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Suitability for agroforestry implementation around Itombwe Natural Reserve (RNI), eastern DR Congo: Application of the Analytical Hierarchy Process (AHP) approach in geographic information system tool

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ABSTRACT

The choice of appropriate land use suitability based on specific environmental and socio-economic factors could ensure sustainable land resource management in rural areas. Different land use suitability assessment approaches exist and have been successfully applied for agroforestry systems, natural or semi-natural ecosystems. In this study, different land use suitability levels for agroforestry were assessed around the Itombwe Natural Reserve (RNI), eastern Democratic Republic of Congo (DRC). Information related to soil unity, topography, climate, road infrastructures, rivers, villages, land use and land cover were analyzed using the Analytical Hierarchy Process (AHP). Moreover, spatial analyses were conducted for determining the matrix that confronts adopted variables and their corresponding weights. After performing the analyses in ArcGIS 10.7, results allowed identifying four agroforestry suitability zones, ranging from very high (~29.2%), high (~22.3%), moderate (~34%) and low (~14.5%) suitable zones. Suitability classes varied with locations (districts). The zoning around the RNI and the produced suitability maps from this study provide a valuable resource for decision-making in targeting areas suitable for agroforestry, and thus, contribute in preserving the RNI from degradation related to inadequate anthropogenic practices.

1. Introduction

Agroforestry is a system or mode of management, or agricultural land exploitation that combines shrubs or trees, and crops (annual or perennial) or livestock (Gold and Garrett, 2009). Associating trees with agriculture has considerable advantages, particularly on soil conservation (Martin, 2020). In past decades, the agroforestry approach has attracted the attention of researchers because of its capacity to reduce land loss and degradation (Cooper et al., 1996), to improve food security (Kiptot et al., 2014) and to mitigate climate change (Mbow et al., 2014). It has been practiced in many countries and provides a wide range of economic, social and ecological services (Alexandre, 2002). In fact, the benefits of planting high-value tree species such as palm, cocoa, etc. are increased on-farm income per capita, improved soil fertility as well as crop productivity, and thus, enhanced households' food and income security (Mbow et al., 2014). The agroforestry also reduces the impacts of climate variability and change by conserving and safeguarding biodiversity and improving air and water quality (Alexandre, 2002; Mbow et al., 2014). Agroforestry is, therefore, of great importance as it offers enormous benefits and capacity to safeguard food security for the

Abbreviation: AHP, analytical hierarchy process; CI, consistency index; CR, consistency ratio; DEM, digital elevation model; DRC/DR Congo, Democratic Republic of Congo; FAO, Food and Agriculture Organization of the United Nations; GIS, geographic information system; MCDA, multi-criteria decision analysis; NTFPs, non-timber forest products; PCA, principal component analysis; RNI, Reserve Naturelle d'Itombwe/Natural Reserve of Itombwe; Aw, tropical wet and dry or savanna climate; AF, Tropical rainforest climate; CFB, temperate oceanic climate; CWB, subtropical highland climate.

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future generation. These benefits made part of discussions in 2004 at the 1st World Agroforestry Congress (Working Together for Sustainable Land Use Systems) in Florida, USA (Nair, 2004).

In Democratic Republic of Congo (DRC), the agroforestry is a common practice by farmers (Bisiaux et al., 2009; Dumont et al., 2015). It was first reported in 1979 by Dubois (Dubois, 1979) in the Mayombe; and then at the Batéké and Mampu plateaux in industrial plantations (Bisiaux et al., 2009). One of the successful examples is the integration of *Acacia auriculiformis* in rotation with cassava and maize (Dubiez et al., 2019).

In South-Kivu province, ~80% of rural households have agriculture as main economic activity, and majorly living an indecent life due to limited livelihood opportunities (Lebailly et al., 2015; SNSA, 2016). More than 80% of farmers are smallholders (with <0.5 ha and majorly located on degraded hills which are highly susceptible to soil erosion) (Heri-Kazi, 2020). The agroforestry is one of the common farming practices in the area; with high legume trees–crop (non-woody and woody plants) integration (Dumont et al., 2015). Conventional farming systems are in continuous pressure due to the lack of agricultural inputs such as mineral and organic fertilizers, pesticides, improved varieties, etc. Such a situation is worsened by other socioeconomic factors such as inaccessibility of some areas due to poor road infrastructures, absence of farm input supply, etc. (Tollens, 2003; Yango, 2011). In such a context, the agroforestry could be a valuable alternative to address the challenges of food, nutrition, energy, livelihood security and environment (Bofa et al., 2000; Louppe, 2015).

The DRC is one of the countries where the agroforestry practice has been adopted across the majority of its territories and much more in the eastern provinces (Dumont et al., 2019). The adoption of this practice has the potential to achieving sustainable agriculture while preserving the country's forest biodiversity since the agroforestery systems will not be only providing food but also wood for cooking and house building. The agroforestry adoption has also the capacity of optimizing the agrosystems' productivity while mitigating the effects of climate change (Hamon et al., 2009; Bayala et al., 2018). Therefore, it is critical to identify suitable areas for expending agroforestry practices in South-Kivu province. The expansion of human activities as a result of the rapid population growth calls for appropriate decisions (policies) to regulate the land use and thus maintain biodiversity and promote sustainable land resource management.

Several approaches have been developed to assess the land suitability before implementing a specific speculation. Many of these approaches are old and consist in assessing biophysical parameters (Hopkins, 1979). However, they are costly and time-consuming. Moreover, the information to be used by these biophysical approaches is, in most cases, incomplete and inadequate, and thus not allowing the integration of short-term changes (Quinta-Nova and Roque, 2018). In recent times, the analysis of Remote Sensing (RS) data provided an important contribution to the Geographic Information System (GIS) and made it possible to cope with the above-mentioned limitations of biophysical assessment approaches.

FAO (1976) defined land suitability as the measure of how well the qualities of a land fit the requirement of a particular crop or agricultural activity. To determine land suitability, a combination of information is applied. The most commonly used approach is the Multi-Criteria Decision Analysis (MCDA); it works essentially with complex data that involve the use of a range of information (Mohammed et al., 2020). MCDA is a choice method for solving the spatial problem deriving from several criteria using the GIS. Influencing factors are evaluated and decisions can be made. One of the most commonly used among the MCDA approaches is the Analytical Hierarchy Process (AHP) (Parimala and Lopez, 2012).

Developed by Saaty in the 1980s (Saaty, 1980), the AHP approach is applicable to all ecosystems; it is widely used in several research fields from the environment, social sciences, economics, etc. (De Steiguer, 2003). With its precise mathematical properties, it provides a comprehensive, rational scheme to structure a problem, and thus, allows a presentation and quantification of elements (Emrouznejad and Marra, 2017; Morandi et al., 2020).

