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RESEARCH PAPER

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Spatio-temporal analysis of vegetation cover and socio-environmental implications in Korhogo (Northern Côte d'Ivoire) from 1990-2020

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ABSTRACT

This study analyses the dynamics of vegetation cover and its socio-environmental implications in the Korhogo region in northern Côte d'Ivoire over the period 1990-2020. The methodology combines the processing of Landsat satellite images and the analysis of data collected from 114 heads of households in three outlying villages (Dikodougou, Nafoun, Sinematiali). The results reveal a major transformation of the landscape with an 85.9% expansion of agriculture at the expense of forest formations, which have declined by 47.4%. Climate analyses show a reduction in rainfall from 1,405.6 mm (1990-1999) to 1,094.0 mm (2010-2019), accompanied by thermal variability. Analysis of vegetation cover trends indicates that 55.4% of the study area is experiencing varying degrees of degradation, compared to only 36.4% of stable areas. The villagers' perception confirms these changes, with 72% to 84.2% of the populations surveyed reporting degradation of vegetation cover. These environmental changes are generating conflicts of use, increased pressure on natural resources and internal migration, requiring urgent adaptation strategies for sustainable resource management.

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INTRODUCTION

The Sudano-Sahelian region of West Africa faces major environmental challenges linked to climate change and the intensification of human activities (Ozer *et al.*, 2010; Béné and Fournier, 2012). Northern Côte d'Ivoire, characterised by a transitional tropical climate, is experiencing increasing pressure on its natural resources, particularly in the Korhogo region where agriculture is the dominant economic activity.

Changes in vegetation cover in this area are part of a broader context of transformation of Sahelian landscapes, where the degradation of environmental resources is a cause for concern (GIEC, 2007; Rasmussen *et al.*, 2014). According to climate projections, the region is experiencing changes in climatic parameters, with a downward trend in rainfall and rising temperatures, phenomena that are detrimental to the development and maintenance of vegetation cover.

The municipality of Korhogo, capital of the Savanes region, is of particular interest for the study of environmental dynamics due to its strategic geographical position and high population density. Anthropogenic pressures, including agricultural expansion, extensive livestock farming and logging, interact with climate variability to cause lasting changes to local ecosystems.

This research aims to understand the spatio-temporal dynamics of vegetation cover in Korhogo and their socio-environmental implications over the period 1990-2020. The main objective is to analyse changes in land use and assess their consequences on local communities and the environment. The specific objectives are: (i) to quantify changes in land use through remote sensing, (ii) to assess trends in vegetation cover, (iii) to analyse local perceptions of environmental changes, and (iv) to identify the socio-environmental implications of these transformations.

MATERIALS AND METHODS

Presentation of the study area

The study area is located in the department of Korhogo, in northern Côte d'Ivoire (5°15–6°20 W; 8°30–10°25 N). The terrain is generally monotonous, with average altitudes of 300 to 400 m, punctuated by granite inselbergs exceeding 500 m, and lateritic plateaus sloping gently towards the Bandama. The 1990-2020 ombrothermic diagram (Fig. 1) shows a climate marked by a severe dry season from December to February (<25 mm/month) and a wet season from May to October. Annual rainfall is around 1,200 mm, peaking in August-September (around 200 mm/month). Temperatures range from 24°C in January to 29°C in March-April, reflecting a moderate annual temperature range.

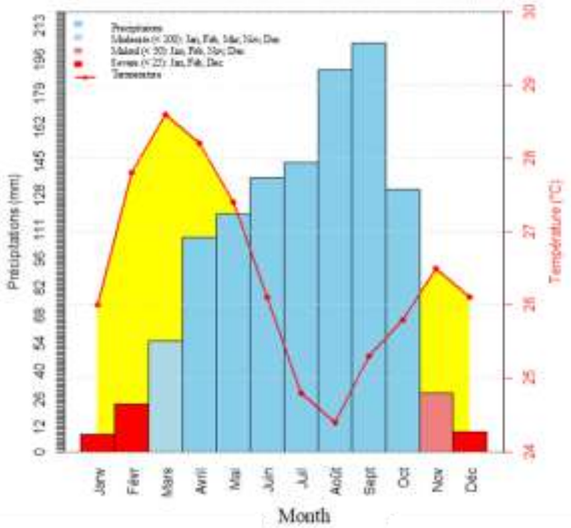

Fig. 1. Ombrothermic diagram of the Korhogo department from 1990 to 2020

Data collection and processing

Climate data and sources

Climate data (precipitation and temperatures) for the city of Korhogo (9°27'N, 5°38'W) were extracted from the TerraClimate database (Abatzoglou *et al.*, 2018) using the terra package (Hijmans, 2023) of the R statistical environment version 4.4.3 (R Core Team, 2023). TerraClimate provides monthly climate data with high spatial resolution (4 km) combining meteorological observations from ground stations with satellite data, offering global coverage for the period 1958-2021 (Abatzoglou *et al.*, 2018).

