6	0.4	0

Note: exp. refers to exponential decay.

3. Results

To explain the individual impact of each of the considered threats on habitat quality, the habitat degradation due to each threat is presented first in this section. Afterward, the combined impact of all threats is described, and finally, the habitat quality under the present land cover and threat conditions is presented.

3.1. *Habitat Degradation Due to Different Threats*

Due to the threat parameterization and the habitat sensibility toward different threats (see Table 2), each considered threat resulted in a characteristic habitat degradation pattern. When considering the combined effect of all threats on habitat quality, as presented in Section 3.2 below, the characteristic pattern of the individual threats was hard to differentiate. For this reason, the resulting habitat degradation from each of the threats is presented individually in the following.

3.1.1. Habitat Degradation Due to Built-Up Areas

Figure 3 shows the spatial distribution and magnitude of habitat degradation due to built-up areas in the study area. The upper branches of the river in the eastern part of the study area were the most affected by the built-up area (habitat degradation of around 0.3). Additionally, the map shows that with an increase in threat distance and a decrease in threat density (settlement density), the threat's influence on the river corridor's habitat quality decreased, as can be seen in the middle course of the river and in the southwest (habitat degradation < 0.1). Built-up areas reduced the habitat quality by a maximum value of 0.34, while for the same areas, the habitat degradation by all threats reached a maximum value of 0.85 (see Figure 6). Thus, built-up areas made up 40% of the overall maximum habitat quality reduction.

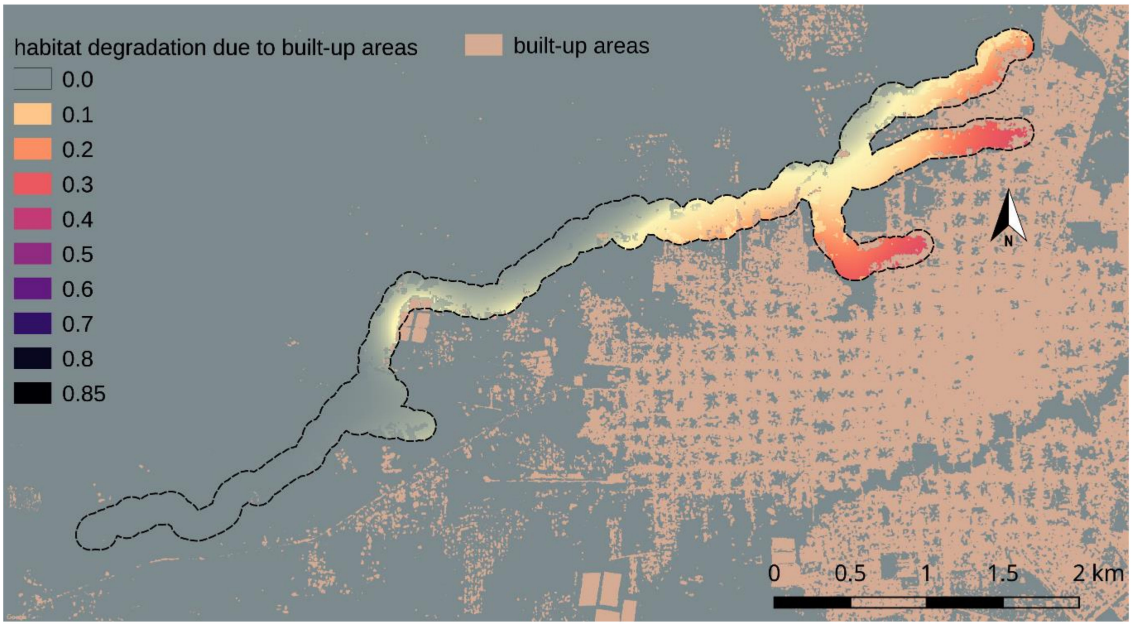

Figure 3. Spatial variation of the threat impact of built-up areas on habitat quality in the study area. The grey shade is used as a background to provide a better illustration.

3.1.2. Habitat Degradation Due to First- and Second-Order Roads

It was clear that the impact of first- and second-order roads correlated with the spatial distribution of the settlements. This resulted in the increased habitat degradation with the increasing density of the road network within areas with settlements. However, the river crossings (bridges) of the first-order roads also had their associated impacts, as can be seen in the western part of the river corridor (Figure 4). Here, even the first-order road passing about 200 m south of the river corridor seemed to reduce the habitat quality to between 0.0 and 0.1. Especially in the middle course of the river, where the second-order road network invaded the river corridor, even the impact of a rather low density of second-order roads was visible. Habitat quality was reduced the most where road networks were present on both sides of the river corridor and where the road network invaded the river corridor.