In the context of the eastern DRC, and particularly the South-Kivu province, promoting agroforestry was constrained by lack of reliable data sets and tools for mapping. This was accentuated by an inadequate decision-making system. Since the agroforestry requires particular land suitability types, it is highly relevant to assess land suitability to guide actions at the provincial/territorial level. On the other hand, few studies have assessed land suitability for agroforestry implementation using RS and GIS in South-Kivu. The use of RS and GIS tools would allow analyzing land suitability with reduced cost and time. Used in Indonesia by combining climatic, soil and topographic data, these RS and GIS tools successfully assessed land suitability based on FAO guidelines, and the land adequacy for various agroforestry crops (Ruting et al., 2007). The same approach was successfully used by Kihoro et al. (2013) in Kirinyaga and Embu (Kenya) for analyzing land suitability through biophysical variables related to soil, climate and topography.

In this study, we determined the suitable areas for agroforestry in the administrative districts around the Itombwe Natural Reserve (RNI) located in South-Kivu province, eastern DRC. We combined soil, topographic and socio-economic data along with factors linked to agroforestry constraints and land use and cover in the study area using the AHP approach coupled with other spatial analyses. The approach aimed to apply geospatial tools to visualize various soil and environmental data in order to reveal trends and relationships between different elements and to classify zones based on agroforestry characteristics and requirements. We therefore obtained a suitability map around the RNI to lead decision-making.

2. Materials and methods

2.1. Study area

(a) Location

The study area is made of seven administrative districts (and or territories), including Mwenga, Minembwe, Itombwe, Kitutu, Haut-Plateau, Kaziba, and Mwana.

The Natural Reserve of Itombwe (RNI) is located in the South-Kivu province, eastern DRC. The RNI was created by the ministerial order No. 038/CAB/MIN/ECN-EF/2006 of October 11th, 2006. It covers ~760,000 ha surface area; although subject to criticism (controversy by autochthonous). Indeed, the exact boundaries of the RNI were not well defined in its creation act by the management authorities nor signified to neighboring communities and other land users. This was mainly due to the insecurity caused by armed forces and political conflicts which made it impossible to finalize the zoning map. Therefore, this explained why in this study, we have selected the entire zone around the RNI as shown by actual available shapefile (Fig. 1).

(b) Topography, climate, soil and vegetation of the RNI

The relief around the RNI is part of the Mitumba mountains range, it rises from low altitude (~600 m) towards the west in the Ruzizi plain and reaches ~3,475 m (Mount Mohi) in the north. Several other peaks are observed and often exceed 2,000 m.

The dominant climate is of the *Cwb* type according to the Köppen-Geiger classification. Temperatures oscillate at ~25 °C in the eastern part (in the Ruzizi plain) and ~15 °C in the highlands. Frequently, night frosts are observed in these areas. Rainfall varies between 1,000 m in the east and >2,000 mm in the western part.

In terms of vegetation, savannah is dominated with *Hyparrhenia* spp., and wood savannah with *Michelsonia* spp. and *Brachystegua* spp. These vegetation types dominate at elevations between ~900 and ~1,700 m. Above ~1,700 m, mountain forest appears and is characterized by *Parinari excelsa, Symphonia globulifera, Carapa grandifolia*, and *Macaranga* spp. alternating with tree ferns (*Cyathea manniana*) in the valleys and wetlands. Peer clearing can also be observed at the top of mountains. Above ~1,900 m, bamboo forest (*Arundinaria alpina*) appears in the mountain forest, then towards the crest of the expanses completely dominated by bamboos.

In the area, swamps, formation of marshes, in wide flat-wetlands in high inland valleys exist, and are not found anywhere else on such an area (M'Keyo, 2000). The presence of a small lake (Lungwe) in the north of the RNI surrounded by high altitude swamps was also mentioned (at ~2,700 m).

The area is home to several rivers that are part of the Congo Basin, of which the most important are Elila, Luama and Ulindi. According to the land use and land cover (from 2015), there are ~10 different land uses and covers around the RNI (Fig. 2). They were obtained from the UCL/ELI platform (http://maps.elie.ucl.ac.be/CCI/viewer/download.php).

(c) Socio-economic situation around the RNI

The ethnic groups found in and around the Itombwe forest are Balega, Bashi, Bafuliro, Babembe, Banyindu, Bavira, and Banyamulenge. Autochthonous people "Bambuti" (pygmies) live in and around the RNI.

According to Airaud (2017), the RNI is continuously subjected to five main pressures: poaching, which was increased with the armed forces' presence that have been rampant throughout the region for the past decades; mining operations that continue to develop in and around the RNI; logging of timber for construction and development; illegal logging through artisanal exploitation, and bush fires. Other pressures were linked to the Non-Timber Forest Product (NTFP) harvest, wood charcoals, livestock transhumance (in the Haut-Plateaux) and trade among cities and towns (Mwenga, Uvira, and Bukavu) (Airaud, 2017).

(d) Biodiversity in the Natural Reserve of Itombwe (RNI)

Although suffering from anthropic pressure, the RNI is rich in term of biodiversity. Airaud (2017) mentioned ~583 bird species and of which ~30 endemic species to Albertine rift, ~72 mammal species among which four were endemic. The study estimated a number of ~40 reptile species among which five were endemic; 39 amphibian species among which 16 were endemic to the RNI. From all these species, more than 56 species were identified as menaced/endangered species (Airaud, 2017). Rare species such as eastern chimpanzee (*Pan troglodytes scheinfurthii*), Grauer Gorilla (*Gorilla beringei graueri*) and forest elephant (*Loxodonta cyclotis*) were also identified in the reserve. The RNI is rich in biodiversity and it is assumed that its richness has not yet been elucidated and its biodiversity has not yet been fully documented (Airaud, 2017).

3. Methods

3.1. Selection of variables used for the agroforestry land suitability analysis

Limited data are available on South-Kivu ecosystems and land resources. In this study, eight variables were used. Due to the lack of data in the area, variables were obtained from freely available databases. These included shapefiles of the RNI, territories, villages, roads, rivers, local aerodromes, and national parks of the DRC (obtained from the Référentiel Géographique Commun "RGC": http://www.rgc.cd/). Freely available satellite images were also used and comprised the Digital Elevation Model (DEM) with a resolution of 30 m. A glove cover for the land cover image of 2015 was also used. The soil and climate data were also considered. These images were freely downloaded from https://maps.elie.ucl.ac.be/CCI/viewer/, https://earthexplorer.usgs.gov/, http://www.isric.org/, and https://soilgrids.org/ (for soil) and Beck et al. (2018) for climate.

All these files were first extracted according to the study area before running spatial analysis and building up the model. The ArcGIS 10.7 tool from Esri (Redlands, California, USA) in the "spatial analysis tool" was used. The variables used in land suitability analysis included the land use and land cover, the slope (in %), elevation (in m), and slope aspect. For the shapefiles, we used roads, rivers, villages, local aerodromes (airplanes), and raters based on Euclidean distances (ED) (in m).

Most of the factors considered in this study had continuous numerical values, such as distance to roads, rivers, villages, slopes, etc., but sometimes it was difficult, if not impossible, to relate these data accurately with the land suitability. Besides, these data had different amplitudes that made them incomparable. One of the challenges was to identify the relative importance or weight of all factors in the multi-criteria decision support process. Several factors (9) in this study needed to be examined simultaneously, but they influenced land suitability unequally. This is attested by the weights given to each criterion in the assessment.

