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Monitoring of anthropogenic effects on forest ecosystems within the municipality of Vallières in the Republic of Haiti from 1984 to 2019

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ABSTRACT

The forest resources within the municipality of Vallières in the Republic of Haiti are subject to ever-increasing anthropogenic pressures, leading to a reduction in their area and the degradation of their ecosystem services. This study quantified the spatial pattern changes of forest ecosystems within the municipality of Vallières from 1984 to 2019 using a cartographic approach coupled with landscape metrics. The evolving trend in the landscape within the municipality of Vallières and its sections reveals that in 35 years the area of forests land has diminished through the fragmentation of the large initial patches, as opposed to the progressive dynamics of agricultural and bare land, mainly under strain from the creation and merging of the patches. The underlying causes of the observed landscape dynamics are demographic pressure coupled with the lack of an appropriate program for the preservation of forest resources and improvement of the standard of living conditions of the local population. Our results justify the implementation of strategies to preserve the rare patches of the forests that remain, taking into account the local socio-economic context.

1. Introduction

The natural landscapes of Haiti, especially the forest ecosystems, are subject to destructive natural phenomena such as cyclones. However, as well as these natural phenomena, the recent demographic explosion has added the effects of anthropogenic activities to the degradation of these natural landscapes (MDE, 2019). Estimated at nearly half of the country's area (27,750 km2) at the beginning of the 20th century, forest cover reduced by between 2% and 5% in 2015 alone (FAO 2015). When forest plantations are taken into account, some authors estimate that about 30% of the territory is covered by wooded areas (Tarter et al. 2016). The reduction of Haiti's forest ecosystems has led to, among other things, the erosion of biodiversity, a degradation of the agricultural quality of soils as a result of erosion, and a scarcity of wood resources (MARNDR, 2010; MDE, 2019).

The municipality of Vallières, located on Haiti's northern massif and once known for its luxuriant forests, has not been spared from the deforestation phenomenon. Indeed, despite the importance of its forest resources in the preservation of watersheds, and their importance for the local economy, this municipality's local populations have become heavily dependent on natural resources to meet their basic needs. Indeed, within the municipality, slash-and-burn agriculture, spontaneous urbanization, and the production of charcoal and wood for construction are all activities responsible for deforestation, which poses a serious threat to the exceptional diversity and endemicity within the municipality of Vallières (IRATAM, 2012).

Although it is clear that in recent decades many forest ecosystems in the municipality of Vallières have been subsequently converted to

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seasonal cultivation (MARNDR, 2011; Célicourt, 2020), no information exists to date on the spatial pattern of land cover changes at the scale of the municipality sections, considered as administrative subdivisions of this municipality. However, these municipality sections are distinct in terms of socio-economic conditions (MARNDR, 2011), which in turn have a large influence on landscape dynamics (Bogaert et al., 2008, Useni et al., 2017a). In the current context of decentralization, the study of landscape dynamics at the scale of municipality sections seems particularly relevant, especially since the (dis)allocation of land coverage and use, which have major impacts on the changes in the landscape of the municipality, depend on the competence of the municipality sections. The scale of municipality section is therefore relevant for any study that could lead to the implementation of a responsible management strategy for forest ecosystems, on which the survival of local populations depends. For this reason, there is an urgent need to understand the impact of the activities of local populations on the dynamics of forest ecosystems in the municipality of Vallières (and its sections), in order to ensure their sustainable management.

Thus, the present study assesses the spatiotemporal dynamics of forest ecosystems in the municipality of Vallières (Haiti) using remote sensing, Geographic Information Systems (GIS) and landscape ecology analysis tools. It is hypothesized that inappropriate management of agricultural development and habitat expansion has led to a spatial pattern change in the landscape, materialized by a decrease in area but an increase in the number of forest ecosystem patches, depending to varying degrees on the socio-economic context of each section.

2. Material and methods

2.1. Study environment: the municipality of Vallières and its sections

The study was conducted in the municipality of Vallières (19°24′00′’-19°33′10′’ N and 71°53′00′’-72°05′00′’ W), located in the north-east department of Haiti. This municipality is divided into three sections, namely Trois Palmistes, Écrevisse or Grosse-Roche and Corosse (Fig. 1). This municipality covers an area of 158.46 km^2 (82.95 for Trois-Palmiste, 47.93 for Corosse and 27.96 for Corosse) with an altitude ranging from 517 m to 1136 m and a relief dominated by a succession of steep mountains. Its climate is of the Af (tropical) type, according to the Köppen-Geiger classification system, characterized by average annual temperatures in the range of 21.1°C to 24.9°C and total annual precipitation reaching 2,036 mm spread over two rainy seasons (May to June and September to December; MARNDR, 2011). The rainy season is interspersed with a winter drought from January to February and a