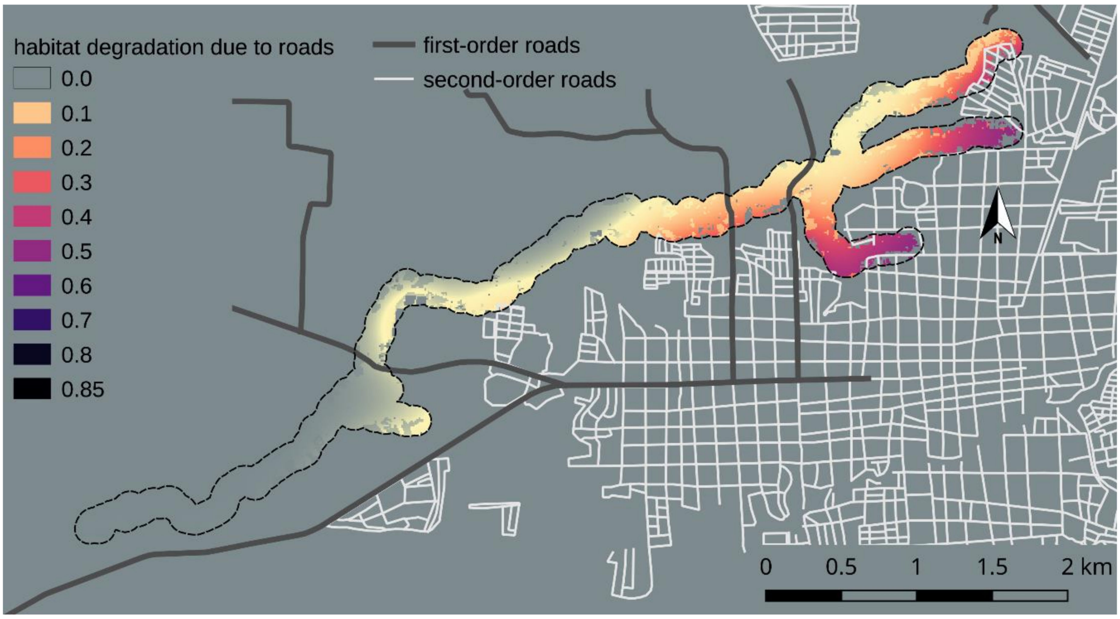

Figure 4. Threat impact of first- and second-order roads on habitat quality in the study area. The grey shade is used as a background to provide a better illustration.

3.1.3. Habitat Degradation Due to Different Degrees of Water Pollution

Water pollution has distinct negative impacts that are dependent on which region in the study area is evaluated. The Pochote River itself and its close riparian areas suffered from degraded habitat quality. The impact of the polluted water was generally the most intense close to built-up areas. The main reasons were solid waste disposal and direct wastewater discharge. Hotspots were the upper branches of the river, closely situated to settlements, and the wastewater treatment plants due to leakage and the discharge of poorly treated or untreated wastewater. In the river corridor sections close to densely populated settlements, the habitat degradation rose to values around 0.3. This is a similar level of threat impact as that from built-up areas. The impact decreased as the distance to the settlement increased, but remained present even further away from the settlements. Only in the far western section of the river corridor was there almost no observable habitat degradation due to water pollution. However, in any case, the threat impact of water pollution on habitat quality was spatially limited to nearby areas along the river course that affected habitats influenced by the river's hydrodynamics (see Figure 5).