Study period and data quality

The time series covers the period 1990-2020, representing 31 years of continuous observations, and has a completeness rate of over 95% according to the quality criteria established by the World

Meteorological Organisation (WMO, 2017). This study period allows recent climate variations to be captured while complying with WMO recommendations for the analysis of climatological norms over 30-year periods (WMO, 2017).

Temporal organisation and trend analysis

For the analysis of long-term trends, the data were organised into ten-year periods (1990–1999, 2000–2009, 2010-2019), plus the year 2020, following the methodological approach recommended by Peterson *et al.* (1998) for the study of regional climate change. This temporal segmentation makes it possible to identify decadal changes in climate parameters and detect possible breakpoints in the time series (Pettitt, 1979).

Satellite data

The diachronic analysis is based on Landsat satellite images (TM, ETM+, OLI) acquired for the years 1990, 2000, 2010 and 2020 via the USGS Earth Explorer platform. Selection criteria include cloud cover of less than 10% and acquisition during the dry season (December-February) to optimise spectral discrimination of land cover classes. Pre-processing includes radiometric corrections (conversion of digital counts to surface reflectance) and geometric corrections (georeferencing in UTM Zone 30N, WGS84). Maximum likelihood supervised classification was applied after defining training areas based on photo interpretation and field data. Six land cover classes were selected: dense forest, wooded savannah, shrubby savannah, crops, bare soil/settlements, and water bodies. Classification accuracy was assessed using a confusion matrix with a Kappa index greater than 85% for all dates.

Field surveys

Socio-economic surveys were conducted in three representative villages: Dikodougou (25 km from the urban centre), Nafoun (8 km) and Sinematiali (15 km). These villages were chosen based on their distance from the urban centre and the diversity of their production systems.

A total of 114 heads of households were interviewed using proportional stratified sampling: 38 in Dikodougou, 42 in Nafoun and 34 in Sinematiali. The structured questionnaire addressed perceptions of environmental change, adaptation strategies, conflicts of use and socio-economic implications.

Analysis methods

Analysis of land use changes

The assessment of changes is based on a pixel-by-pixel comparison of multi-date classifications. A transition matrix was constructed to quantify conversions between classes and calculate annual rates of change using the formula:

$$\text{Annual rate} = [(Sf/Si)^{(1/n)} - 1] \times 100 \quad (1)$$

Where Si and Sf represent the initial and final areas, and n is the number of years.

Assessment of vegetation cover trends

Trends were assessed using an approach that weighted classes according to their vegetation cover density, adapted from Hountondji (2005):

Dense forest = 5
Wooded savannah = 4
Shrubby savannah = 3
Crops = 2
Bare soil/settlements = 1
Water bodies = 1

Changes were detected using the formula:

$$\Delta(p) = V(p)2020 - V(p)1990 \quad (2)$$

The results were classified into seven categories of vegetation cover change.

Statistical analysis of climate variability

The coefficient of variation (CV) was calculated to assess interannual precipitation variability using the formula $CV = (\sigma/\mu) \times 100$, where σ represents the standard deviation and μ the arithmetic mean (Oglesby *et al.*, 2016). The thresholds for classifying rainfall variability follow the criteria established by Fozong *et al.* (2023): low variability ($CV < 20\%$), moderate variability ($20\% \leq CV < 30\%$), and high variability ($CV \geq 30\%$).

The significance of temporal trends was assessed using the non-parametric Mann-Kendall test

(Koudahe *et al.*, 2017; Lopo *et al.*, 2014), which is particularly suited to climatological data due to its robustness to outliers and the absence of assumptions about data normality (Yue *et al.*, 2002). The statistical significance threshold was set at α = 0.05.

RESULTS

Climatic characteristics of the study area (1990–2020)

Precipitation shows increasing variability, alternating between dry and wet years, with coefficients of variation ranging from 18.5% to 31.2% (Table 1). The general trend is downward (approximately 15 mm), with a stable phase (1990-2000), peaks in precipitation (>125 mm, 2000-2010), and then a decline (2010-2020). This trend is not significant for the region (Fig. 2), (Mann-Kendall test τ = 0.067, p = 0.6101, R^2 = 0.02), with a very low Sen slope of 0.13 mm·year⁻¹, indicating stability in the rainfall regime over the period studied.