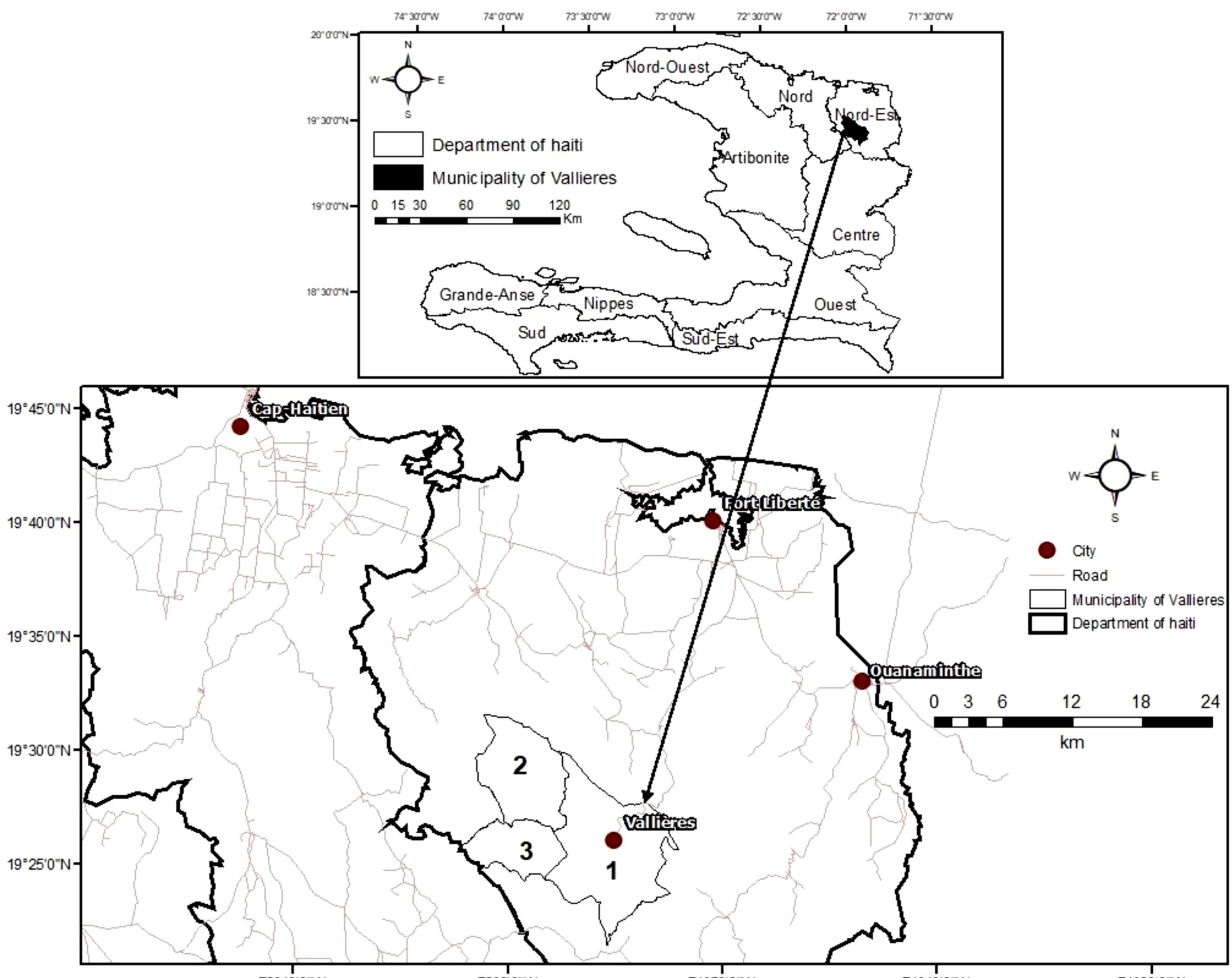

Fig. 1. Location of the municipality of Vallières within North-East of the Republic of Haiti and its communal sections: Trois Palmistes (1), Grosse Roche (2) and Corosse (3).

summer drought from June to August (IRATAM, 2012; Célicourt, 2020). The natural woody vegetation within the municipality of Vallières consists essentially of forest ecosystems dominated by *Pinus occidentalis* L. The population, estimated at 23,536 inhabitants (IHSI, 2015), is mainly engaged in subsistence agriculture, livestock, trade, the exploitation of wood for building and the production of firewood/charcoal, etc. (PADEDD, 2008). There are also mining resources (copper and gold) whose exploitation remains essentially artisanal (MARNDR, 2011). The municipality sections, although dominated by agricultural activities, have contrasting socio-economic characteristics. Thus, the Trois Palmistes section, which is the capital of the municipality of Vallières, contains the devolved services of the Haitian state (town hall, general tax office, etc.). The Corosse and Grosse Roche sections are difficult to access by road, despite the construction of new roads (MARNDR, 2011). In the communal sections of Trois Palmistes and La Grosse, about 60% of the land is used for agriculture, compared with 75% in Corosse (MARNDR, 2008).

2.2. Choice of data and materials used

To monitor and detect land cover changes within the municipality of Vallières, three Landsat images with a spatial resolution of 30 m were used. These images were acquired on 30/01/1984 (Multispectral Scanner System sensor), 23/12/1998 (Thematic Mapper sensor) and 01/12/2019 (Operational Land Imager sensor). These dates correspond to the dry season within the region, in order to minimize the effect of clouds and their shadows (Clerici et al., 2006). Additional data includes shapefiles illustrating the boundaries of the municipality of Vallières and its sections, from the Centre Nationale de l'Information Géo-Spatiale (CNIGS). The pre-processing and spatial analysis of Landsat images was carried out with ENVI 5.3 and ArcGiS 10.5.1 software.