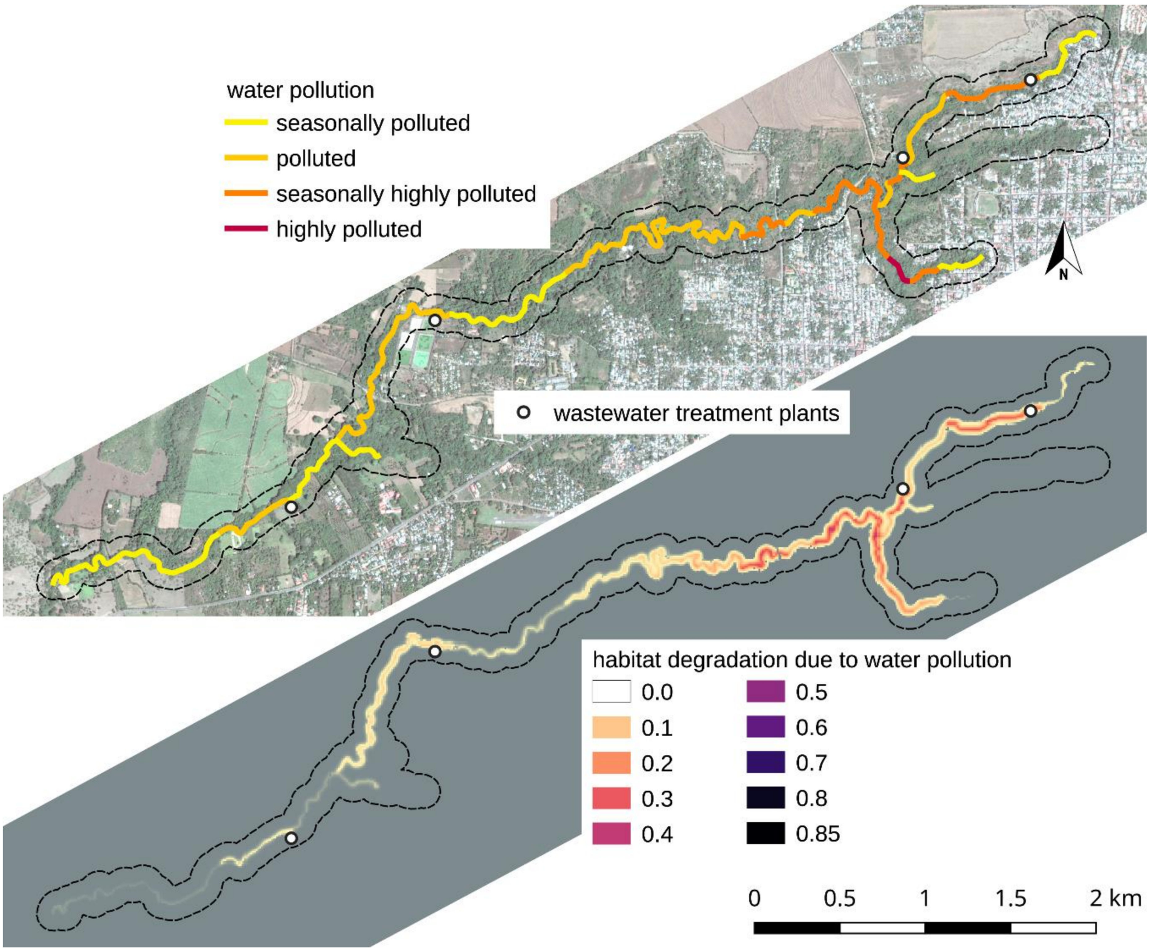

Figure 5. Spatial variation of water pollution (top) and habitat degradation due to different degrees of water pollution (bottom) in the study area. The grey shade in the bottom picture is used as a background to provide a better illustration.

3.2. Habitat Degradation Due to the Combination of All Threats

Figure 6 shows the combined habitat degradation due to the combination of all threats. The individual, spatially distributed characteristics of each single threat can clearly be observed in the image at the bottom of the figure illustrating the combined overlaying of habitat degradation from all threats. The signature of the habitat degradation due to the water pollution running along at the core of the river corridor can easily be detected but was intensified through the additional habitat degradation due to the two other threats. Furthermore, the highest combined habitat degradation due to built-up areas, road networks, and water pollution was detectable in areas of the upper branches of the river corridor with the combined threat impacts of at least >0.6 and up to 0.85. With the parameterization used in this study, combinations of all three threats (as can be observed where the river course is showing dark colors) or combinations of the impact of built-up areas and road networks led to the highest habitat degradation of at least >0.6. Such drastic habitat deterioration occurred in the upper branches of the river corridor and at parts of the river course in the corridor section after the three river branches merged. Considering the degree of habitat degradation due to the combination of all threats, the river corridor could be roughly categorized into three sections: one where all three threats strongly interacted, resulting in very high degradation levels (section a in Figure 6). This section of the river corridor was characterized by formal and informal settlements (see Figure 1), as well as by dense road networks and untreated wastewater discharges, leading to high levels of water pollution. Habitats in this section of the river corridor had already been destroyed by built-up areas invading the corridor at several points. Additionally, habitats had deteriorated to extremely low-quality habitats as a result of different threat combinations. Section b shows moderate levels of habitat degradation and could be delimited as the middle course of the river corridor (see Figure 6). Here, the combination of water pollution and roads had the most significant impact. The impact of built-up areas was at its smallest here. Section c, representing the downstream part of the river corridor after the river has left the city boundaries, showed very low habitat degradation levels. Here, only water pollution originating from the built-up areas of the city had an impact. The effect of the other two threats appeared to be marginal. These results show a reasonable spatial progress of habitat degradation from high levels due to the combination of all threats along the river corridor section closest to the city, to moderate and lower levels of habitat degradation when the river had left the city boundaries, where only water pollution remained a direct threat to habitat quality. The fact that habitat degradation due to water pollution was at its highest downstream from built-up areas and wastewater treatment plants is plausible since wastewater from these areas drains in this direction due to the terrain topography and piped systems.

Figure 7 displays satellite images that were used to highlight parts of the river corridor in section a where the interaction of all three threats can exemplarily be observed (1) and another part of the river corridor in section b where moderate levels of habitat degradation and the impact of water pollution originating from a malfunctioning wastewater treatment plant can be identified (2).