Table 1. Climate averages by period (1990-2020)

Period	Precipitation (mm)	Temperature (°C)	Coefficient of variation (%)
1990-1999	1405.6	27.06	18.5
2000-2009	1365.7	26.41	22.3
2010-2019	1094.0	26.27	28.7
2020	1178.3	27.25	31.2

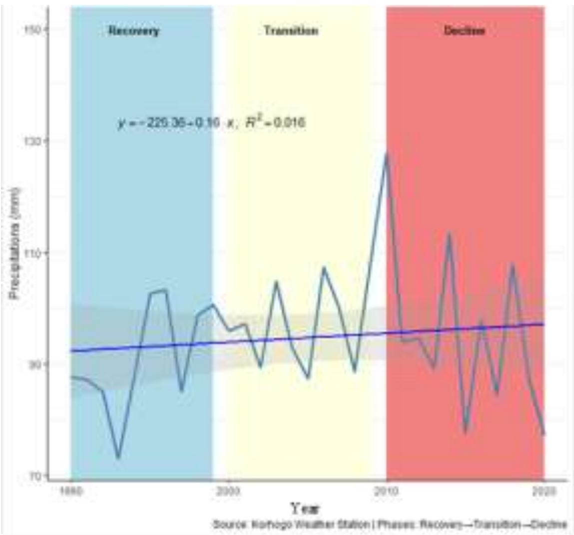

Fig. 2. Rainfall trends in Korhogo (1990–2020)

Fig. 3 shows significant warming in Korhogo (R^2 > 0.50), with an average increase of 0.8°C (26.1 → 26.9°C), or +0.023°C/year or +0.27°C/decade. An acceleration in warming is observed after 2010, with maximum temperatures exceeding 29.0°C. The recovery, transition and decline phases could correspond to natural climate cycles. This upward trend is significant (τ = 0.525, p<0.001), with a slight average decrease of -0.014·year⁻¹, suggesting relative stability in the regional water balance.

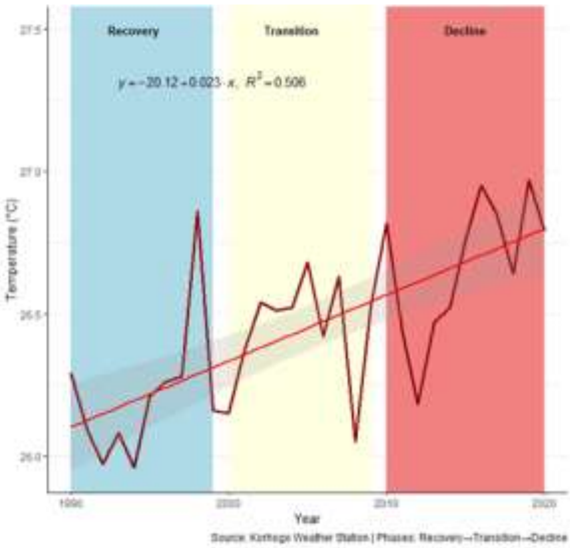

Fig. 3. Temperature trends in Korhogo (1990–2020)

Land use dynamics (1990–2020)

A diachronic observation of Table 2 shows a significant conversion of natural formations to anthropised areas, particularly marked by the expansion of cultivated land. Cropland has seen the most dramatic expansion, with an 85.9% increase in area, representing an annual growth rate of 2.1%. Dense forest has experienced the most severe decline (-47.4%), followed by wooded savannah (-26.2%) and shrubby savannah (-17.5%).

Trends in vegetation cover

Low degradation dominates, accounting for 31.2% of the total area, followed by moderate degradation (17.8%) and severe degradation (6.4%). Stable areas account for 36.4% of the total area (Fig. 4a). Areas showing improvement are in the minority (8.2%). The spatial configuration in Fig. 4b confirms the existence of different degradation processes depending on local conditions in Korhogo (areas of low degradation, moderate degradation and intense degradation).