2.3. Preprocessing of Landsat images

The different images used were reprojected into the UTM (Universal Transverse Mercator) / Zone 19 N system, based on the WGS 84 (World Geodesic System) reference ellipsoid. Subsequently, the orthorectification of the Landsat images of 1984 and 1998 was verified on the basis of the Landsat image of 2019, using 64 invariant and well-distributed ground control points throughout the study area. The geometric accuracy of the calibration between different scenes was less than 1 pixel, to ensure the efficiency of the landscape change analysis (Mas, 2000).

2.4. Supervised classification and validation of classification quality

False composite colors of Landsat images were made by combining the near-infrared, red and green bands, the first two channels being adapted for vegetation discrimination (Bonn and Rochon, 1992). Moreover, 640 training zones of all land cover were collected from field visits using GPS (Garmin 66s with an accuracy of 3 m) and visual interpretations of the false composite color with the help of personal knowledge of the study area and high resolution images, such as Google Earth, between October and November 2019. Of these points, 360 training zones were used for supervised classification of Landsat images, based on the maximum likelihood algorithm. Statistical training sites were used to calculate the probability of membership of each pixel to one of the land cover types (Mas, 2000). Initially, eight land cover types were identified and eventually grouped into three categories: agricultural land (fallow, pasture, crops and agroforestry systems), forest land (deciduous forest and coniferous forest) and bare land (bare soil, built-up land, and roads). According to (Zerga et al., 2021), bare lands are areas of land that have been without natural cover or have degraded, either due to erosion, over-grazing or crop cultivation, or through use as urban fabric for residential purposes; forest lands are areas covered by natural or planted trees; agricultural lands are areas prepared for growing crops, areas currently covered with crops, or areas covered with grass and used for livestock grazing.

Subsequently, 280 homogeneous plots were used to evaluate the reliability of the supervised classification of the Landsat images used. As a result of the variation in area coverage of land cover within the municipality of Vallières and its sections, the numbers of reference points were diverse. The LULC types, which have large area coverage such as Enset-based agroforestry, cereal crops, grazing land and forests (natural and plantation forests, including eucalyptus), 50 reference points were considered for each of them. There were 15 reference points of bare land. This evaluation was performed using the Kappa coefficient, and to determine overall accuracy two indices were derived from the confusion matrix and deemed appropriate for the validation of supervised classifications. The raster format of the classified land cover types was then converted into a vector format.

2.5. Analysis of the landscape spatial pattern dynamics

The anthropogenic impact on the morphology of the Vallières Municipality landscape and its sections was highlighted from the calculation of the average area (AA), the percentage in landscape (PLAND), the median area (AMED), the class area (CA), the patch density (PD), defined as the ratio between the number and the total area of the patches within the territory considered, the largest patch index (LPI), defined as the ratio of the largest patch area to the class area, the disturbance index (U), defined by (O'Neill et al., 1988) as the ratio of the cumulative area of anthropogenic land cover (Agricultural and Bare land), and the cumulative area of natural land cover (Forest land). The classified images were compared from two periods, 1984–1998 and 1998–2019.

Furthermore, the decision tree algorithm proposed by Bogaert et al. (2004), which is essentially based on the main elements of the landscape configuration, such as the patch number (expressed in this study through the patch density) and the class area, allowed the identification of the spatial transformation processes that underlie the changes observed within the three land cover classes studied. Comparing $t_{obs} = a_0/a_1$ values (0 is considered the initial year of the period and 1 the terminal year of the period) with the predefined $t = 0{,}5$ allowed for the dissociation of fragmentation from dissection (Barima et al., 2016). Values less than 0.5 suggest fragmentation; those between 0.5 and 0.59 reflect dissection tending toward fragmentation. In contrast, values greater than or equal to 0.6 suggest dissection.

3. Results

3.1. Classification and mapping

Evaluation of the performance results of the classified Landsat images indicates overall accuracy values ranging from 97.50% to 98.93% (Table 1). These accuracies were confirmed by the Kappa coefficients, whose values varied from 96.13% to 99.45%, suggesting a good discrimination of land cover. However, some confusion was noted in 2019, particularly since 6.15% of the pixels in the bare land were classified as agricultural land while 2.15% of the agricultural land pixels were classified as forest land. With user accuracies between 99 and 100%, the forest land was least affected by the samples of the other forms of land cover. The 1998 Landsat image shows a better classification of the bare land, with 98.36% of the pixels correctly classified. Producer's accuracy (PA) of the individual classes of the three classified maps ranged from 93.85% (bare land in 2019) to 100% (forest land in 1984 and 1998; agricultural land in 1998). The user accuracy (UA) was lowest for the agricultural land in 2019 (94.79%) in 2019 and the highest for the agricultural and forest land (100%) in 1984 (Table 1).

Three land cover maps were produced, illustrating the evolutionary trend of land cover within the municipality of Vallières and its sections (Fig. 2). The visual analysis of the landscape spatial evolution between 1984 and 2019 shows an overall spatial reduction of forest land mainly

Table 1
Accuracy assessment matrix for the classified Landsat images of 1984, 1998 and 2019. The cells of the matrices represent the pixels. UA=User'accuracy ; PA= producers' accuracy. The columns represent actual location of samples on the ground, while rows display classified data showing location of samples in the classified images. Diagonal numbers showed in bold are the correct classifications. The off diagonal numbers in rows and columns are misclassifications or errors.