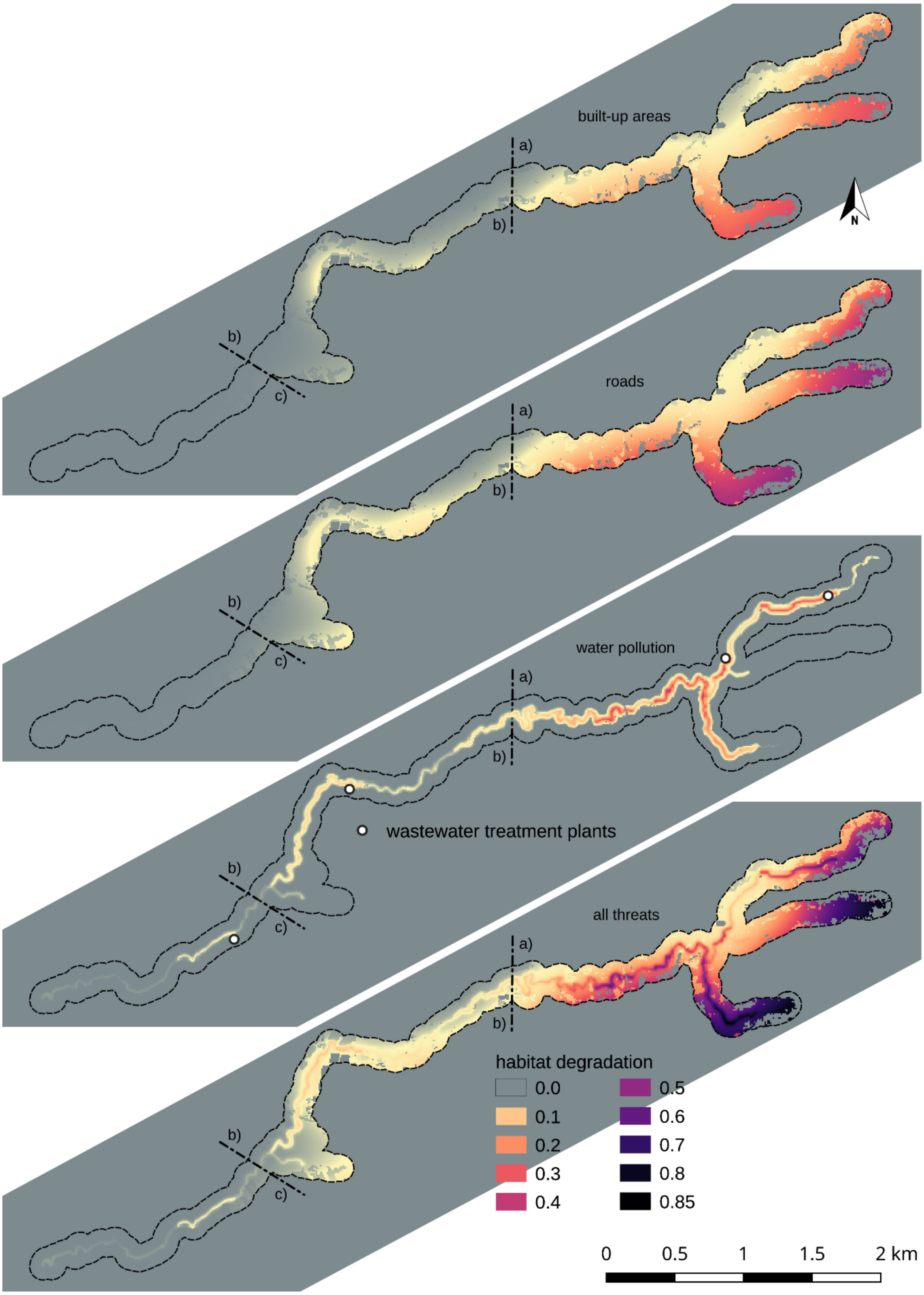

Figure 6. Habitat degradation due to all individual threats and the combination of these, divided into sections with very high (**a**), moderate (**b**), and very low habitat degradation levels (**c**). The grey shade is used as a background is used to provide a better illustration.