3.2. Analytical Hierarchy Process (AHP) and determination of variables' weights

In this study, the Analytical Hierarchy Process (AHP) was used. The process was developed by (Saaty, 1980, 1990) and is currently known to

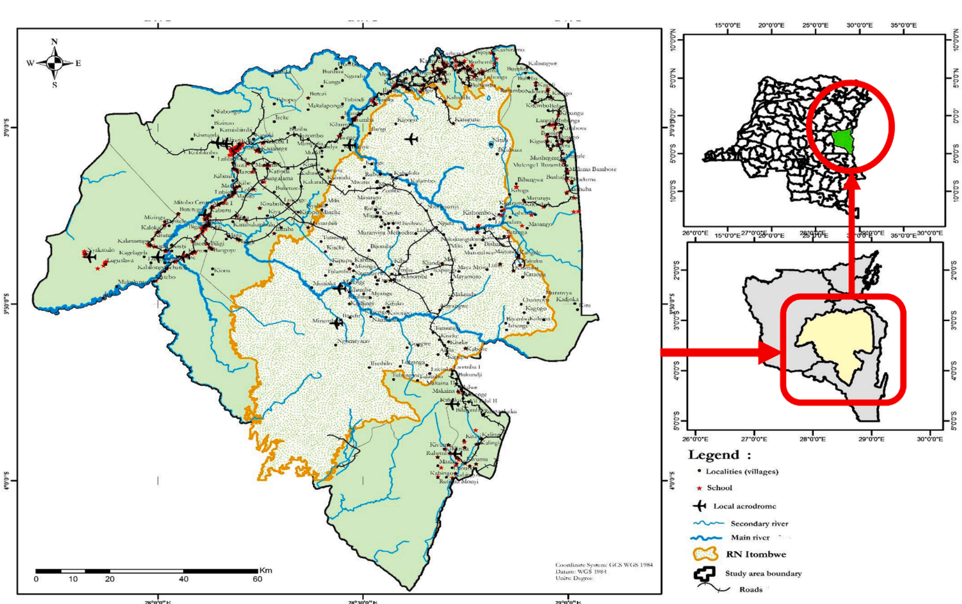

Fig. 1. Study area around the National Reserve of Itombwe (RNI) in South-Kivu province, eastern DR Congo.

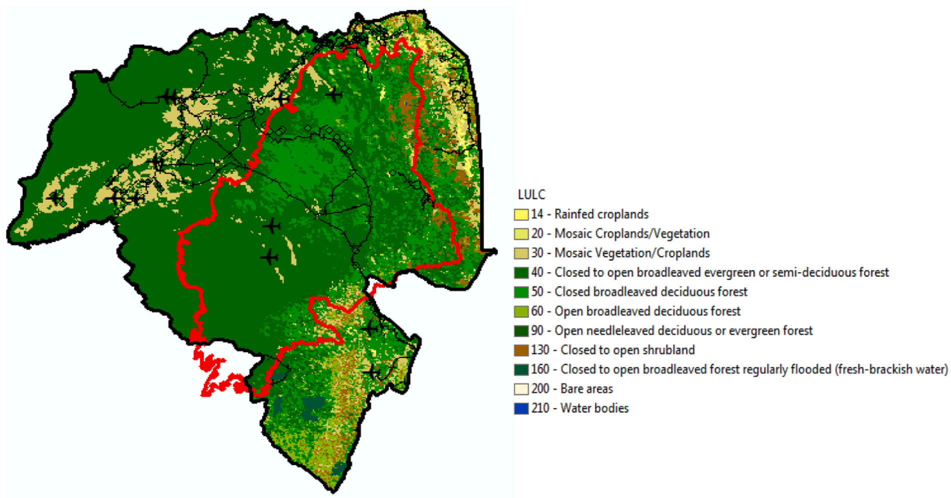

Fig. 2. Land use and land cover change around the Natural Reserve of Itombwe in South-Kivu, eastern DR Congo (extracted from the image obtained from http://maps.elie.ucl.ac.be/CCI/viewer/download.php).

be an effective tool for dealing with complex decision making. In addition, the AHP incorporates a useful technique to verify the consistency of the decision maker's assessments, thus reducing bias in decision-making process. The AHP consisted of making a two-by-two comparison of all the selected criteria. Criteria with equal importance were assigned a value of 1, and a value of 9 was assigned for those that were of extreme importance in the comparison matrix (Table 1).

The matrix obtained after two-by-two (pairwise) comparison was presented. The consistency of the 9^{th}-order matrix has also been evaluated. The comparisons made by this method were subjective and the AHP tolerated inconsistency by the amount of redundancy in the approach. If this consistency index failed to reach a required threshold level, the responses to the comparisons were re-examined. After this step, the spatial analyses were performed in ArcGIS 10.7 as shown in Fig. 3. We firstly started with the raster images' reclassification. Analyses based on the determination of the "Euclidean Distance" (in m) for roads, rivers, villages, and local aerodromes were also performed.

The slope and the slope aspects were generated by ArcGIS using the DEM. The rasters obtained after these steps were also reclassified into different classes according to their constraints to the implementation in the agroforestry. The classes obtained were reclassified according to a five-level scale as suggested by Saaty (1980) and which were similar to "Likert scale" (Lewis and Erdinç, 2017). These classes were named: "Very high, High, Moderate, Low, and Marginal suitable". Once all the criteria were recalculated, the "Weighted Overlay" tool was used to produce the suitability classes. For each criterion, a weight factor given in Table 1 was used at the end when producing the final result. At the end, the resulting raster was then reclassified into four suitability classes.

4. Results

4.1. Suitability classes around the RNI

Results showed that the Consistency Index (CI) was calculated as follows: $CI = (\lambda\max - n)/(n-1)$ with λmax: the maximum eigenvalue of the matrix, and n: the number of criteria (here n was 9). CI have been compared to a random matrix RI (Random Inconsistency Index, RI for n=9 was 1.46). The derived CI/RI ratio, called the Consistency Ratio (CR), was also obtained (Table 2). To validate the matrix and the weights obtained for each criterion, a threshold as required by Saaty (1980) was adopted, i.e., the CR value had to be less than 0.1. For our case, CI was estimated at 0.08 and a CR of 0.07 which was lesser than 0.1. Thus, a good consistency and coherence were observed for the selected criteria.

Table 1
The fundamental scale for pairwise comparison matrix according to Saaty (1980).

Intensity of importance	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective criteria
3	Low importance of one over another	Judgments and experience slightly favor one criterion over another
5	Strong or essential importance	Strongly favored by judgments and experience
7	Judgments and experience strongly favor a criterion	A criterion is strongly favored and its dominance established in practice
9	Absolute or high importance	The evidence favoring one criterion over another is of the highest probable order of affirmation
2,4,6,8	Intermediate values between the two adjacent importance or judgments	When adjustment is needed
Reciprocals	If criterion *i* has one of the above numbers designated to it when compared with criterion *j*, then *j* has the reciprocal value when compared with *i*.	