	Classified data					
	Reference data	Forest land	Agricultural land	Bare land	Total	PA (%)
1984	Forest land	**123**	0	0	123	100.00
	Agricultural land	0	**96**	2	98	97.96
	Bare land	0	0	**59**	59	100.00
	Total	123	96	61	280	
	UA	100.00	100.00	96.72		
		Overall accuracy= 98.93 Kappa Coefficient= 98.33%				
1998	Forest land	**122**	0	0	122	100.00
	Agricultural land	1	**95**	1	97	97.94
	Bare land	0	1	**60**	61	98.36
	Total	123	96	61	280	
	UA	99.19	98.96	98.36		
		Overall accuracy= 99.67% Kappa Coefficient=99.45%				
2019	Forest land	**121**	1	0	122	99.18
	Agricultural land	2	**91**	0	93	97.85
	Bare land	0	4	**61**	65	93.85
	Total	123	96	61	280	
	UA	98.37	94.79	100.00		
		Overall accuracy= 97.50% Kappa Coefficient= 96.13%				

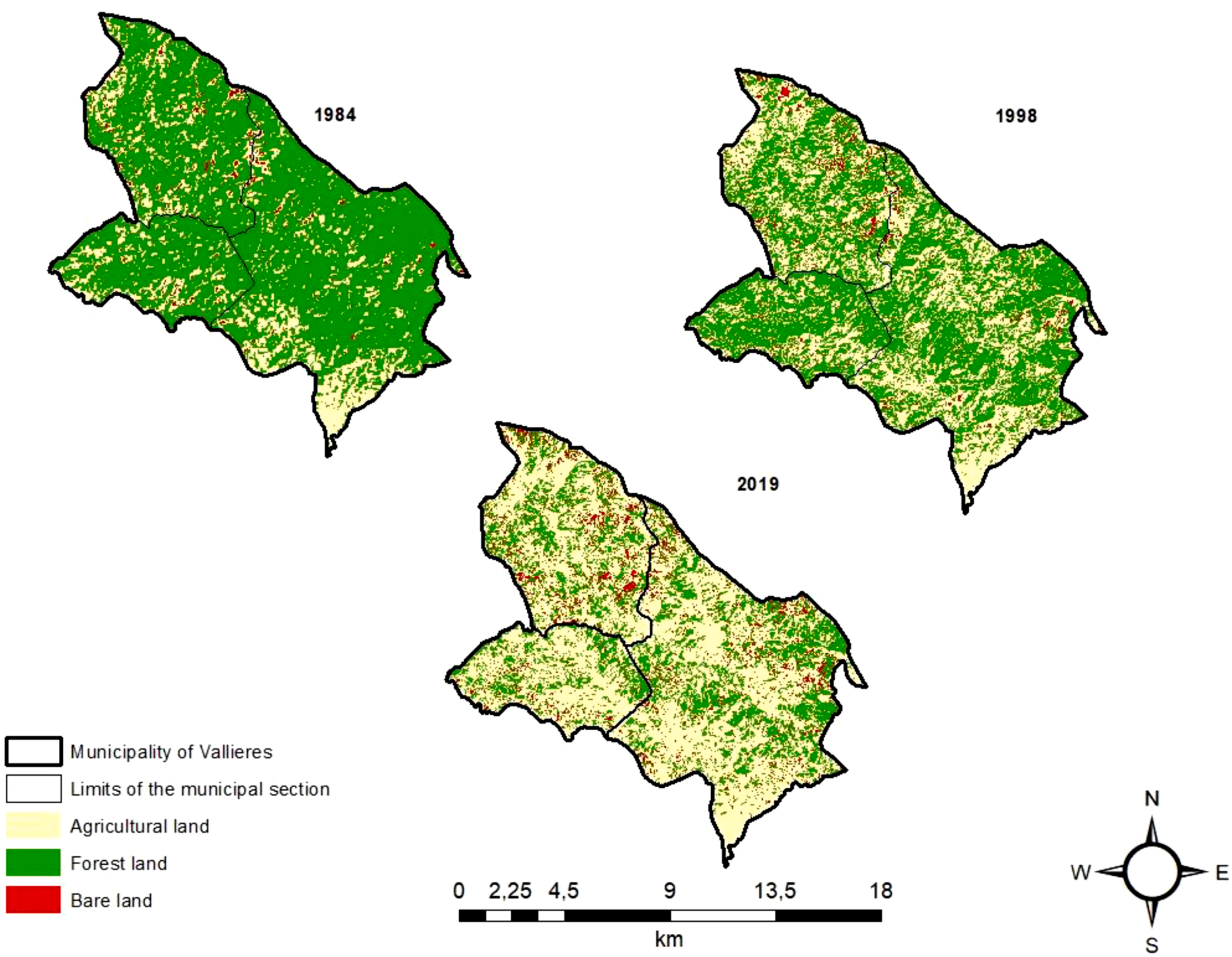

Fig. 2. Land use and land cover in the municipality of Vallières and its sections during the study periods. Maps have been obtained from supervised classification of Landsat images from 1984, 1998 and 2019 based on the maximum likelihood algorithm.

in favor of agricultural land, but also in favor of bare land, though to a lesser extent (Fig. 2).