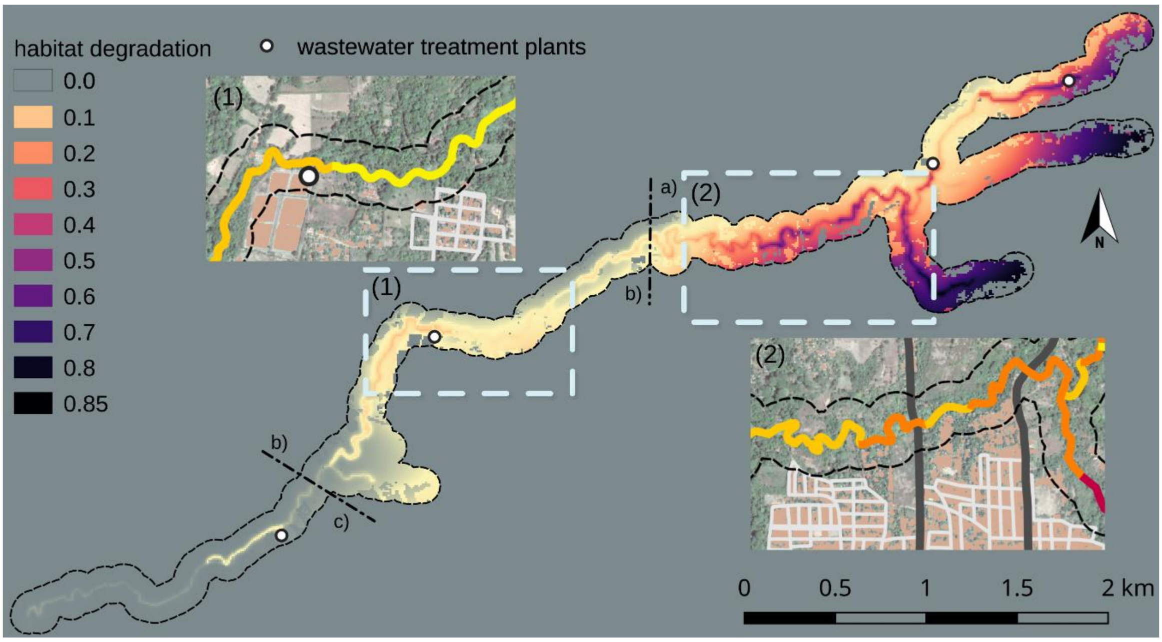

Figure 7. Habitat degradation as a result of the combination of all threats in the study area. Rectangles and the respective satellite images show areas that are discussed in more detail in the text: (1) residential areas invading into the river and (2) wastewater treatment plant (satellite images obtained from Google Earth Pro). The grey shade is used as a background to provide a better illustration. (**a**) Very high, (**b**) moderate, and (**c**) very low habitat degradation levels.

3.3. Habitat Quality

The model results for habitat quality are presented in raster maps with habitat quality scores ranging from 0 to 1. Variability in habitat quality across the landscape resulted from the habitat suitability of different land covers and the impacts of the different threats that degraded the habitat quality to different degrees, as described in Section 2.2.3. Figure 8 (top) shows the theoretical habitat suitability of the existing land cover without considering any impact of threats, while Figure 8 (bottom) shows the result of the habitat quality model applying all three threats along the study area on a pixel-basis. Dark green indicates the highest habitat quality score of 1. A habitat quality score of 1 indicates that high vegetation cover is present and there exists no habitat degradation. The habitat quality map clearly displays the high degradation of habitats due to built-up areas (red colors). The yellowish pixels on the map indicate habitat quality scores between 0.6 and 0.9. These areas are all suitable habitats to some degree. Different distances from the threat source or low habitat suitability scores resulted in a diverse spatial distribution of habitat qualities. The comparison of the habitat quality map with the habitat suitability map based on the original LULC raster (Figure 8) and the habitat degradation map (Figure 5) shows that areas of high vegetation, which were considered to be a habitat with a suitability score of 1, were on average at a greater distance from threats and preserved a higher habitat quality score.