Table 3 presents classes for each criterion selected for the agroforestry implementation's land suitability analysis around the RNI. The percentages of classes were determined according to the total surface of the study area. Results showed that for climate, more than half (~58%) of the area was classified as moderate for agroforestry suitability and ~10.5% were very suitable. Regarding the elevation, ~26.6% of the area were marginally suitable (>2,000 m) and, therefore, unsuitable for the agroforestry implementation. The dominant soils were Cambisols (~40.8%) and Acrisols (~42.2%); the latter had a strong to very strong suitability. Ferralsols (~13.8%) were classified as marginal due to their poverty in nutrients and the risk of aluminum and iron toxicity. More than ~46.6% of the area were classified as easily accessible by road (< 5 km) and were considered as very highly suitable for agroforestery. Only ~4.1% lands were classified as unsuitable because they were at more than 30 km from the road. The same trend could be observed in terms of distance from localities (agglomerations), local airports, and rivers. As far as the topography was concerned, ~34.9% and ~26.4% of the land presented a very high and high suitability, respectively. Suitability maps of these nine classification criteria are presented in Fig. 4.

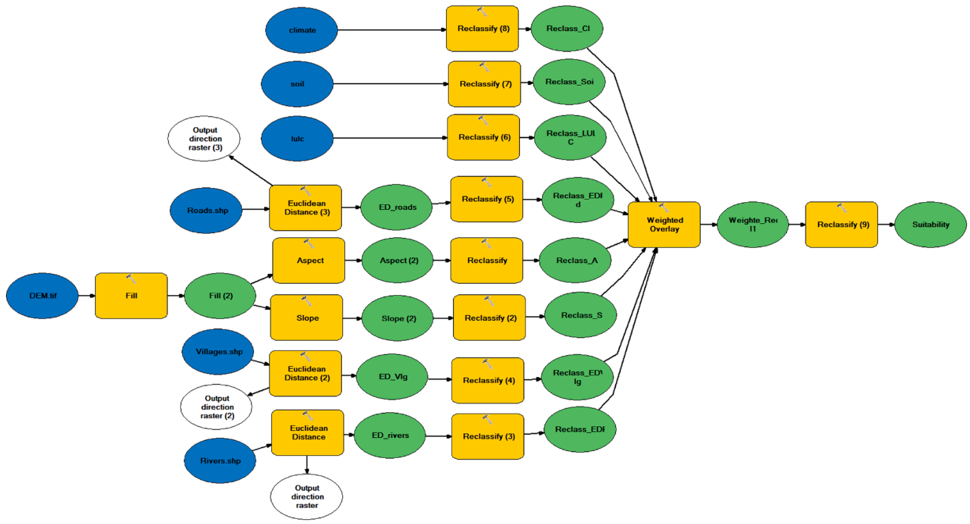

Fig. 3. Suitability for agroforestry implementation around RNI analysis workflow through ArcGIS 10.7 ModelBuilder tool.

The combination of eight criteria to determine land suitability for agroforestry implementation around RNI is presented in Fig. 4. After applying weights to each criterion (weighting the input layers) and its reclassification into four classes by overlaying them using the "Weighted Overlay" tool of spatial analysis in ArcGIS 10.7, the following classes were observed: the first class of very high suitability represented ~29.2% (220,400 ha) of the total study area, followed by the class of high suitability with ~22.3% (167,200 ha). The moderate and low suitability classes represented ~34% (258,400 ha) and ~14.5% (114,000 ha) of the total surface area, respectively (Fig. 5).

The proportions of suitable areas varied with administrative districts around the RNI (Fig. 6b). Most suitable areas were observed in Hauts-Plateaux (~62%), Kaziba (~66.3%), and Minembwe (~34.2%). The Mwenga district had the least proportion of suitable areas (~8.9%). Less suitable areas were mostly located in Kamituga (~38.7%), Mwana (~32.1%) and Mwenga (~33.2%). In summary, very high and high suitable areas were predominant in Itombwe (~90.6%), Minembwe (~89%), Hauts-Plateaux (~85.9%) and Kaziba (~78.5%). These zones/districts should, therefore, be privileged in expanding the agroforestry practice around the RNI.

5. Discussion

Importance of Analytical Hierarchy Process (AHP) in the evaluation of land suitability around the RNI

In this study, the suitability of land for agroforestry implementation was successfully assessed using the AHP and GIS. Nine factors, including climatic, pedological and topographical factors, were selected and their links were calculated using weighted overlay. The weight of each factor was determined by AHP, and finally the land suitability index for agroforestry implementation was calculated using a linear additive combination model. The application integrated MCDA theory including AHP and GIS, and thus, avoided the problems resulting from the uncertainties, subjectivities and characteristics of the traditional land suitability assessment hierarchy process (Feizizadeh et al., 2014).

In this study, consistency and coherence were assessed by CR and CI; the CR value found was 0.07 which remained <0.10 and, therefore, the process was consistent and the weights could be used. This MCDA process is widely used worldwide as showed by Kurttila et al. (2000) and (Quinta-Nova and Roque, 2018). These authors' results showed that three criteria including soil potential, slope (%) and slope aspects helped identify the land which could be subjected to conversion and/or changes in terms of management, to assist the decision-makers in setting priorities and making the best land use decisions. In reducing complex decisions to series of two-by-two comparisons and then synthesizing the results, AHP helps in capturing both the subjective and objective aspects of a decision (Malay, 2016).

Other methods have been tested to determine the weights of these factors, such as the parametric method (Albaji et al., 2009), the ordered weighted mean (Mokarram and Aminzadeh, 2010), Electre Tri (Mendas and Delali, 2012), the membership approach (Ahamed et al., 2000; Cengiz and Akbulak, 2009), relational analysis, simple overlay maps in

Table 2
Pairwise comparison matrix for multi-criteria decision problems (weights, Consistency Index (CI) and Ratio (CR)).

Criteria	Land use	Elevation (m)	Aspect	Slope (%)	ED to Road (km)	ED to villages (km)	ED to rivers (km)	Climate	Soil	Matrix	Weight (%)
Land use	1.000	0.143	0.250	0.250	0.200	0.125	0.250	0.143	0.333	0.2308	01.92
Elevation (m)	7.000	1.000	0.500	0.333	0.250	0.200	0.200	0.111	4.000	0.4356	03.62
Aspect	4.000	2.000	1.000	0.125	0.143	0.500	0.250	0.167	0.200	0.4832	04.03
Slope (%)	4.000	3.000	8.000	1.000	0.125	0.167	0.125	0.500	7.000	0.7711	06.42
ED to road (km)	5.000	4.000	7.000	8.000	1.000	0.143	0.250	0.200	0.500	1.2968	10.80
ED to villages (km)	8.000	4.000	2.000	6.000	7.000	1.000	0.333	0.125	0.333	1.8036	15.022
ED to rivers (km)	4.000	5.000	4.000	8.000	4.000	3.000	1.000	0.333	0.200	2.6674	20.213
Climate	7.000	9.000	6.000	2.000	5.000	8.000	4.000	1.000	0.111	4.3184	28.96
Soil	3	0.250	5	0.143	2	3	5	9	1.000	1.116	09.30
									Sum	12.006	1.000
ED= Euclidean distance									Consistency index (CI)		0.0867
									Consistency ratio (CR)		0.07

Table 3
Classification criteria used in the land suitability analysis for agroforestry implementation around the RNI.