3.2. Compositional dynamics

The results of land cover change between 1984-1998 and 1998-2019, based on the evolution of PLAND, show that the forest land that was the dominant matrix of the landscape in 1984 and 1998 has been replaced by agricultural and bare land that have increased within the municipality of Vallières and its sections. In the Corosse section, deforestation seemed to be most marked between 1998-2019, compared with the period 1984-1998. As for the agricultural land, this has experienced a progressive dynamic, since its area has tripled within the municipality of Vallières and its sections, and has thus become the new dominant land cover of the landscape in 2019 (Fig. 3).

3.3. Spatial pattern dynamics and anthropogenic landscape change

Between 1984 and 1998, the municipality of Vallières experienced an increase in the forest land PD followed by a decrease in CA, suggesting dissection ($t_{obs}= 0.73 > t = 0.5$) as the dominant spatial transformation process (Table 2). At the level of municipality sections, the trend toward dissection of forest patches was also observed during this same period ($t_{obs} = 0.71$ for the Trois Palmistes section, $t_{obs} = 0.68$ for the Grosse Roche section, and $t_{obs} = 0.86 > t = 0.5$ for the Corosse section). The second period (1998-2019) was characterized by a decrease in CA in parallel with an increase in the PD of forest land within the municipality of Vallières, which is an indication of a transition from dissection to fragmentation ($t_{obs}= 0.52 > t = 0.5$) as the dominant spatial transformation process. The Trois Palmistes section also experienced dissection tending toward fragmentation of forest land patches ($t_{obs} = 0.58 > t = 0.5$), while in the Grosse Roche and Corosse sections, forest land underwent patch fragmentation ($t_{obs} = 0.49$ et $t_{obs}= 0.43 < t = 0.5$) reflected by an increase in PD followed by a decrease in their CA (Table 2).

This trend of dissection and fragmentation of forest land patches was also observed by the decrease in the LPI of forest patches within the municipality of Vallières between 1984 and 2019 from 98.99% to 26.82%. It should be noted that this decrease was most significant between 1998 and 2019, as the value of LPI fell from 94.22% to 26.82%, an approximately fourfold decrease in 21 years (1998-2019). This process was also observed in the three municipality sections where the LPI of