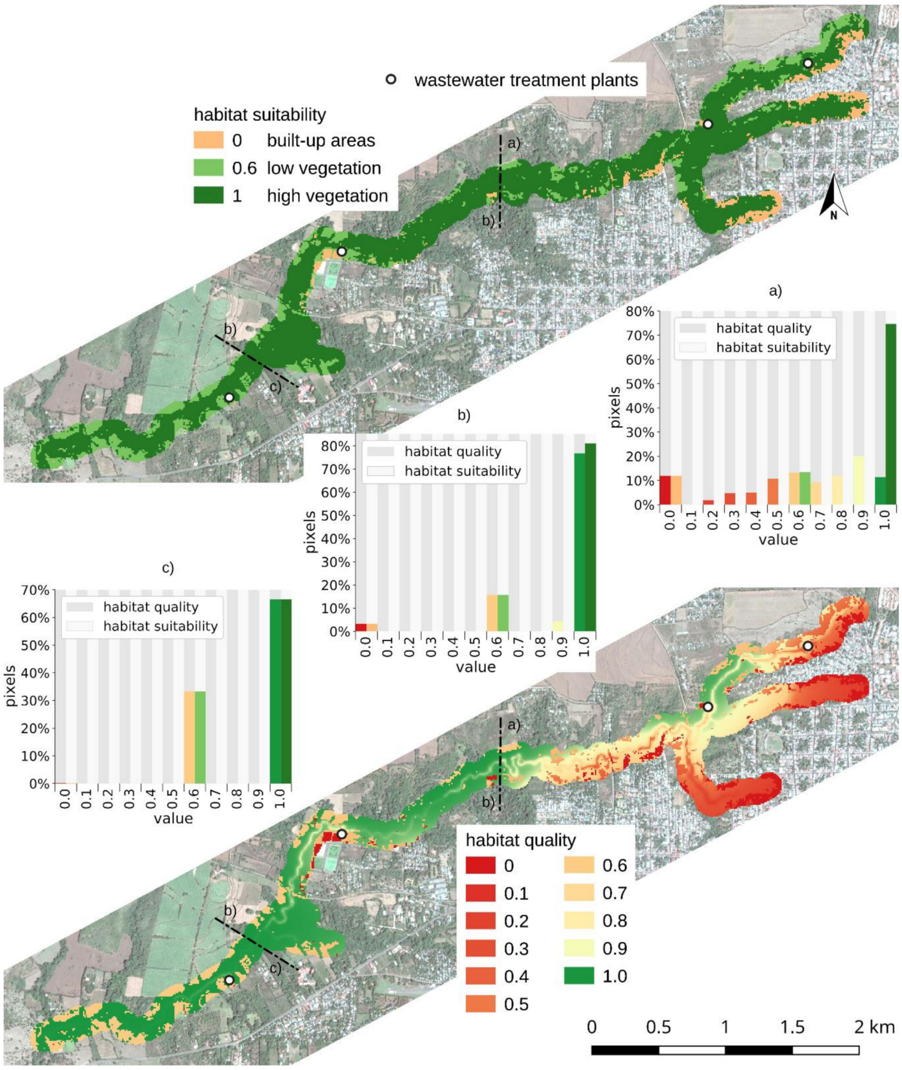

Figure 8. Habitat suitability map (top) and habitat quality map (bottom) resulting from the application of threats (Table 2). Histograms in the middle illustrate pixel distributions of the three river corridors sections with very high (**a**), moderate (**b**), and very low habitat degradation levels (**c**).

It is noticeable that the lowest habitat quality scores were found in the upper branches of the river of section a, although a significantly high amount of high vegetation, which in the absence of threats would provide a high habitat quality, was present (see the top of Figure 8). This part of the river and its riparian area were surrounded by built-up areas and a second-order road network representing the part of the study area that was closest to the city center. Additionally, many points of discharge of untreated wastewater led to the highest water pollution of the whole river corridor. This was certainly a result of the high settlement density in this area. The high vegetation was considered particularly sensitive to threats, which resulted in a higher degradation of its specific habitat quality. This area also contained most of the sealed surfaces, such as built-up areas (roads excluded), which were classified as non-habitat land covers having a habitat quality of 0. Only very few areas with optimal habitat quality were left in this part of the river corridor. This was a result of the combined habitat degradation of all threats, as can be seen in Figure 7, which led to reductions of the habitat quality, giving scores of up to 0.85 and generally >0.5 in large parts of the upper river section a. The habitat quality increased downstream until suddenly patches of low habitat quality close to a wastewater treatment plant appeared (section b). Further downstream (section c), the habitat quality mostly correlated with the habitat suitability scores, where mediocre habitats represent patches of lower quality. In this western section, no further habitat degradation was observed.

The histograms of habitat quality distributions of pixels in the study area shown in Figure 8 for the sections a, b, and c of the river corridor provide further insights into the degree of habitat degradation as a result of all combined threats. For section a, the accumulated percentage of pixels with habitat quality values ≤0.6 was over 40, while the percentage of pixels with a habitat suitability of ≤0.6 (areas with low vegetation or built-up areas) was less than 30. This means that the overall habitat quality ≤0.6 was about 40% higher because of the presence of threats compared to the landscapes habitat potential. The 40% more pixels with habitat quality values ≤0.6, which was about 12% of all pixels of river corridor section a, were covered by high vegetation, which was degraded in its habitat quality by more than 0.4. Another observation was that very few pixels had a habitat quality score <0.2, which means that low vegetation (habitat suitability = 0.6) in this section experienced a maximum habitat quality degradation of 0.4. A reason for this could be the lower sensitivity to threats of low vegetation. In the histograms for sections b and c, a much less pronounced distribution of different habitat qualities can be observed. For section b, the habitat degradation of higher vegetation was limited to 0.15 and for lower vegetation to less than 0.1. In section c, the high vegetation was not degraded at all and the low vegetation was only degraded to a very slight degree (<0.05).

4. Discussion

The InVEST model allows for assigning different habitat suitability scores to different land covers or land uses. In the absence of threats, these scores are equal to their habitat quality. A limitation to a certain amount of land cover, i.e., different habitat suitability inputs, is not given by the model. Hence, more than just the three land cover classes considered in this study could be used. In our case study, a large part of the river corridor had a high vegetation cover, which was assumed to have an optimal potential habitat suitability (habitat suitability score = 1). In contrast, in the source areas of the three river branches, the habitat suitability score was partly 0 due to built-up areas (including street networks) physically invading the river corridor to a significant degree. Medium habitat suitability was associated with areas with low vegetation, which was the case due to agricultural land use in the northern part of the northern river branch, as well as in the western part of the river corridor. Low vegetation and medium habitat suitability were also present along the middle stretch of the river corridor without the presence of agriculture. The level of habitat degradation differed between each of the three river corridor sections. In section c, there was hardly any degradation caused by the threats and the habitat quality largely reflected the habitat suitability.

The moderate values of habitat quality entirely originated from agricultural land use (score = 0.6). In section b, a slight habitat quality reduction due to riverside settlements or poorly treated wastewater discharge was found. The city is currently expanding toward river section b, which could result in habitat degradation similar to section a, unless protective measures are taken. Section a was characterized by the lowest quality due to the heavy building development, whether in the form of streets or buildings. Additionally, the water quality had a clear influence here due to discharges of the untreated urban wastewater. According to Bach and Kipp [17], this section also has the highest incidence of illegal solid waste disposal [17], a threat that was not considered in this study. For this area, restoring recreational benefits could be more successful than improving environmental conditions for increasing the biodiversity. On the other hand, restoring low-quality habitats located further away from settlements to encourage biodiversity could be more successful.

