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Research Article

Estimation of greenhouse gas emissions from remote sensing and field data in the Wari-Maro forest reserve and its periphery (Benin)

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Abstract

Land use affects the structure and functioning of forest ecosystems, thus affecting greenhouse gas fluxes. Greenhouse gas emissions (Carbon Dioxide, Methane and Nitrous Oxide) were assessed in the Wari-Maro Forest Reserve (FCWM) and its periphery between 2005 and 2020. To achieve this, the methodological approach applied is based on the use of activity data (AD) from 2005 and 2020 land use and land cover maps derived from satellite images and emission factors (EF) from forest inventory data conducted in 2005 and 2020. The analysis of the results shows that the peripheral zone has the highest emission factor evaluated at 87.22 t.eq-CO_2 /ha/year against 47.37 t.eq-CO_2/ha/year recorded in the Forest Reserve. The total Carbon Dioxide (CO_2) emissions due to deforestation in the Forest Reserve are 5106.78 t.eq-CO_2/ha/year against a global emission of 65402.23 t.eq-CO_2/ha/year for the periphery. This high emission of the peripheral area is the result of the high anthropogenic pressure in this area. Those due to degradation are 2880.53 t.eq-CO_2/ha/year in the Forest Reserve against 1049.67 t.eq-CO_2/ha/year in the periphery. This strong emission of the forest reserve is due to the destruction of the vegetation notably the dense forests and the gallery forests. The amount of Methane (CH_4) and Nitrous Oxide (N_2O) increases progressively from the Forest Reserve (319.49 t.eq-CO_2/ha/year and 26.80 t.eq-CO_2/ha/year) to the periphery (2658.08 t.eq-CO_2ha/year and 222.99 t.eq-CO_2/ha/year) probably due to the extent of agricultural and livestock production activities in this area.

Keywords: Deforestation, satellite images, greenhouse gases, forest reserve, Benin

Introduction

In Benin, as in other countries of the world, forests provide several services including food, energy, fodder, timber, biodiversity protection, and regulation of the hydrological cycle (PAGEFCOM II, 2020). These forests are also known to sequester large amounts of carbon, approximately 45 % of the total carbon stock in major terrestrial reservoirs (Sabine et al., 2004). However, land use change and land use patterns are significant sources of greenhouse gas (GHG) emissions to the atmosphere (Friedlingstein et al., 2010; Mngadi et al., 2021; Mersin et al., 2019-2020; Pham et al., 2019; Ülker et al., 2018; Mersin et al., 2019-2020; Mshelia et al., 2021; Ganamé et al., 2021).

Over the last thirty years, Benin has experienced significant deforestation, the fundamental causes of which are abusive exploitation for illicit trade (timber, firewood, charcoal) and moreover the pauperization of the rural population inducing the expansion of the practice for survival needs, slash-and-burn agriculture, the development of selective plantations of trees with nutritional value, the practices of abusive use of vegetation fires (MCVDD, 2019). Indeed, from 1978 to 2010, Benin lost nearly 85% of its dense forests and over 30% of its vegetation cover (FAO, 2010). The Food and Agriculture Organization of the United Nations (FAO) has estimated that approximately 75,000 ha of forest have been destroyed each year between 1990 and 2010. This figure would place Benin among the countries with the highest deforestation rates in the African sub-region, resulting in significant CO_2 emissions (MCVDD, 2019).

The inventory of greenhouse gases (GHG) established in all sectors for the 1990-2015 time series shows that Benin's total emissions are estimated at 7,792 Gg CO_2-eq in 2015. The balance of emissions and absorptions reveals that the trend is moving, from the year 1997, towards positive net emissions (MCVDD, 2019).

In addition, projections of the nation's direct GHG emissions (reference and mitigation scenarios) over the period 2016 to 2030 further confirmed the significant GHG mitigation potential offered by forest ecosystems and other land uses. The reference scenario including forestry led to total net GHG emissions of 19,616 Gg CO_2-eq in 2030 compared to 22,877Gg CO_2-eq (forests excluded), i.e. a decrease of about 14,2 %. However, this mitigation potential of forests could decrease by up to 20 % in the coming years in the absence of real policies for sustainable management of forest ecosystems (PAGEFCOM II, 2020).