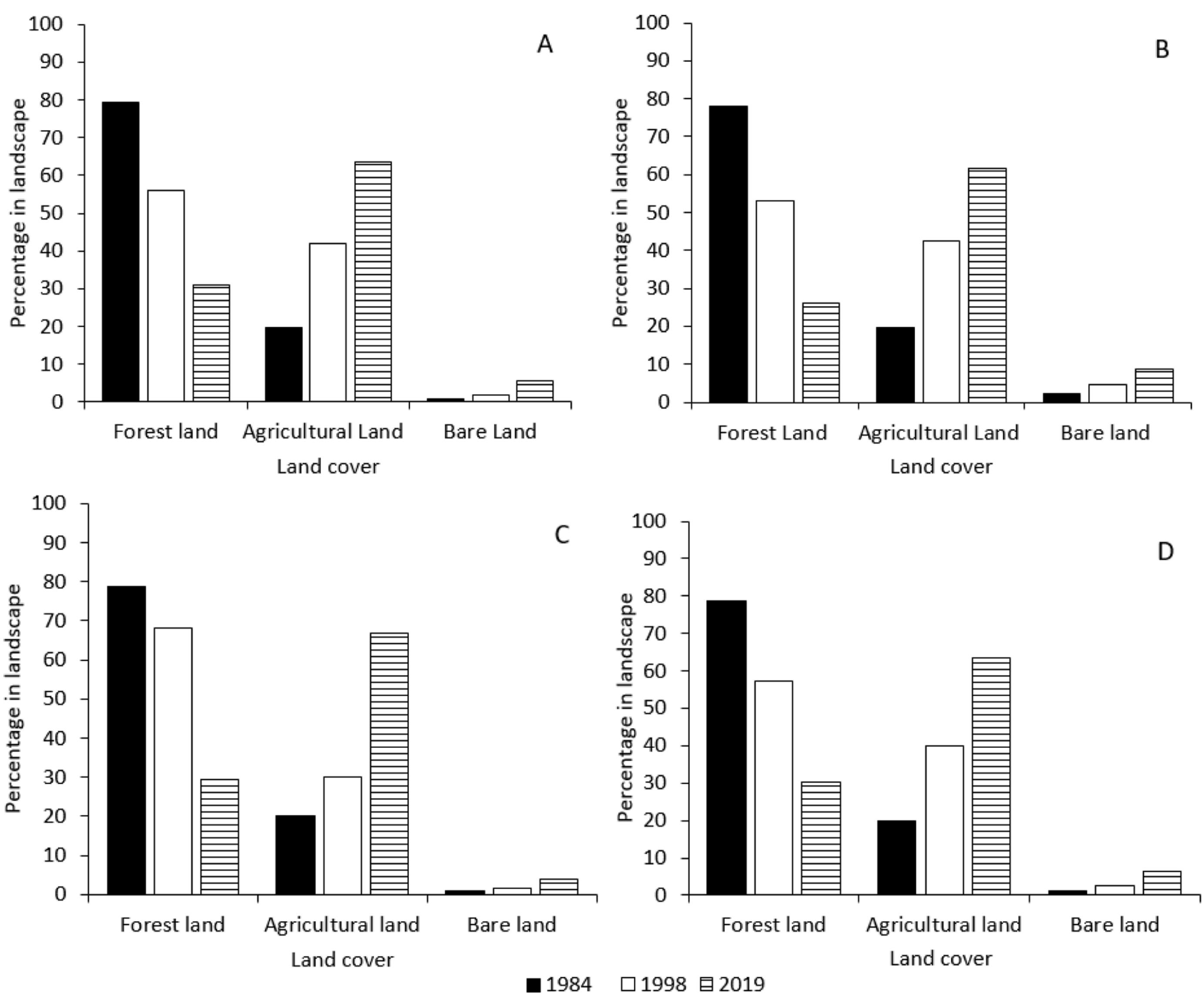

Fig. 3. Evolution of the PLAND of forest, agricultural and bare land within the Trois Palmistes section (A), Grosse Roche section (B), Corosse section (C) and the municipality of Vallières (D) in 1984, 1998 and 2019. The data are derived from the classification of Landsat images based on the maximum likelihood algorithm.

Table 2
Evolution of CA (km^2) and PD expressed as number of patches per km^2 winthin the municipality of Vallières and its sections in 1984, 1998 and 2019. These two metrics help in identifying the spatial transformation process according to the decision tree algorithm of Bogaert et al. (2004)

	Year	Landscape metric	Trois Palmistes section	Grosse Roche section	Corosse section	Municipality of Vallières
Forest land	1984	CA	64.86	36.33	21.78	122.97
		PD	0.66	0.22	0.32	0.47
	1998	CA	45.86	24.81	18.82	89.49
		PD	5.91	6.21	2.13	5.20
	2019	CA	26.80	12.25	8.18	47.23
		PD	40.01	41.46	38.75	40.17
Agricultural land	1984	CA	16.18	9.18	5.59	30.95
		PD	31.45	21.89	32.73	34.83
	1998	CA	34.29	19.84	8.30	62.43
		PD	26.25	27.26	56.03	30.53
	2019	CA	51.79	28.87	18.39	99.05
		PD	31.28	42.06	72.48	25.23
Bare land	1984	CA	0.69	1.13	0.26	2.08
		PD	124.10	106.67	135.14	116.03
	1998	CA	1.49	2.09	0.49	4.07
		PD	186.43	193.41	521.39	303.46
	2019	CA	4.52	4.11	1.09	9.72
		PD	277.25	243.67	343.72	325.38

forest patches decreased from over 90% in 1984 and 1998 to 18.78%, 8.77% and 13.29% in 2019 respectively in the Trois Palmistes, Grosse Roche and Corosse sections. This reflects a dynamic of large forest patch fragmentation in the landscape into a large number of small patches, probably coupled with greater spatial isolation, especially during the second study period. The decrease in AA and AMED of forest land also indicates the preponderance of small forest patches in the landscape of the municipality of Vallières and its sections. Accordingly, the amplitudes of spatial pattern dynamics are, in fact, stronger, particularly in the Grosse Roche and Corosse sections (Table 3).

Between 1984 and 1998, creation was the dominant spatial transformation process of the agricultural and bare land within the municipality of Vallières and its sections as the PD and CA increased (Table 2). On the other hand, the processes of patch aggregation and creation were dominant, respectively, for agricultural land and bare land from 1998 to 2019. Indeed, the increase in the CA was accompanied by a decrease of PD in agricultural land, but an increase in the PD. The agricultural zone in the three municipality sections showed an increase in PD and CA, suggesting creation as the dominant spatial transformation process. The Trois Palmistes and Grosse Roche sections also experienced the creation of bare land patches as the dominant spatial transformation process, while patch aggregation was observed in the Corosse section (Table 2). This tendency towards the merging of the small patches of the agricultural and bare land in the landscape was also reflected in the increase of their LPI over time, also in the AA and AMED (Table 3).

The extent of anthropogenically driven change of the landscape in the municipality of Vallières and its sections was illustrated by the U index. The value of the U index has increased eightfold in 35 years, from 0.27 in 1984 to 2.30 in 2019 in the municipality of Vallières. The almost tenfold increase in the value of the U index in Trois Palmistes section (0.26 in 1984 and 2.10 in 2019), the Grosse Roche section (0.28 in 1984 and 2.69 in 2019) and the Corosse section (0.27 in 1984 and 2.38 in

Table 3
Quantifying of landscape anthropisation from the evolution of the LPI (%), AMED (km^2) and the AA (km^2) of forest, agricultural and bare land within the municipality of Vallières and its sections in 1984, 1998 and 2019.