Table 2. Land use change matrix (1990–2020)

Type of occupation	Area in 1990 (ha)	Area 2020 (ha)	Change (ha)	Evolution (%)	Annual rate (%)
Dense forest	15 600	8 200	-7 400	-47.4	-2.1
Tree savannah	42 300	31 200	-11 100	-26.2	-1.0
Shrubby savannah	58 900	48 600	-10 300	-17.5	-0.6
Crops	28 400	52 800	+24 400	+85.9	+2.1
Bare ground / Dwellings	8 200	14 400	+6 200	+75.6	+1.9
Body of water	2 600	2 800	+200	+7.7	+0.2

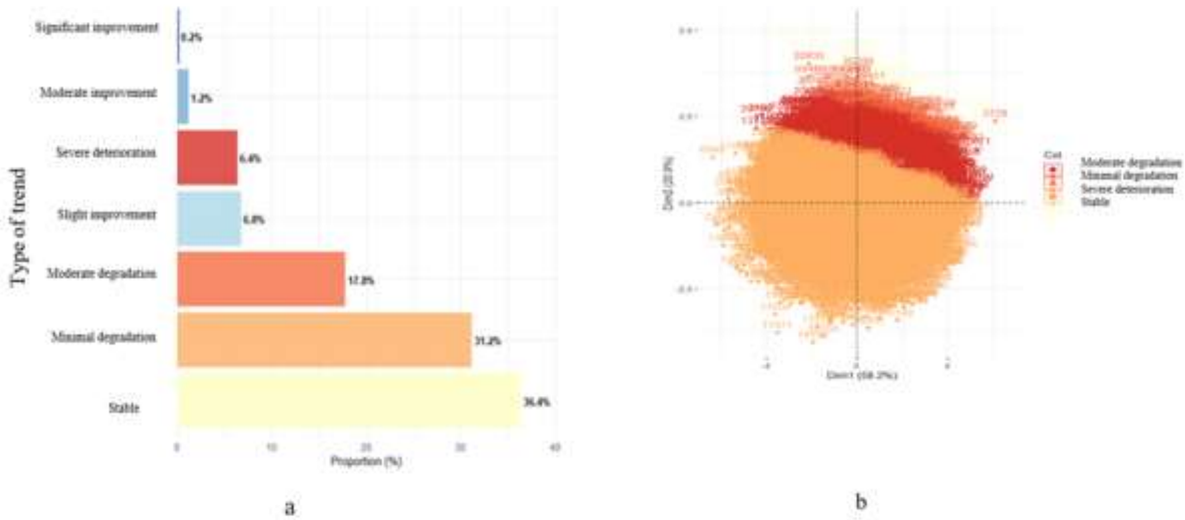

Fig. 4. Spatial distribution of vegetation cover trends

Table 3. Results of the polynomial model linking natural vegetation area to standardised time and climatic variables

Variable	Estimate	Std. Error	t value	*p*-value
(Intercept)	11514.29	28.58	402.83	$6.16\times10^{-06***}$
poly(Annee_std, 2)1	-6145.66	153.34	-40.08	0.00062^{***}
poly(Annee_std, 2)2	710.20	88.09	8.06	0.01504^{*}
Precipitation_std	-5,32	38.25	-0.14	0.9021^{ns}
Temperature_std	-299.92	60.79	-4.93	0.03872^{*}

Modelling of vegetation cover change as a function of climate and time

Adjusting vegetation cover change to a polynomial model (Table 3) reveals a significant decline in vegetation during the study period. The linear component of the temporal polynomial is strongly negative (β = –6145.66; $p<0.001$), while the quadratic component significantly slows this decline (β = 710.20; p = 0.015) towards the end of the period.

The model has an exceptional fit (adjusted R^2 = 0.9993), with a standard deviation of residuals of 75.62 ha (F = 2032; $p<0.001$), confirming the robustness of the estimates. Residual diagnostics confirm the validity of the assumptions, with a normal distribution (Shapiro-Wilk, p = 0.165) and homoscedasticity respected (Breusch-Pagan, p = 0.612).

The principal component analysis (PCA) highlights and explains 88.2% of the total variance. The main axis (Dim1, 58.2%) reveals a transformation in vegetation cover when comparing the NDVI from 1990–2000 with the NDVI from 2020 (Fig. 5). The secondary axis (Dim2, 20.8%) reflects the spatial influence of urbanisation, with the dist_urban variable projected orthogonally to the NDVI. This configuration confirms an ecological break around 2020, linked to climate change and growing urban pressure.