Unfortunately, this is the case for the Wari-Maro classified forest, which is constantly subjected to anthropogenic pressures of several kinds, namely: agricultural expansion, uncontrolled harvesting of forest products, vegetation fires, the invasion of too many transhumant cattle herds and overgrazing. All of these human activities have become more intense since the end of the project of management of Agoua, Monts Kouffé and Wari-Maro forest reserves in 2006 (PAGEFCOM II, 2020). This bitter observation is seriously prejudicial to the forestry policy of conservation, preservation of natural biodiversity and consequently the achievement of sustainable development objectives in Benin. The degree of degradation, intensity and importance of anthropogenic pressures in this forest reserve has significantly impacted the carbon storage capacities.

The quantification of carbon stocks and GHG emissions of Benin's forest ecosystems is therefore necessary in the context of the United Nations Framework Convention on Climate Change (UNFCCC). These will help to better understand the potential for mitigating climate change by improving carbon sequestration and significantly reducing GHG emissions under the Kyoto Protocol, especially the Clean Development Mechanisms (CDM) and Reducing Emissions from Deforestation and Degradation (REDD) of forests. It is also important to focus on strategies for more detailed monitoring of carbon stock dynamics in Benin in relation to climate variability. To this end, several approaches are deployed such as the use of land cover (spatialized land cover typology by remote sensing) (Ponce-Hernandez, 2007; Hapsari, 2010) and forest inventories (Fukuda et al., 2012) apply allometric equations based on the measurement of trees, including canopy closure (Wauters et al., 2007).

The presentation of the geographic setting of the Wari-Maro forest reserve and its periphery, data and methods, results, and discussion are the main articulations of this article.

Materials and Methods

Data used

The data used are of two categories: the activity data (AD) and the emission factors (EF).

The activity data (AD) in this case the land use and land cover maps of 2005 and 2020. These maps served as a basis for analysis of deforestation (activity data) which is a source of CO_2 emissions.
Emission factors (EF) from the processing of in situ data (forest inventory) from 2005 and 2020.

Materials and tools

They are made up of:

- a Global Positionning System (GPS) receiver GARMIN, ETREX 30 for the rallying of the points of inventory;
- a pi tape to measure the Diameter at Breast Height (DBH) of trees;
- a SUUNTO clinometer to measure tree heights;
- Inventory cards for recording data collected on the trees.

Method of data collection

The non-destructive estimation method was adopted for the development of carbon stock mapping of woody aboveground biomass. Stratified sampling was used to randomly distribute plots within each identified vegetation type. Square plots were adopted in accordance with the recommendations of the Niamey workshop (2008) on the harmonization of inventory systems in West Africa. A total of 64 plots of 30 m x 30 m each at least 0.5 km apart were installed in the study area, including 42 plots in the FR and 22 plots in the periphery. All trees with a diameter at breast height (dbh) greater than 10 cm were included in each plot. The scientific or vernacular names of the trees, total height, and girth ($C \geq 15$ cm) were the main data collected. In addition, the vegetation type, the type of soil and topographic location were also collected.

Method of calculating aboveground biomass

The allometric equation of Nakou (2014) was used to estimate woody aboveground biomass. It is a model of the Sudano-Guinean savannahs of Benin, including the Wari-Maro classified forest, used by Issifou Moumouni (2020). This model has the following formula:

$$\mathrm{AGB(t/ha)} = 1{,}3087 \times 10^{-4} \times \mathrm{D}^{2{,}4949} \times \rho^{1{,}1804}$$

TCMI = 101.8; RES = 0.258
AGB = Woody aboveground biomass in tons (t); D = Tree diameter in cm at 1.3 m, ρ = Specific gravity in g.m-3; TCMI = Theoretical criterion of minimum information; RSE = Residual standard error.

This equation depends in part on the specific density of the wood. The average specific densities were obtained from the Global wood density database and the database of Zanne et al. (2009).

Method for estimating activity data (AD)

Activity data describes the magnitude of a human activity resulting in greenhouse gas emissions or removals, which takes place over a specified time period and area. In this research, activity data are generated at the scale of land use and land cover units and aggregated into four categories (forest land, savannah land, cropland, and other land). The IPCC (2006) guidelines describe three different approaches to representing activity data, i.e., the change in area of different land categories. These approaches are presented in ascending order with respect to the amount of information provided (Issifou Moumouni, 2020).

- Approach 1 identifies the total area for all individual land-use categories in a country, but does not provide information on the nature and extent of conversions between land uses.