Parameters/ Criteria	Suitability	Classes	Number of pixels	Area (%)	Suitability index
Climate	Very high	*Aw3*	2938	10.5	0.8–1.0
	High	*Cwb*	1259	4.5	0.6–0.8
	Moderate	*Cfb*	16400	58.6	0.6–0.4
	Low	*Af*	9625	34.4	0.4–0.2
Elevation	Very high	<500 m	5484	19.6	0.8–1.0
	High	500–1000 m	7023	25.1	0.6–0.8
	Moderate	1000–1500 m	5428	19.4	0.6–0.4
	Low	1500–2000 m	4002	14.3	0.4–0.2
	Marginal	>2000 m	6044	21.6	0.2–0
Soil	Very high	Acrisols	11808	42.2	0.8–1
	High	Cambisols	11417	40.8	0.6–0.8
	Moderate	Plinthosols	895	3.2	0.6–0.4
	Low	Ferralsols	3862	13.8	0.4–0.1
Euclidean distance to the road	Very high	<5 km	13040	46.6	0.8–1.0
	High	5 to 10 km	6799	24.3	0.6–0.8
	Moderate	10 to 20 km	5232	18.7	0.6–0.4
	Low	20 to 30 km	1762	6.3	0.4–0.2
	Marginal	> 30 km	1147	4.1	0.2–0
Aspects	Very strong aptitude	< 5%	9766	34.9	0.8-1.0
	Strong aptitude	5 à 20%	7387	26.4	0.6-0.8
	Moderate ability	> 20%	10830	38.7	0.6-0.1
Euclidean distance to rivers	Very strong aptitude	<3 km	11948	42.7	0.8–1.0
	Strong aptitude	3 to 10 km	6575	23.5	0.6–0.8
	Moderate ability	10 to 15 km	5232	18.7	0.6–0.4
	Marginal ability	15 to 20 km	3022	10.8	0.4–0.2
	Not adapted	> 20 km	1203	4.3	0.2–0.0
Slope orientation	Very high	Dish	6435	23.0	0.8–1.0
	High	North	6380	22.8	0.6–0.8
	Moderate	South	4393	15.7	0.6–0.4
	Low	East	7219	25.8	0.4–0.2
	Marginal	West	3553	12.7	0.2–0.0
Euclidean distance to towns	Very high	< 5 km	16230	58.0	0.8–1.0
	High	5 to 10 km	7778	27.8	0.6–0.8
	Moderate	10 to 15 km	2042	7.3	0.6–0.4
	Low	15 to 20 km	1175	4.2	0.4–0.2
	Marginal	20 km	756	2.7	0.2–0.0

ArcGIS (Kuria et al., 2011; Falasca et al., 2014), and the FAO framework. Regression-based analysis and Principal Component Analysis (PCA) are also used (Elsheikh et al., 2013). However, these methods have drawbacks in determining criteria weights. The FAO 1976 framework remains widely used in land suitability assessment (Olaleye et al., 2008; Feizizadeh et al., 2013; Elsheikh et al., 2013; Ahamed et al., 2017). Besides, much research did not integrate the AHP approach. Results from this study suggested that AHP should be integrated in such analysis along with the FAO framework for assessing land suitability for better results as also supported by other scholars (Elsheikh et al., 2013; Ahamed et al., 2017). The weighted overlay analysis was effective to resolve spatial complexity in suitability analysis and site selection based on general measurement of dissimilar and diverse impacts. In our case, all the created criteria layers were combined with each other in ArcGIS to apply the weighted overlay techniques (Girvan et al., 2003). The suitability for agroforestry development has been found using weighted overlay techniques based on AHP and MCDM (Multi-Criterion Decision Making) approaches.

Factors affecting the agroforestry land suitability around RNI

Nine factors were combined to assess suitability for agroforestry, and from these factors, four had contributed up to 84% of the suitability. These were climate types (~28.9%), Euclidean distance to rivers (~20.1%), to local villages, local airports (15%) and roads (10%). This observation seemed quite obvious given the geographical location of the study area. Indeed, areas with high aptitude were those from the *Aw3* and *Cwb* climate types. These climate types alternate wet periods (of ~9 months) with dry periods (~3 months). These climates are suitable compared with the typical equatorial climate where it rains all year round; limiting the seedling and nursery establishment and other field preparation works. Equatorial conditions also constrain the optimum growth of species that do not tolerate excess water (Zimmermann et al., 2009; Ghannoum and Way, 2011). The accessibility to water points by reducing the Euclidean distance to rivers, the easy access to materials (inputs) with the accessibility to roads, villages/agglomerations, and local airports had made some areas more suitable than others. That is why suitable areas were more predominant in districts like Kaziba and Hauts-Plateaux than Mwenga, Kitutu, Mwana, etc. (M'Keyo, 2000). These latter areas had almost impracticable roads, making it difficult to access production inputs. Another aspect was related to the presence of active armed rebel groups across these areas making them unsafe for producers (Vlassenroot and Huggins; 2005; Metre, 2011; Maphosa, 2013; Vogel and Musamba, 2016).

Selection of tree species for dissemination in areas around RNI

The effectiveness of the agroforestry practice would be experienced if a rather "ecological" adequacy was observed between the tree species and the main crops produced in areas around the RNI. This implies that species selection should depend on farmers' needs, the trees diversity and the farmers' choice, the availability of plant materials, costs and the investment returns, maintenance and management, the market and economic diversification. Choice of tree species should also seek the valorization of local species or think about exotic species that can easily be adapted to local environments (Cooper et al., 1996); (Dumont et al., 2015, 2019). These trees should allow finding fruits without picking them from the RNI by local communities surrounding it. Establishing trees within agricultural systems would avail Non-Timber Forest Products (NTFPs) such as nuts, oil, honey, seeds, and mushrooms without necessarily invading the RNI (Dumont et al., 2015).

The majority of populations around the RNI are rural, with firewood as the main source of energy, and the lumber and sawn timber are the main house construction materials. Woods are also used for staking and tree leaves as fodder. An appropriate choice of tree species to be disseminated in the study area is a critical determinant for successful agroforestry implementation across selected suitable areas. We could recommend, for example, the *Sesbania sesban* (L.) and *Leucaena leucocephala* (Lam.). In the same context, a list of ~120 tree species, shrubs and lianas were investigated and proposed by Dumont et al. (2015); of which ~78 species were native and ~42 of exotic origin. These authors suggested also how these ranges of species could be integrated into agricultural, livestock or forest production systems in the low, medium, and high altitude areas of North- and South-Kivu. Seedling nurseries were made and tree plantlets were provided to some local organizations for plantation (Fig. 7).