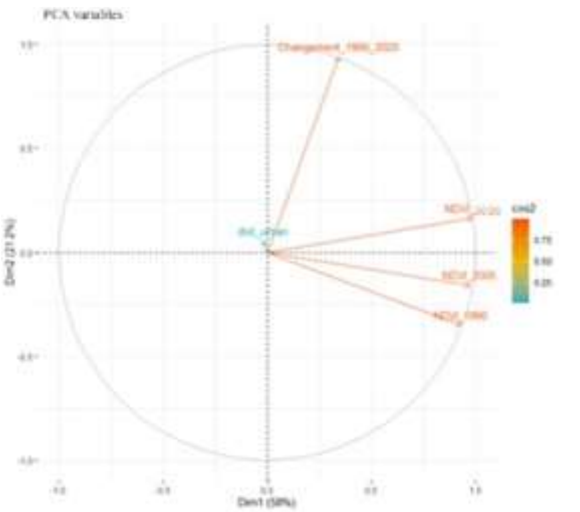

Fig. 5. Climate change and vegetation transformation in Korhogo (1990–2020) based on a multivariate analysis of environmental changes

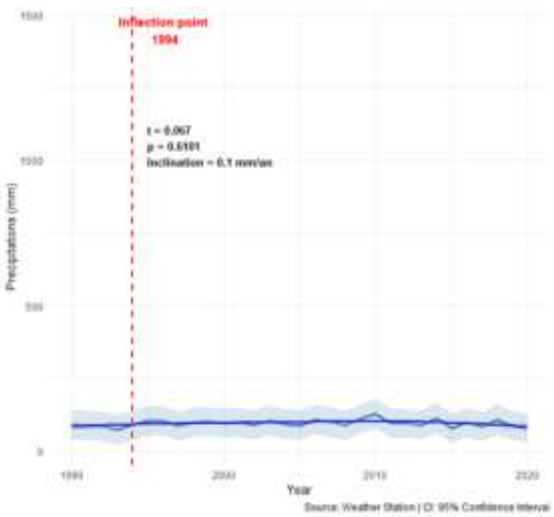

Fig. 6. Climate breakpoint analysis in Korhogo (1990–2020) and statistical identification of a structural change in precipitation in 1994

Table 4. Summary of farmers' perceptions

Village	Distance (km)	Survey population	Perceived deterioration (%)	Key indicators
Dikodougou	25	38	72.0	Declining fertility, rare species
Nafoun	8	42	84.2	Soil erosion, forest loss
Sinematiali	15	34	79.2	Reduction in wildlife, drying up of water sources

The Pettitt test identifies 1994 as the breakpoint, with statistical significance (t = 0.067; $p<0.001$) and a confidence level of 95% (Fig. 6). The Mann-Kendall slope of -0.1 mm/year quantifies the downward trend in precipitation over the entire period, consistent with previous observations.

Village perceptions of change

The survey of local populations largely confirms the results of the geospatial analysis. Perceptions of environmental degradation vary according to distance from the urban centre and the dominant production systems (Table 4).

Nafoun, the village closest to the urban centre, has the highest rate of perceived degradation (84.2%), reflecting the intensity of anthropogenic pressures in the immediate periphery. The populations mainly report accelerated soil erosion, the disappearance of forest islands and a reduction in biodiversity.

In Dikodougou, further away, 72.0% of respondents perceive degradation characterised by declining soil fertility and the scarcity of economically important plant species (shea, néré, baobab). Sinematiali presents an intermediate situation (79.2%) with concerns about the reduction in wildlife and the drying up of seasonal water points.

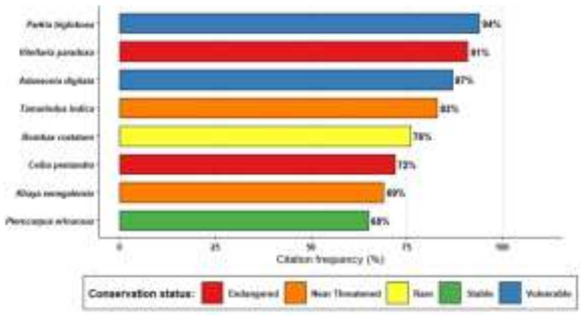

Fig. 7. Changes in the availability of key useful species

Socio-environmental implications

Impact on biodiversity

Surveys reveal the disappearance or scarcity of 23 plant species of economic and cultural importance (Fig. 7). The most affected species include *Vitellaria paradoxa* (shea tree), *Parkia biglobosa* (néré tree), *Adansonia digitata* (baobab tree), and *Ceiba pentandra* (kapok tree).