- Approach 2 introduces tracking of land-use conversions between categories (but is not spatially explicit).

- Approach 3 extends Approach 2 by tracking land-use conversions on a spatially explicit basis. Under a REDD mechanism, land-use changes will need to be identifiable and traceable in the future. Thus, Approach 3 is the only approach that meets this objective and was used in this research.

The activity data analysis model called "emissions trajectory" was used (Figure 2). This model is based on transitions between land use and land cover units to produce activity data that are sources of CO_2 emissions/absorption. The units represented are: GF (gallery forest), DDF (dense dry forest), WL (woodland), TSS (tree and shrub savannah), PT (plantations), WB (water body), FF (field and fallow), AG (agglomeration) and RS (rocky surface). There are also stability (St), deforestation (Df), degradation (Dg), natural recovery (Nr), reforestation (Re) and improvements (Im). The pre-deforestation reference year is represented by t1 and t2 the post-deforestation year (Issifou Moumouni, 2020).

Landsat images (Morakinyo *et al*., 2021). They combine two types of estimates: deforested areas (ha) and proportions of transitions between land use classes. Both estimates are subject to various sources of error that propagate into a total error on each activity data. The error associated with each AD is estimated by following the classical error propagation rule for the product of uncertain quantities (Issifou Moumouni, 2020).

$$S(AD)=AD\times\sqrt{\left(\left(\frac{S(\hat{A})}{\hat{A}}\right)^2\left(\frac{S(prop)}{prop}\right)^2\right)} \qquad \text{(Eq.1)}$$

With (AD): the standard error on the AD of interest, $(\hat{A})$: the standard error on the deforestation estimate, A the deforestation estimate, S $(prop)$: the standard error on the proportion of the transition of interest and $prop$ the proportion of the transition of interest. A 95 % confidence interval can be calculated by multiplying (AD) by the coast Z = 1.96.

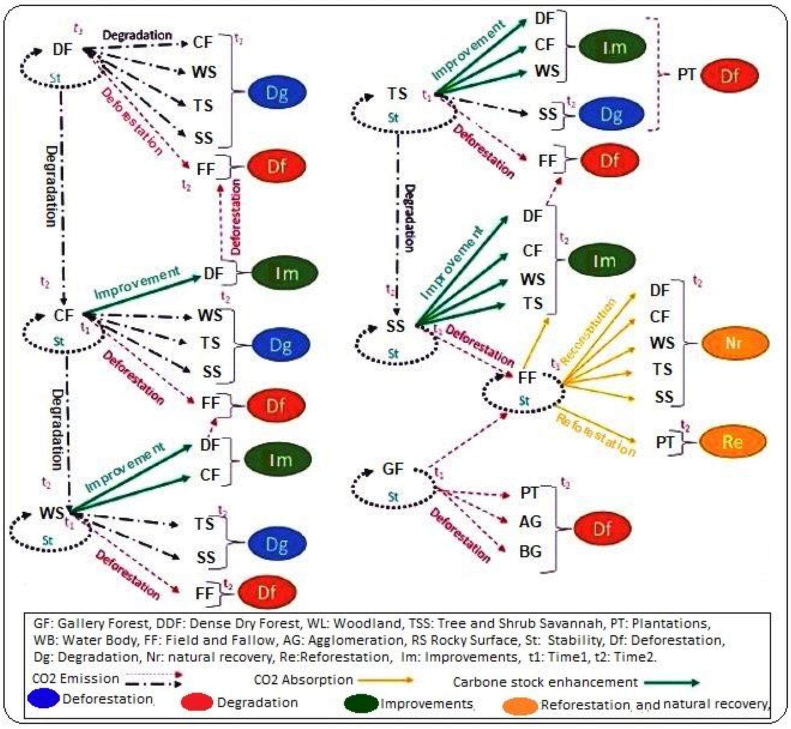

Fig1: CO2 emission trajectory in the Wari-Maro forest reserve and its periphery
Source: Issifou Moumouni, 2020

Total uncertainty on activity data

The activity data (AD) are the product of the deforestation estimate (in ha) derived from the proportions of the transitions between 2005 and 2020 obtained from

Method of estimating CO_2 emission factors

Emission factors are coefficients that quantify the emissions or removals of a gas per unit of activity data. Emission factors are based on sample measurements, averaged at different levels of detail depending on the methodology used. The IPCC (2006) provides three levels for the classification of greenhouse gas (GHG) emissions and removals.