Agroforestry in South-Kivu in general and particularly in areas around the RNI should be aimed at increasing the population production of tree products such as fruits, firewood and construction wood, and fodder production for self-consumption and sale in order to improve the living conditions of local communities. In South-Kivu, the agroforestry approach was generally applied and linked only to erosion management which was, one of (if not the major) the land degradation factors in the region (Dumont et al., 2015; Chuma et al., 2021b). However, its implementation effectiveness lied in explaining the agroforestry impact on the water erosion, which is a serious threat in the region. It also promoted a good choice and adaptation of combination techniques with cropping systems; starting with the development of pilot sites while improving training and extension services on the approach. This

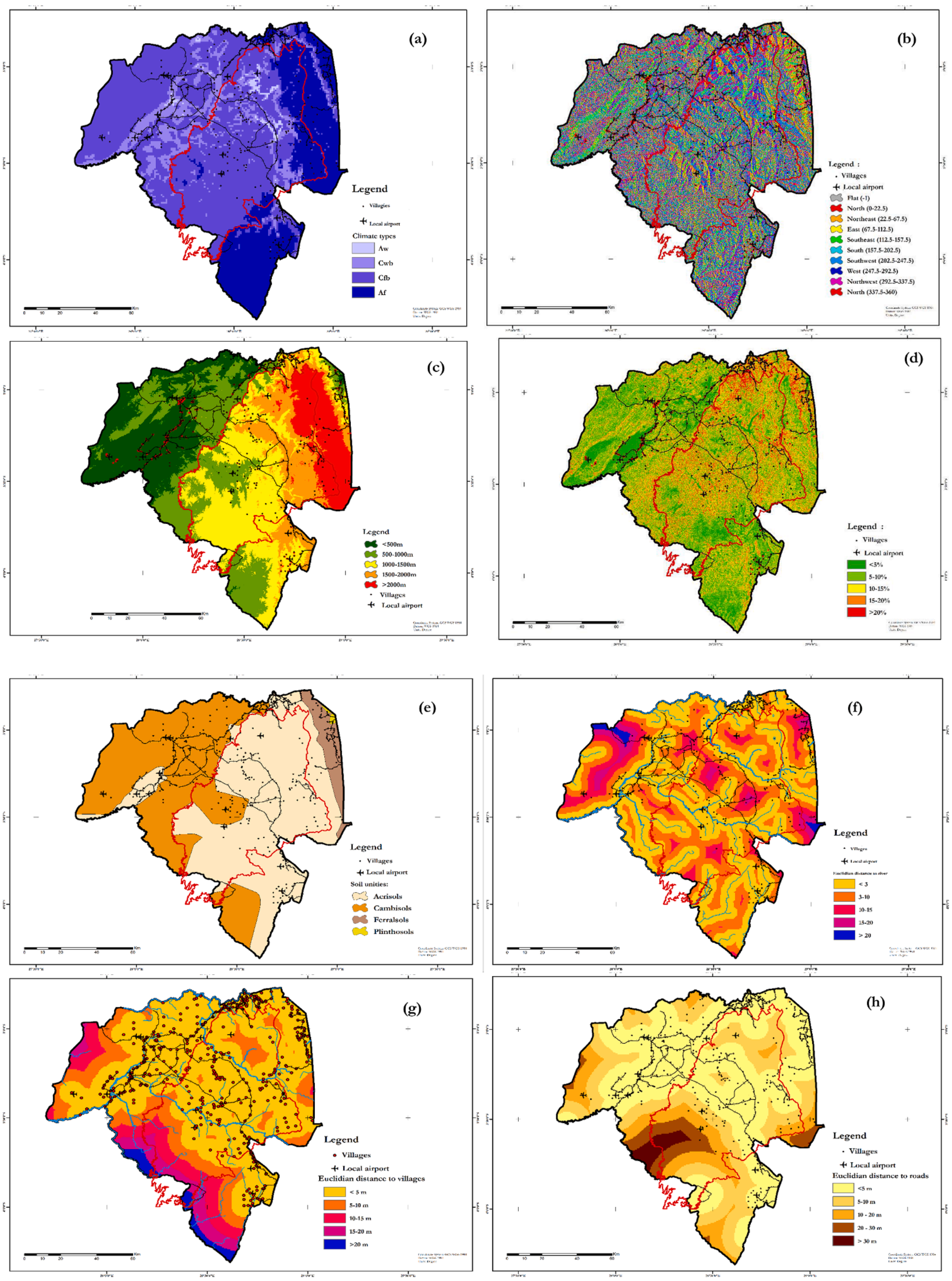

Fig. 4. Factors integrated to determine the suitability map for agroforestry implementation around the RNI, eastern DR Congo. We combined slope (in %), climate types (a), slope aspect (b), elevation (c), slope (d) and soil unities (e); Euclidean distance to river (f), villages and airport (g), roads (h), and the land use and land cover (Fig.2).

operating approach had sometimes caused confusion in these areas among involved stakeholders (Dumont et al., 2015; Chuma, 2019).

Agroforestry would also generate income, produce biopesticides, while providing environmental services such as fertilization (by recycling of organic matter from leaves of green manures, by fixing biological nitrogen using leguminous or fighting against soil water erosion). Formerly, in South-Kivu, the agroforestry was used for riverbank stabilization, road and roadside stabilization, gully rehabilitation and erosion control (Wouters et al., 2010), afforestation and commercial tree plantations, and integration of trees into pastures. Hence, the practice provided some environmental services such as soil water erosion control, soil fertility improvement, water conservation, microclimate improvement and creation that could improve agricultural productivity and landscape resilience. Chuma et al. (2021a) showed the crucial role of trees in gully stabilization in South-Kivu. Reduced erosion (soil loss) in areas covered by perennial crops such as tea plantation and other tree species in a South-Kivu watershed had also been reported (Chuma et al., 2021b). Dumont et al. (2015) detailed the products of agroforestry and included: timber, construction and fuelwood (charcoal), wood, stakes, straw fibers, vegetables, fruits, nuts, honey, seeds, fodder, locally edible caterpillars, mushrooms, cosmetics, medicines, seeds, tannin, spices, insecticides, and a range of other food products.