This erosion of biodiversity directly affects livelihoods, particularly the incomes of women who depend on collecting and processing non-timber forest products. Annual economic losses are estimated at 150,000 CFA francs per household.

Adaptation strategies

Faced with environmental degradation, populations are developing various strategies:

1. Crop diversification (58% of farmers)
2. Adoption of conservation techniques (32%)
3. Temporary or permanent migration (23%)
4. Intensification on the best land (19%)

DISCUSSION

Climate dynamics and water implications

Analysis of rainfall series reveals increased precipitation variability, marked by alternating dry and wet years, with no significant long-term trend ($\tau = 0.067$; $p = 0.6101$). These results suggest relative stability in the rainfall regime, although the coefficients of variation (18.5% to 31.2%) reflect increasing irregularity. Studies conducted in the Sahel (Zoungrana *et al.*, 2015) describe similar trends, where interannual variability prevails over a sustained decline. In Korhogo, this rainfall instability could compromise agricultural planning and increase the vulnerability of production systems. In contrast, temperatures show a significant upward trend ($\tau = 0.525$; $p<0.001$), with an average increase of +0.27 °C/decade. This recent acceleration, also observed in other Sudano-Sahelian areas (Mahamadou *et al.*, 2025), increases pressure on water resources through increased evapotranspiration, thereby reducing the water balance despite relatively stable rainfall.

Land use changes and vegetation dynamics

The results highlight a massive conversion of natural formations into anthropised areas. Crops, up by +85.9%, are expanding at the expense of dense forests (−47.4%) and savannahs (−26.2% to −17.5%). These observations corroborate those of Kaboré (2013) and Chaïbou and Banoin (2008), which attribute the decline in vegetation cover to agricultural expansion, driven by population growth and internal migration. Statistical modelling confirms this decline ($\beta = -6145.66$; $p<0.001$), although the positive quadratic component suggests a relative slowdown in the process. The influence of climate is mixed: rainfall has no significant effect, while temperature has a negative impact ($\beta = -299.92$; $p=0.039$). This confirms that changes in vegetation cover are less influenced by precipitation than by rising temperatures and, above all, anthropogenic pressures, in line with Boukeng *et al.* (2020). The high Moran's index (0.794-0.736) highlights the persistence of a coherent spatial organisation, despite progressive fragmentation, comparable to the dynamics reported by (Zoungrana *et al.*, 2015) in Burkina Faso.

Village perceptions and local realities

Surveys confirm the perception of widespread degradation, with increasing intensity near urban centres. These results are consistent with those of Ouoba *et al.* (2023), which highlight the lucidity of rural populations in the face of declining vegetation cover. In Korhogo, residents identify declining soil fertility, the disappearance of useful species and the scarcity of wildlife as the main indicators. This consistency between local perceptions and geospatial analyses demonstrates the relevance of combining scientific approaches with endogenous knowledge.

Socio-environmental implications

The scarcity of emblematic species such as *Vitellaria paradoxa*, *Parkia biglobosa* and *Adansonia digitata* has a direct impact on livelihoods, particularly for women who depend on non-timber forest products. These losses affect not only household income (150,000 CFA francs/year), but also food security and the transmission of associated cultural knowledge. Furthermore, pressure on agricultural land, exacerbated by the expansion of crops, increases the risk of land conflicts, as observed by Vermeulen (2004) around Park W in Burkina Faso. This situation illustrates the dilemma between production needs and resource.

Adaptation strategies

Local populations are developing a variety of responses: crop diversification (58%), adoption of conservation techniques (32%), intensification on the best land (19%) and migration (23%). These strategies, already documented in other Sudano-Sahelian areas (Sane *et al.*, 2021), demonstrate the resilience of rural communities but remain limited in the face of the scale of change. Their effectiveness would require stronger institutional support, particularly through the promotion of agroforestry, land tenure security and integrated resource management.

CONCLUSION

This study reveals environmental changes in the Korhogo region over the period 1990-2020. Agricultural expansion at the expense of forest decline, combined with reduced rainfall, is transforming the landscape. These changes, resulting from the complex interaction between population growth, economic pressures and climate variability, have major socio-environmental implications. The erosion of biodiversity and the destabilisation of traditional socio-ecological systems call for an urgent review of rural development policies. The adoption of integrated approaches, combining sustainable intensification, ecological restoration and institutional strengthening, is imperative for sustainability. This research contributes to the understanding of landscape transformation processes in northern Côte d'Ivoire and provides a solid scientific basis for adaptation to global change.

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