- Level1: use of default emission factors provided by the Emission Factor Database, or by IPCC guidelines; the latter suggests that this method "should be feasible for all countries".
- Level 2: Use country-specific emission factors or more specific non-implicit factors. These could include emission factors from the Emission Factor Database if they are country-specific.

- Level 3: More advanced methods are used as well, including models and inventory measurement systems designed for the national context, repeated over time, driven by high-resolution activity data, and disaggregated at sub-national to local scales.

Properly applied, Level 2 and 3 methods should provide estimates with greater certainty than lower levels (Issifou Moumouni, 2020). It is therefore, the methods of Level 3 were adopted to estimate emission factors in this research.

Emission factors are derived from estimates of carbon stock changes in the various carbon compartments of a forest. The IPCC (2006) recognizes five carbon storage compartments: aboveground biomass, belowground biomass, litter, dead wood and soil organic carbon. In the context of this work, the above-ground woody biomass is used to estimate emission factors. To calculate above-ground biomass losses due to deforestation, emission factors in CO_2 equivalent are calculated in accordance with IPCC (2006) recommendations in the context of REDD+ using the following equation:

$$\mathrm{EF}=\left(\mathrm{B}_{\mathrm{a-2005.j}}-\mathrm{B}_{\mathrm{a-2020.j}}\right)\times \mathrm{CF}_{(\mathrm{ba})}\times \mathrm{CCF}_{(\mathrm{eqCO2})} \text{(Eq.2)}$$

EF: emission factors t.eq-CO_2/ha;
Ba: Aboveground biomass in t.DM;
j: Transition of interest;
CF (Ba): Carbon fraction of dry Biomass equal to 0.5 and
CCF (CO_2-eq): Carbon Conversion Factor in CO_2 equivalent equal to 44/12.

Total uncertainty on emission factors

The standard error associated with the carbon fraction in dry biomass (CF) is 0.206. The 95% confidence interval around FC is therefore ± 0.03. Since the emission factor is the product of biomass (Ba) by CF and CCF, the uncertainty associated with EF is estimated following the classical error propagation rule for a product of uncertain quantities (Issifou Moumouni, 2020):

$$\mathrm{EFC}=\mathrm{Ba}\times\sqrt{\left(\left(\frac{\mathrm{EBa}}{\mathrm{Ba}}\right)^2+\left(\frac{\mathrm{EFC}}{\mathrm{FC}}\right)^2+\left(\frac{\mathrm{EFCC}}{\mathrm{FCC}}\right)^2\right)} \quad \text{(Eq.3)}$$

With EFC: the error on CO_2 emission factors (t.eq-CO_2/ha) and EBa: the error on aboveground biomass Ba (tMS/ha); ECF: the error on the carbon fraction in dry biomass (tMS/ha) and ECF: the error on the conversion factor to CO_2 equivalent (t.eq-CO_2/ha).

Methods for assessing historical emissions (HE) from deforestation and degradation

The calculation of historical emissions from deforestation and degradation is done by multiplying activity data (AD) by emission factors (EF) with reference to the recommendations of the IPCC (2006) Good Practice Guidance on Greenhouse Gas Inventories. The EF correspond to the areas lost by each land category during transitions due to degradation and deforestation. The EF are the amount of carbon released to the atmosphere during transitions (deforestation, degradation) (IPCC, 2006). The basic formula for estimating the amount of GHG emissions can always be expressed as the multiplication of Activity Data (AD) by the Emission Factor (EF) (Issifou Moumouni, 2020), as follows:

$$\mathrm{HE}=\sum_{\mathrm{classe=i}}\mathrm{AD_i}\times \mathrm{EF_I} \quad \text{(Eq.4)}$$

HE: Historical Emissions in t.eq-CO_2;
AD: activity data in ha;
EF: emission factors in t.eq-CO_2/ha.

Historical removals are estimated by multiplying the activity data by the removal factors (AF). The AF corresponds to the amount of carbon absorbed during natural recovery (transition from cropland to forest land), improvements (forest land remaining forest land) and reforestation.

$$\mathrm{HA}=\sum_{\mathrm{classe=i}}\mathrm{AD_i}\times \mathrm{AF_I} \quad \text{(Eq.5)}$$

GHG emissions from the Agriculture, Forestry and Other Land Use sector AFAT consist of gases other than CO_2, namely methane (CH_4) and nitrous oxide (N_2O), generated by agricultural production, livestock and land management activities. Emissions from energy use in agriculture consist primarily of CO_2 and, to a lesser extent, CH_4 and N_2O. All emissions are expressed, for convenience and to facilitate comparison across domains, in tons of CO_2 equivalents (t.eq-CO_2) (Issifou Moumouni, 2020).