The individual assessment of the three different threats enabled a higher resolution investigation of the spatially distributed relative impacts of urban threats. This kind of analysis is critical for taking counteractive measures to reduce the impact of specific existing threats (e.g., conservation or protection measures along roads or reducing water pollution from point sources), as well as for providing more sustainable planning of urban areas and road networks close to the river corridor.

4.1. The Consideration of Additional LULC Classes for More Detailed Habitat Suitability Inputs

Using more land cover classes would allow for a more nuanced description of the spatial distribution of habitat suitability. Our land cover, i.e., habitat suitability input, was based on a land-use classification of a satellite image [4] with only punctual validation using ground truth information. Using this methodology, a further classification of land-use classes, such as irrigated and rain-fed agriculture, as well as a consideration of bare soil, would be possible. However, for this study, which aimed at a first assessment of the model's ability to simulate the impact of typical urban threats, this was not considered useful. As a result of the classification methodology applied, a consideration of agricultural land cover would result in fewer areas formerly classified as low vegetation, which instead would be classified as (irrigated or rain-fed) agriculture. Specifically, areas north of and in the southwestern section of the river corridor would have their statuses changed. Agricultural areas are much less suitable as a habitat and could even be considered a non-habitat. Thus, a habitat suitability much lower than 0.6 (as for low vegetation) should be assigned to these areas. Particularly in the southwestern section of the river corridor, agricultural areas were invading the river corridor.

In a study by Rimal et al. [28], eight LULC classes (urban, agriculture, forest, shrub, barren, water, grass, and snow) were considered regarding their habitat suitability using InVEST. Urban, as in our study, was considered a non-habitat, but so was snow. Shrub and grass were assigned a habitat suitability score of 0.6, as in our case for low vegetation, and forest was assigned a score of 1, as in our case. However, with agriculture (suitability score of 0.3), as well as barren and water (both 0.2), additional LULC classes with slightly different suitabilities were included. This parameterization could be integrated into future analyses.

4.2. The Consideration of Additional LULC Class or Other Data Sources as Threats

Additionally, agricultural areas could be included as a threat in habitat quality modeling. A distance-related approach is reasonable when considering the negative impact of fertilizer, herbicides, and pesticides leaching out of agricultural areas on surrounding habitats. Due to topography and groundwater flow, rivers are particularly prone to these threat impacts. Fertilizers influence the growth of algae and pesticides affect species at every level of the food chain. The effects of agriculture on habitats are habitat loss, fragmentation, and pollution, among others. Past studies [29–31] have included agriculture as a threat to habitat quality from which model parameterization estimates could be derived.

The classification of bare soils could provide a substitute for either low vegetation or built-up areas. In the former case, this could be considered with a lower habitat suitability than 0.6, and in the latter case, a slight increase could be considered. Bare soil could hardly be considered a significant threat to the surrounding habitat; hence, in substituting built-up areas, which are considered a threat, this could result in higher habitat quality scores.

A more detailed classification of high vegetation based on the methodology applied here would hardly be possible without extensive efforts to attain more ground truth information, which is unreasonable for a screening assessment. More ground truth information could help to identify larger patches with higher suitability scores and smaller patches with lower scores. If more ground truth information is available, a more sophisticated LULC classification, similar to the one proposed by Chapa et al. [4], could be useful for distinguishing additional habitat types and suitabilities.

Additional urban threats of importance to river corridor habitat quality are the wastewater discharges of industries, which could be parameterized differently from domestic wastewater discharges, and the disposals or inflow of solid waste. The impact of industrial wastewater could be considered in a very similar manner as the impact of domestic wastewater in this study, but the impact of solid waste could be challenging since the waste could be transported and redeposited downstream, a dynamic process that cannot be described by the model's algorithms as it is currently programmed. This is a limitation in the threat consideration capability of the model. However, for the case study presented here, industrial wastewater discharge was absent and solid waste disposal was considered to be much less important than the three threats considered here. A review of all publications using the InVEST software showed that these threats have not been considered in other studies so far. In comparison to other studies of habitat quality modeling in the context of urban threats [29,32–36], this is the first study that has considered the combination of threat impacts from built-up areas, road networks, and water pollution, as well as utilizing a high-resolution habitat suitability input. It is also the first application of the model to a river corridor.

Xu et al. [37] included nine different threats in their study of impacts of land-use change on habitat quality in the Taihu Lake Basin. Additional to the typical urban threats considered in our study, they also included, for instance, industrial and mining land and paddy fields as threats to habitat quality. However, urban land use and roads affected habitat quality the most compared to other threats.

4.3. Critical Reflection on the Model Parametrization and Model Limitations

A significant challenge is presented by the parameterization of the InVEST model as it allows for a very detailed parameterization. There is a high degree of uncertainty regarding the habitat suitability of different LULC classes (habitat suitability score) regarding the potential impact of a threat (a given threat's weight and sensitivity score of habitats to that threats) and in what magnitude (maximum effective distance, decay over space) threats impact the suitability of habits in different LULC classes.