	Year	Landscape metric	Trois Palmistes section	Grosse Roche section	Corosse section	Municipality of Vallières
Forest land	1984	LPI	98.24	98.24	99.78	98.99
		AA	1.41	4.55	3.10	2.12
		AMED	0.01	0.02	0.01	0.01
	1998	LPI	93.10	93.05	98.51	94.22
		AA	0.17	0.04	0.47	0.19
		AMED	0.00	0.01	0.00	0.00
	2019	LPI	18.78	8.77	13.29	26.82
		AA	0.02	0.02	0.02	0.04
		AMED	0.00	0.01	0.00	0.00
Agricultural land	1984	LPI	35.10	35.10	12.16	4.69
		AA	0.00	0.02	0.01	0.04
		AMED	0.00	0.00	0.00	0.00
	1998	LPI	18.73	11.45	31.18	10.29
		AA	0.04	0.16	0.02	0.03
		AMED	0.00	0.00	0.00	0.00
	2019	LPI	57.93	62.35	43.50	60.70
		AA	0.04	0.32	0.21	0.09
		AMED	0.01	0.01	0.01	0.00
Bare land	1984	LPI	9.35	9.35	9.72	3.47
		AA	0.01	0.01	0.01	0.00
		AMED	0.00	0.00	0.00	0.00
	1998	LPI	16.13	45.32	23.69	2.70
		AA	0.01	0.01	0.01	0.00
		AMED	0.00	0.01	0.00	0.00
	2019	LPI	2.43	4.56	66.76	3.00
		AA	0.02	0.01	0.02	0.01
		AMED	0.01	0.01	0.01	0.02

2019), expresses an important dynamic of the decrease in the proportion of forest land and its conversion into anthropogenic land cover.

4. Discussion

4.1. Methodological approach

Landsat images are freely available and can be advocated for large-scale studies, as they provide a global view of the entire landscape (Bamba et al., 2010; Barima et al., 2011; Mama et al., 2013). Coupled with the reduced amount of land cover identified in this study and a good knowledge of the region, the supervised classifications of Landsat images resulted in acceptable values for the map accuracies produced (Mama et al., 2014). Furthermore, the basic data used to analyze the dynamics of the anthropogenic change of forest ecosystems in the municipality of Vallières are derived from landscape metrics related to the area and patch numbers, which are likely to elucidate the fragmentation of complex landscapes (Burel and Baudry, 2003; Bogaert and Mahamane, 2005). It should be noted that few landscape metrics have been used in this study, since most are highly correlated (Bogaert and Mahamane, 2005).

4.2. Slash-and-burn agriculture and deforestation in the municipality of Vallières

The analysis of the landscape dynamics within the municipality of Vallières shows that forest land has been replaced by anthropogenic formations (agricultural and bare land). The results obtained illustrate that the extent and rate of deforestation reached an annual rate of 1.92% between 1984-2019, which remains well above the rates recorded between 1985 and 2018 at the level of the national parks of La Visite (1.2%), the national park of Macaya (1.4%; Salomon et al., 2021). The Corosse section records the highest rate of disturbance and loss of forest land (2.41%) during the second period studied (1998-2019), due probably to the opening of a new road that facilitates intensive trade in charcoal and timber for construction. Our results corroborate the findings of (Marsik et al., 2011) and Newman et al. (2014) that there is a link between the presence of roads and deforestation dynamics. In addition, the Corosse section has a higher population density, estimated at 181.47 inhabitants/km^2, compared with 148.12 inhabitants/km^2 for the Grosse-Roche section and 142.21 inhabitants/km^2 for the Trois-Palmistes section (IHSI, 2015). This reveals the relevance of the influence of population density on deforestation, as confirmed by (Aide et al., 2013) in the Caribbean region and elsewhere (Kouakou et al., 2017; Useni et al., 2017b).

Anthropogenic effects on forest lands were illustrated by the fragmentation and isolation of patches due to agricultural and bare land expansion in the landscape. Anthropogenic impact was also demonstrated by the presence of a higher amplitude of spatial dynamics of forest patches as opposed to agricultural and bare land, particularly in the Grosse Roche and Corosse sections. This situation could be explained by the precarious socio-economic conditions of the population, coupled with the absence of local services (care, water, sanitation, agricultural bank, etc.) from the Haitian state in these areas (MARNDR, 2008 et 2011). These results also corroborate the findings of Versluis and Rogan (2010) in Fonds-Verrettes, where anthropogenic activities have contributed to the change in landscape dynamics in favor of agriculture. This implies that the acquisition of fertile soils for agriculture, particularly slash-and-burn agriculture, is at the root of forest degradation in the areas of Haiti's landscape dominated by forest patches. Indeed, being deprived of any state support, the population in rural Haiti, with little possibility of economic diversification, considers forest resources as the main means to sustain its livelihood (IRATAM, 2012). Moreover, with limited financial means that do not allow local populations to purchase agricultural inputs such as chemical fertilizers, forest soils have been pervasively overrun by agricultural households in the region due to their chemical fertility. In this context, the yield of main crops has been increased by the slash-and-burn cropping system, as demonstrated by maize (of 0.79 t/ha) and bean (0.36 t/ha) yields that are significantly lower than the yields obtained in fertile lands, which are around 4 t/ha for maize and 1.5 t/ha for beans (MARNDR, 2017). Thus, following the intensification of agricultural activities and urban expansion under the effect of population growth, the forest ecosystem land has tended to disappear from the landscape, given the limited nature of geographical space according to the choralogy (Bogaert et al., 2015).