The estimation of CH_4 and N_2O emissions was done using CO_2 equivalent. The advantage of the CO_2 equivalent is that it takes into account an average of all the greenhouse gases (GHGs) that contribute to global warming. Thus, the use of the Global Warming Potential of carbon dioxide (GWP of CO_2 = 1) over a period of 100 years allowed the conversion of the amount of CO_2 emitted annually into CH_4 and N_2O. For the 100-year GWP, the ton of CO_2 equivalent (t.eq-CO_2) is equal to 1 for CO_2, 25 for CH_4 and 298 for N_2O (IPCC, 2007).

$$\mathrm{E_{CH4}}=\left(\frac{\mathrm{HE(t.éq-CO_2}}{\mathrm{PRG}(CH_4)}\right) \quad \text{(Eq.6)}$$

$$\mathrm{E_{N_2O}}=\left(\frac{\mathrm{HE(t.éq-CO_2}}{\mathrm{PRG}(N_2O)}\right) \quad \text{(Eq.7)}$$

(CH_4): historical methane emissions, GWP: Global Warming Potential; E (N_2O): historical nitrous oxide emissions; HE: historical emissions in t.eq-CO_2.

Results

Activity data from land use changes and CO_2 equivalent emission factors from the forest inventory were used to calculate historical emissions in the FRWM and its periphery.

Land use and land cover in the FRWM and surrounding area in 2005 and 2020

Four categories of land cover and land use were used to calculate the activity data. These are forest lands, savannah lands, cropland and other lands. Figure 2 shows the spatial and temporal distribution of land use and land cover units in the forest reserve and surrounding area in 2005 and 2020.