A zoning project has been developed and proposed by the RNI to the local communities for validation and approval. The project included three zone types: a zone where only scientific research will be authorized; a buffer zone called "for sustainable management" with 3 km wide surrounding the entire RNI area; and the “multi-purpose use zone” which includes residential areas, agricultural areas, agropastoral areas,

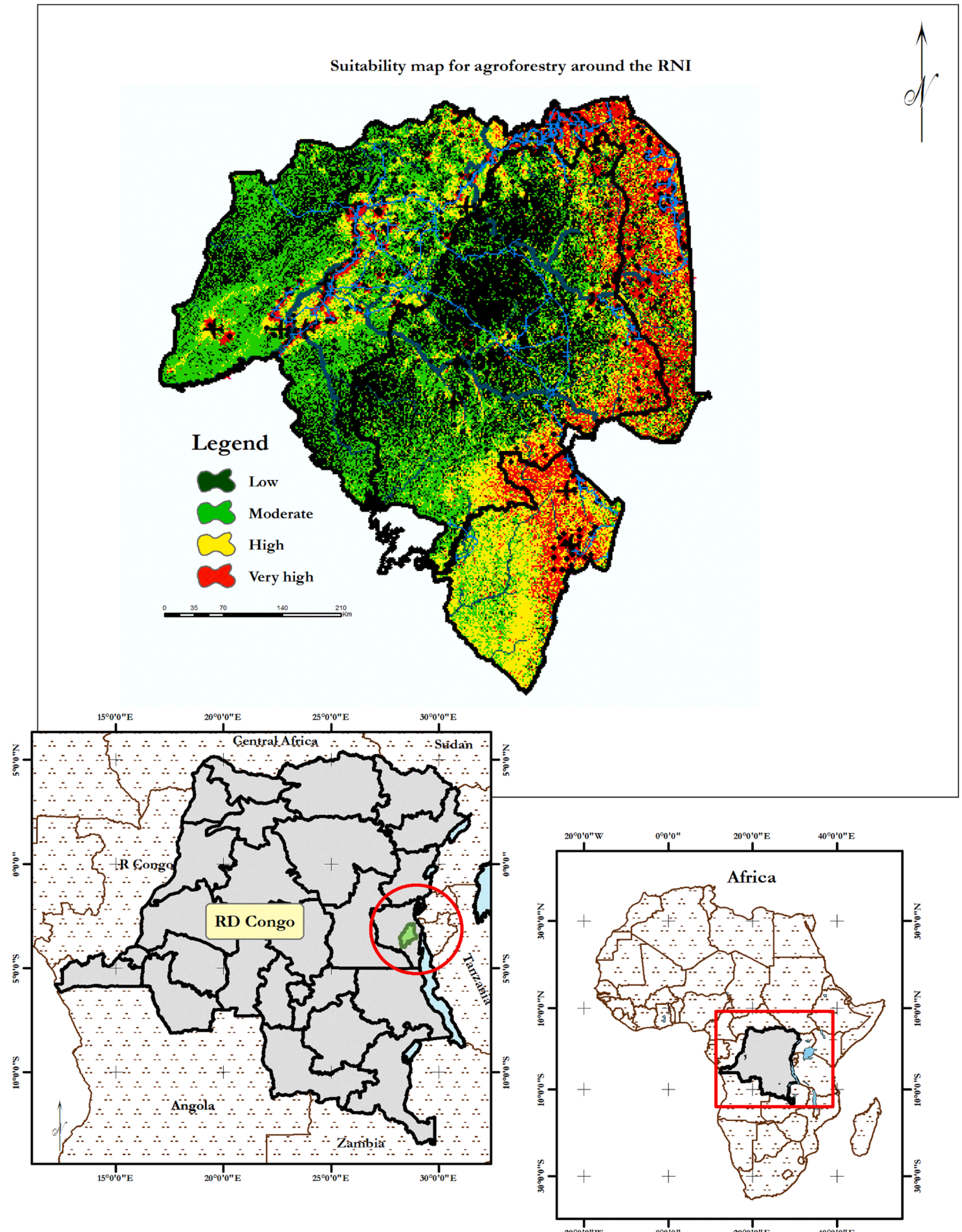

Fig. 5. Suitability map for agroforestry implementation around the RNI, eastern DR Congo.

areas to be reforested, areas of permanent production forest and areas where hunting will be authorized (Airaud, 2017). The results obtained from this study can, thus, be used by extension agents or decision-makers or farmer support structures in the local communities for successful implementation of agroforestry practices around the RNI. Our study will also constitute a guide or support in improving the field productivity in this area while increasing resilience to climate change, improving the environmental conditions around the reserve, and increasing the well-being of the surrounding communities.

Implementing the agroforestry will thus allow the inclusion of trees and shrubs in the cropping systems in order to increase crop productivity, profitability and diversity while making them sustainable ecosystems. These trees provide multiple functions not only to the producers but also to the environment in which they grow. This approach can, therefore, improve rural welfare by diversifying local populations' production with tree sub-products such as fruits, leaves, etc., staple crops and livestock while conserving biodiversity and soil fertility around the RNI. Such positive effects of agroforestery have been reported in a case study in Indonesia (Wangpakapattanawong et al., 2017).

The trees incorporated in the agrosystems will provide shelter for livestock, a place for anti-pathological agents such as birds and other insects to live, which would reduce the use of pesticides, while recycling nutrients and organic matter to the soil to promote the growth and production of annual crops. It will also reduce high fertilizer requirements. Increasing the soil organic matter content allows for good nutrient and water conservation which is important for optimum plant growth and productivity. The nutrient cycling through the agroforestry system is shown in Fig. 8.

Another positive aspect of the tree integrated to agrosystems is the provision of wood products such as tree sticks for construction, staking, building, and thus, reduced anthropogenic pressure on the RNI. The pressure due to harvesting and search for NTFPs will also be reduced since the population could get them through agroforestry. One prerequisite for successful agroferestery uptake by local communities is an appropriate choice of tree species to be disseminated; these should meet

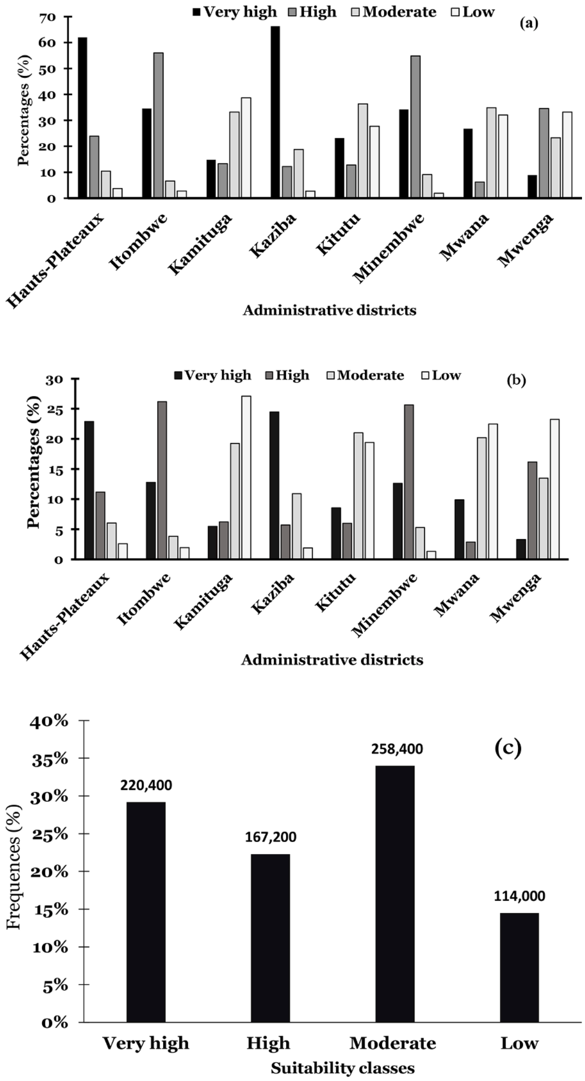

Fig. 6. Variation of suitability classes for agroforestry implementation around RNI in different administrative districts (a), according to each suitability class (b) and suitability class proportions (%) and area (in hectare) for all the selected areas (c) (Value above each bar represents the surface area in ha).

the needs and requirements of the community. The ways trees can better produce ecosystem services of regulation, provide and support to the local community have been discussed by Kuyah et al. (2016) and FAO (2016). Agriculture and forestry had long been separated scientifically and institutionally, so the agroforestry approach had come to link the two and thus provides a bridge between them.