It should also be noted that the forest trees are being cut for the exploitation of timber, charcoal and firewood. Indeed, charcoal and firewood have emerged as the only fuels accessible in more than 70% of households in urban areas and more than 90% of households in rural areas (Racicot, 2011), in a context of increasing impoverishment of the rural population of Haiti, which lives below the poverty line (May, 2015; Hérard, 2019). Faced with this, the exploitation of wood species is generally considered a logical palliative and is usually carried out in an indiscriminate manner (Bellande, 2009). It is true that tree species have played and will continue to play an important role as alternatives to fuel and to solve construction material problems in Haiti. However, the extent to which these factors vary from one area to another, and from one period to another, is leading to an uneven distribution of forest cover loss. For example, from 1984 to 1998, changes in forest land were less significant in the Corosse section due to its reduced accessibility, as evidenced by the absence of a road linking it to other areas. In addition, this section recorded relatively modest population growth during this period (1984-1998), in contrast to the second period from 1998 to 2019 (PADEDD, 2008; IRATAM, 2012). Thus, between 1998 and 2019, the Corosse section recorded the highest forest loss (about 60%), the highest among all sections within the municipality of Vallières and the country, which recorded only 7% of forest cover loss between 2001 and 2017 (MDE, 2019). The accentuated degradation of forest land has led ineluctably to the creation of bare land, as demonstrated in this study, which covered approximately 3.94% of the landscape in the municipality section of Corosse, 6.88% in Trois-Palmistres in 2019 and up to 9, 09% of the landscape in the municipality section of Grosse Roche. These results corroborate those of the General Agricultural Census indicating that 25% of agricultural land has been abandoned following soil degradation in Grosse Roche, against 20% in Trois Palmistes and 15% in Corosse (MARNDR, 2008). This situation is also attributable to the weak capacity of the various stakeholders (the Town Hall, the Boards of Directors of the Communal Sections, etc.) for effectively addressing the problem of forest management and preservation. Indeed, it is well recognized that the higher environmental degradation in developing countries compared with developed countries is due to differences in socioeconomic development and enforcement of environmental regulations (FAO and PNUE, 2020).

4.3. Implications for land use planning, management and conservation

This study revealed that agricultural and energy production contributes to the regression of forest ecosystems, probably associated with the loss of plant species; this is typical for most forest areas in Haiti (MARNDR, 2010; Salomon et al., 2021). Fragmentation is recognized as the primary cause of the erosion of biodiversity, among other things through habitat loss as demonstrated in our study. Moreover, the remaining forest fragments may be increasingly isolated, limiting the exchange of propagules between populations of animal and plant species. Yet, natural vegetation is a vital component of the ecosystem by providing ecosystem services like wildlife habitats, regulation of climate, provision of various forest products, etc. Therefore, it is important to preserve the few remaining forest patches by opting for the improvement of land tenure security, the improvement of more sustainable agricultural practices by producers, and the implementation and enforcement of existing forestry legislation. Indeed, our results show that the expansion of agricultural areas leads to significant deforestation. In a context of poverty and the high cost of mineral fertilisers, farmers' clear forests to plant their crops for two to three years, before opening up new ones when they observe a downward trend in yield. Such a practice could lead to land saturation as geographical space is a limited resource (Bogaert et al. 2015), in an area where the population growth rate remains high while the yield of the main crops remains below their potential. At the same time, there is a need to train local farmers in the practice of agroforestry. Tree species of the Fabaceae family capable of creating symbioses with bacteria for nitrogen fixation for the benefit of crops or those capable of creating mycorrhizal symbioses exist in the region (Koohafkan and Liline, 1987). In order to promote exchanges between plant/animal communities in isolated fragments, planted corridors of native plant species should be created. This approach has already been tested in Benin (Bogaert et al., 2011). Although wood no longer plays an important energy role worldwide and is being replaced by other energy sources (coal, gas, nuclear energy), wood continues to play an important role in Haiti where it meets more than 70% of energy needs. However, our results show that the wood resource is becoming scarcer in the Vallières landscape, which has both economic (loss of employment and income for charcoal producers) and social consequences (the lack of wood energy limits the amount of food cooked and therefore has negative consequences for nutrition and health). It should be noted that the rapid development of the charcoal network is a popular reaction to the dysfunctional electricity supply system in Haitian cities. Thus, in order to reduce the collection of wood for energy production, new techniques and practices need to be adopted, such as the search for species with high calorific value in order to increase the yield of carbonisation, the substitution of wood energy by renewable energies, the energy recovery of waste and the improvement of energy efficiency through the use of improved stoves (Bangirinama et al., 2016, Useni et al., 2017a).

5. Conclusion

The present study evaluates the landscape changes within the municipality of Vallières (Haiti) and its sections through landscape metrics coupled with remote sensing and Geographic Information Systems (GIS). Our central hypothesis stated that the inappropriate management of the expansion of agricultural and bare land in the landscape has led to the fragmentation and isolation of forest ecosystem patches, to varying degrees from the socio-economic context of each section; based on our observations and analyzes, we confirm this hypothesis. Indeed, the results reveal that the creation of new agricultural land areas, followed by their merger, has led to a modification of the spatial pattern of the landscape within the municipality of Vallières and its sections. In this context, the forest land has been increasingly threatened by anthropogenic activities. Thus, between 1984 and 2019, the proportion of forest in landscape has reduced markedly in the landscape through the fragmentation of its patches. Indeed, the forest land that largely dominated the landscape between 1984 and 1998 has been found in 2019 to be in a fragmented state within an agricultural matrix. The precarious socio-economic conditions of the rapidly growing local population, coupled with the absence of a policy of good governance of forest land, are responsible for the observed landscape dynamics.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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