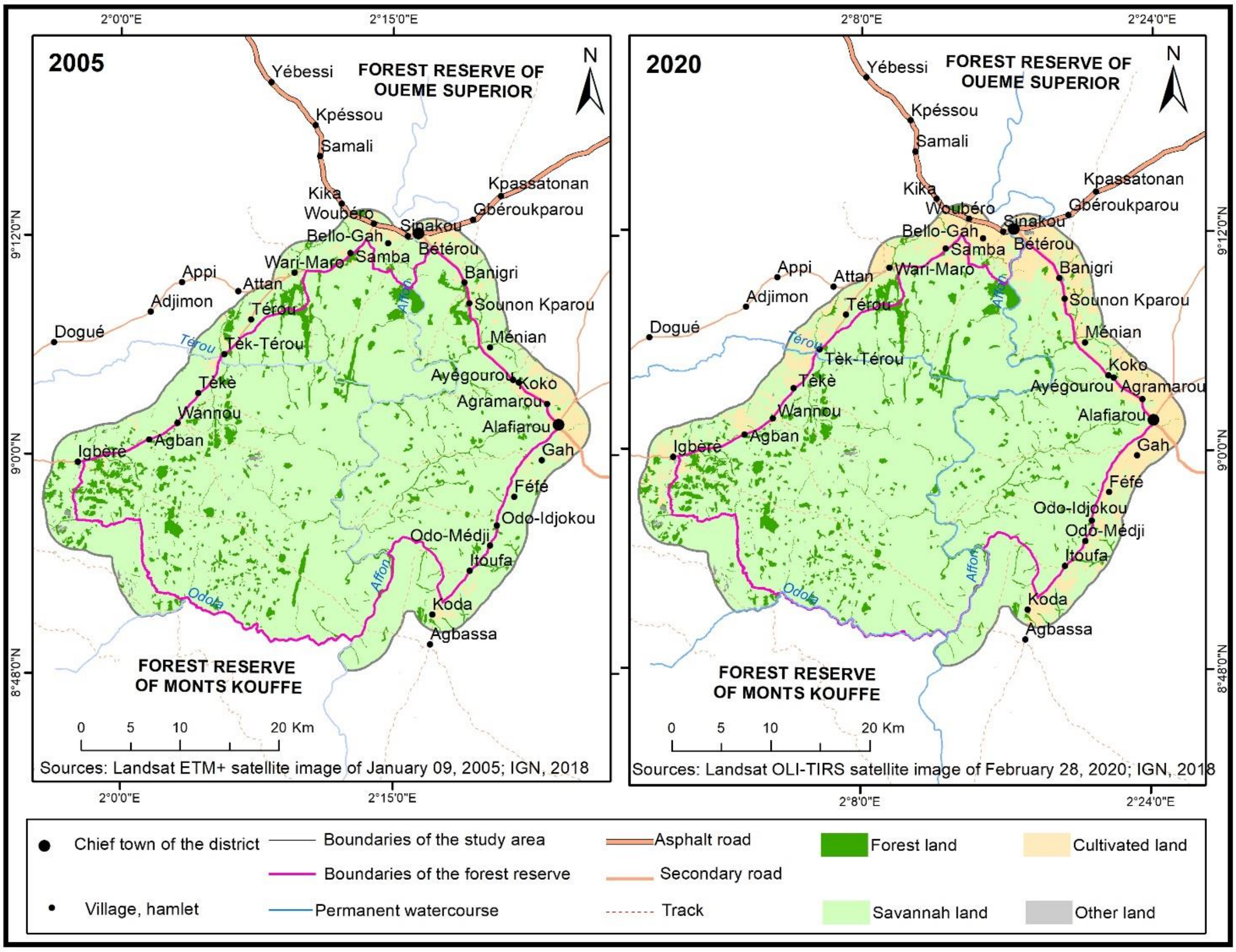

Fig. 2: Land use in Wari-Maro forest reserve and its periphery

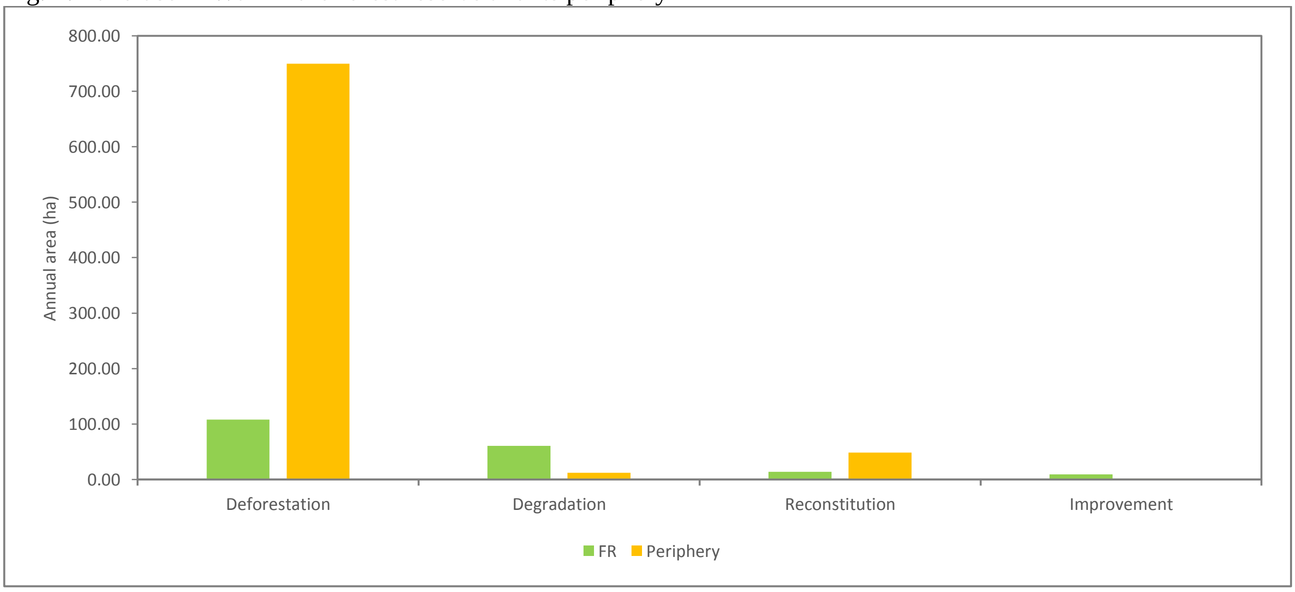

Fig. 3: Activity data between 2005 and 2020

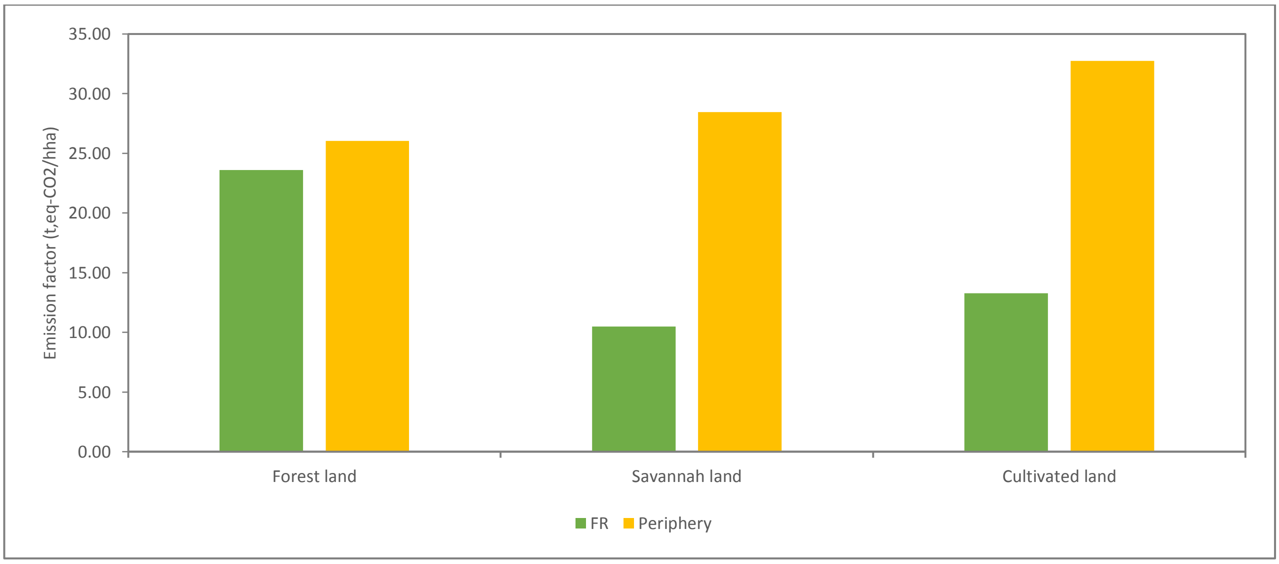

Fig. 4: Emission factor between 2005 and 2020

Activity data

Activity data are the areas per year transiting from one land use class to another during a period of interest. The transitions of interest in this work are those related to deforestation, degradation, reconstitution and improvement (Issifou Moumouni, 2020). Figure 3 presents the activity data produced in the Forest Reserve (FR) and its periphery between 2005 and 2020.

Analysis of Figure 3 shows that between 2005 and 2020, net deforestation is estimated at 107.81 ha/year (i.e., 0.10%) and net degradation at 60.81 ha/year (i.e., 0.05 %) in the forest reserve, while they amount to 749.82 ha/year (i.e., 1.69 %) and 12.03 ha/year (i.e., 0.03 %) in the periphery, respectively. The high deforestation recorded in the periphery could be the result of disturbances in this area, particularly agricultural and pastoral activities. The results obtained by Issifou Moumouni (2020) with the same approach confirm the high deforestation in the periphery. However, this result differs in terms of values, probably due to the intensity of anthropogenic activities and cultivation techniques practiced in the area. In spite of this, the natural reconstitution of the vegetation cover is occurring at 13.81 ha/year or 0.01% in the forest reserve as opposed to 48.83 ha/year or 0.11 % in the periphery. An improvement of 9.15 ha/year or 0.01 % is recorded in the forest reserve compared to 0.93 ha/year or 0.00 % in the periphery.

CO_2 emission factors per unit of land use

The emission factors per unit of land use are presented in Figure 4.