While the model allows for very differentiated characterizations of habitat suitabilities and threat impacts, the resulting habitat quality is very unspecific and unidimensional given it summarized as a habitat quality score between 0 and 1. Hence, only the overall habitat quality is considered without the consideration of specific species' vulnerability to different threats. Some species will be more affected than others by habitat quality degradation. However, with the consideration of different types of threats, the specific impact of each threat on different species could be considered and incorporated into habitat protection or restoration strategies. Relating the modeling results to habitat quality for specific species is only possible by relating specific species with specific LULC classes. Considering the different impacts on different species for the same habitat (i.e., LULC class) is not possible with the model, and the impact on species is only possible on a "per habitat" basis.

4.4. Suggestions for Improvements and Further Studies

To improve the parametrization of the LULC, more field-based and long-term ecological studies are necessary. In his comprehensive literature review, McKinney [24] concluded that urbanization impacts on native species have been insufficiently studied, with most scientific knowledge stemming from urban–rural gradient studies of habitat and species losses [38–40]. To improve the habitat quality modeling, a better parameterization of the habitat suitability of different land cover types, threat impact characteristics, and land-cover threat sensibilities is required. The present strong reliance on expert's knowledge and parameters of InVEST model datasets [14,31] has also been criticized by Gong et al. [41]. Empirical field studies are necessary to improve this parameterization. Existing field studies are often limited in their spatial extent (e.g., usually not covering a river corridor of 1.6 km^2, and therefore only provide partial information) and do not consider species' niches [42]. The conceptual approach presented here has the specific advantage of low data requirements regarding LULC classification and threat identification. It enables a rapid assessment of habitat quality and threats due to urbanization. This qualifies the presented approach for strategic urban and conservation planning for practitioners. An identification of high habitat quality hotspots could be used to prioritize conservation efforts used to protect the most intact habitats against urbanization. Additionally, the identification of hotspots of ongoing environmental degradation and low-quality habitats could be used to best orient restoration efforts to avoid further degradation. However, the chances of a successful recovery should also be evaluated.

Habitat quality can be decreased or maintained without a change in land cover or land use via protection rules. If the protection considerations are also applied to the model, the amount of uncertain parameters increases further (e.g., in terms of how and to what degree environmental regulation or geophysical characteristics (e.g., topography) may ensure habitat quality against different threats). To keep this study of impacts of typical urban threats on habitat quality of river corridors comprehensible, protection was not considered in the present modeling. Protection was excluded in this study's modeling to maintain the comprehensibility of urban threats on habitat quality. However, in the study area, the river branch located south of the two other branches is well protected because of its canyon-like topography, which impedes access to the river corridor from all directions except for the western end of the branch. This may allow for high vegetation to still be maintained in these areas, although the river branch is surrounded by densely urbanized areas that represent the oldest settlements of the entire city. A consideration of this "topographical" protection in the model would have been possible and would have led to a reduced impact of threats (built-up area and road network), resulting in a higher habitat quality. Knowing this area, a higher habitat quality as modeled in this study would reflect the actual conditions in this specific section of the studied area better.

The consideration of additional ecosystem services provided by the river corridor's ecosystems could be advantageous. In an application of the InVEST model, Lin et al. [43] found that habitat quality positively correlated with the ecosystem services of soil retention and carbon storage. Considering additional ecosystem services could contribute further arguments toward the protection and restoration of threatened or deteriorated ecosystems.

5. Conclusions

The precise nature of the LULC classification used in this study allowed for a high spatial resolution analysis of variations in threat impacts on habitat quality. This high spatial resolution enabled a precise assessment of small-scale changes in habitat quality along a river corridor with a width of only 200 m. A specific strength of this study was the detailed assessment of the impacts of different levels and types of threats on habitat quality along the river corridor. A reasonable conclusion could be drawn for the underlying cause–effect relationships and impact characteristics of various threats: built-up areas caused area-based habitat quality degradation, water pollution caused longitudinal water-borne habitat quality degradation along the river corridor, and streets caused longitudinal habitat quality degradation when next to the river corridor. Specifically, typical urban threats that impacted river corridors, including point source water pollution via the discharge of untreated wastewater, built-up areas invading the river corridor, and streets crossing it, have been successfully modeled. Thus, the capability of the InVEST model to consider different types of typical urban threats was proven. The results show a general applicability of the model to simulate the impacts of different threats on the habitat quality of urban river corridors.

The Natural Capital Project is currently developing the Urban InVEST application, which is a modified version of InVEST specifically designed for urban areas, including "tools to show how incorporating the value of nature into urban design can deliver better outcomes for people and the planet" [44]. Urban InVEST is intended to be used for the spatially explicit modeling of urban ecosystem services (e.g., habitat quality, urban water management, heat island mitigation, mental health benefits). We believe that our study sheds important insights on how to support practical model development, such as in the case of Urban InVEST.

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