In the study area, different tree species are needed to meet the requirements of different ecological niches and local livelihood strategies. Depending on the location in the landscape and their characteristics, trees provide a wide range of wood and non-wood products such as fruits, fodders, firewood and medicines, and perform important ecological functions such as combating erosion, improving soil fertility, and regulating the climate (Dumont et al., 2015). Thus, the tree in the ecosystem allows water regulation, serves as boundaries among farms, reduces the effects of wind and provides habitat for animals. It also provides shelter for animals and humans (farmers or farm workers). Finally, the tree constitutes a carbon store and, therefore, gage for climate resilience. Some of the tree species of agroforestry importance include *Moringa oleifera* (Moringa) for its multiple food and medicinal uses and its ability to grow on non-fertile soils, *Persea americana* (avocado tree), *Psidium guajava, Sesbania sesban*, etc. (Dumont et al., 2015).

A non-exhaustive list of tree species adapted to the conditions of North- and South-Kivu Provinces was elaborated by Dumont et al. (2015). These species were classified according to their use, adaptation, and nutritional composition (in mineral elements and vitamins).

It is generally agreed that the conservation of a natural resource and biodiversity requires designing of protected areas and an appropriate management of areas surrounding the reserves. Agroforestry could contribute significantly to this conservation approach by increasing diversity and productivity of agricultural production, providing habitats for animals and other living organisms around protected areas, and thus reducing pressure on the RNI. Moreover, Schroth et al. (2004) stated the potential of agroforestry in biodiversity conservation as follows: ".... the effective integration of agroforestry into conservation strategies was, without doubt, the institutional and decision-making challenge.... ».

6. Limits of the study

This study applied the AHP combined with GIS in mapping suitable zones for agroforestery in a natural reserve located in eastern DRC. AHP helped to determine level and weights of selected criteria since weights and scores need to be designated carefully (Kritikos and Davies, 2011; Nefeslioglu et al., 2013). Free online available data were used in this study; these data sometimes had limited resolution for a better accuracy. The utilization of very high-resolution (VHR) satellite images could help in evaluating finer areas. Also, the identified areas have to be inspected at the field level along with some other local and regional parameters before implementing agroforestry around the RNI.

The suitability map generated was based on all tree species and a limited number of parameters, while the best way should be to focus on important species to local communities. For more beneficial and accurate results, the study could demand emphasizing on some important species, such fruit and medicinal plant species, which may have a

Fig. 7. Seedling nursery in a village around the RNI for agroforestry implementation in the Hauts-Plateaux.

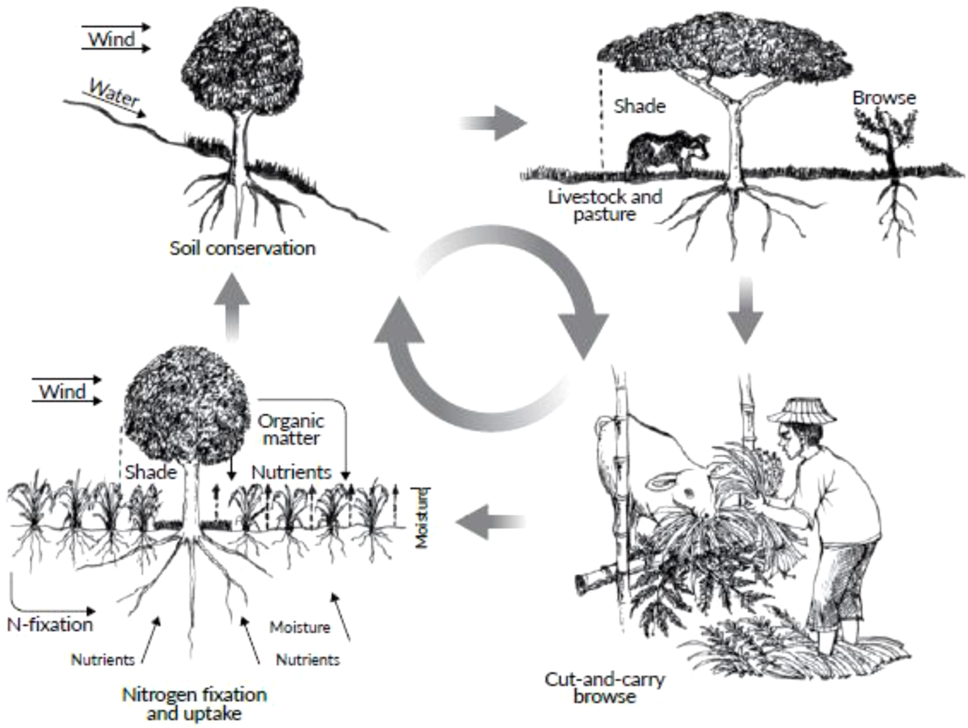

Fig. 8. Nutrient cycling in the agroforestry system (Modified from Xu et al., 2013).

significant economic value.

7. Conclusion

Using the AHP approach integrated into a GIS tool was convenient in the analysis of land suitability for agroforestry around the RNI located in eastern DRC. The approach provided an excellent mechanism for transforming numerical data with different magnitudes into suitability classes. The integration of the AHP method with GIS thus provided a powerful and accurate combination for the analysis of land suitability. The results obtained provide effective approaches to increase efficient land use and a better approach to implement agroforestry in the region. In areas such as South-Kivu where few investigations on agroforestry have been conducted, suitability maps from this study would allow identifying areas with high potential for agroforestry. We inventoried four agroforestry suitability classes: more than a quarter (~29.2%) of the area surrounding the RNI had a very strong suitability to agroforestry, while ~34% and ~14.5% were moderate or not suitable areas, respectively. In regard to administrative districts around the RNI, three had a large proportion of suitable areas than others. We recommend considering local communities' needs and knowledge (logistic and technical capacity) in implementing agroforestry as a resource management strategy around the RNI. The generated suitability map will serve as a decision-making support tool for successfully implementing a sustainable agroforestry system around the RNI.

Availability of data and materials

The authors want to declare that they can submit the data at whatever time based on request. The data used for the current study are available from the corresponding author on reasonable request.

Consent for publication

Not applicable.

Ethics approval and consent to participate

Not applicable.

Funding

Not applicable.

Declaration of Competing Interest

The authors declare that they have no competing interests.

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