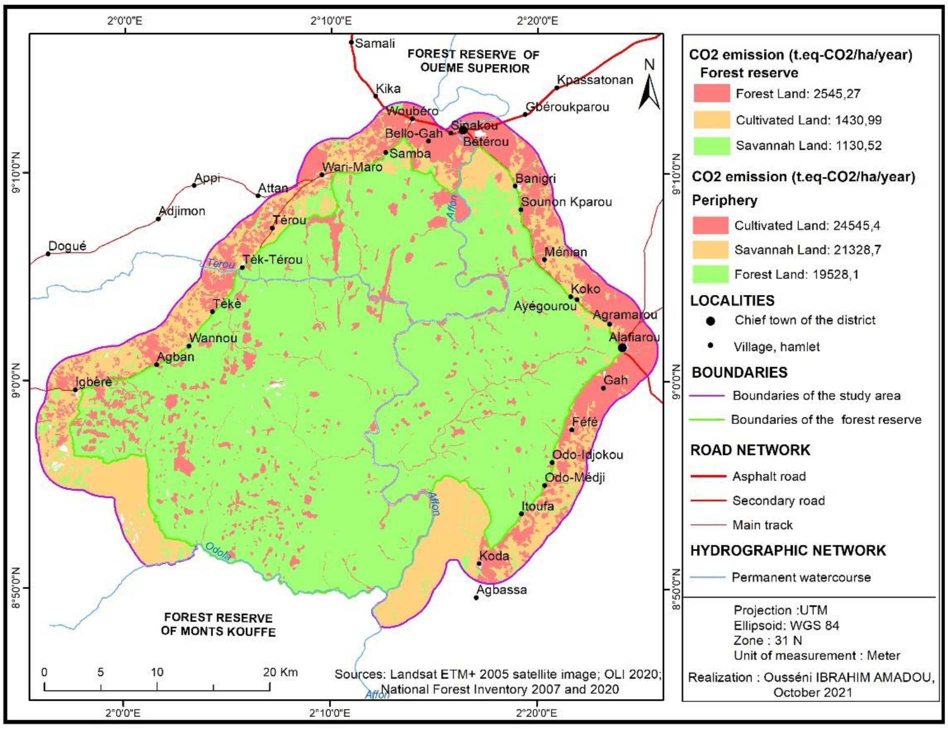

Fig. 5: Historical emissions from deforestation in Wari-Maro forest reserve and its periphery

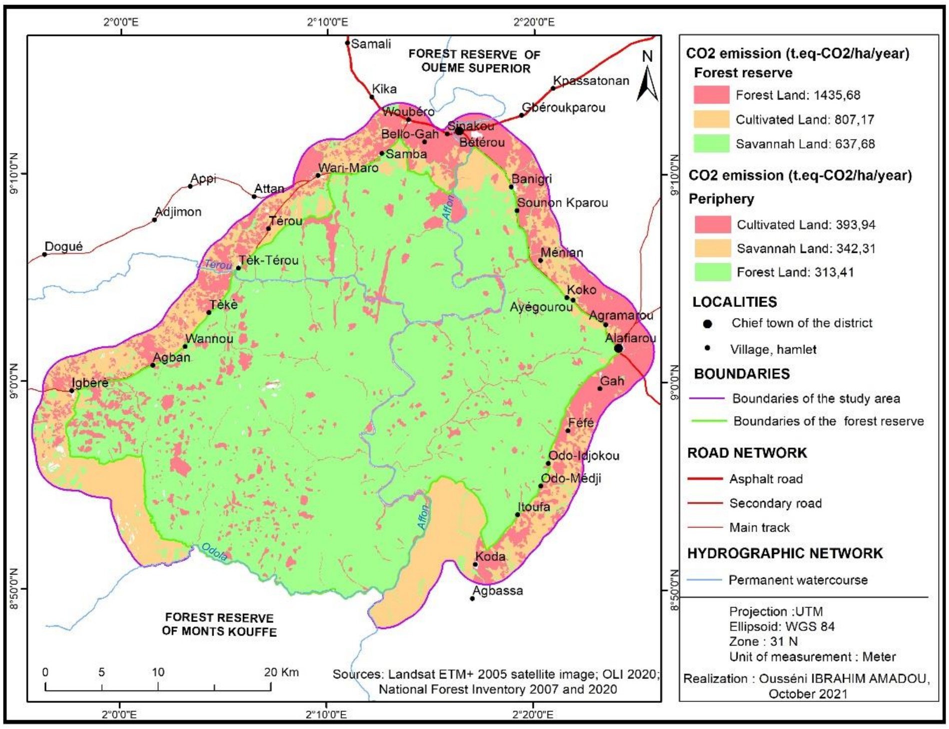

Fig. 6: Historical emissions from degradation in Wari-Maro forest reserve and its periphery

The examination of Figure 4 reveals that in the forest reserve, forest lands present the largest amount of emission factor evaluated at 23.61 t.eq-CO_2 /ha, while savannah lands present only 10.49 t.eq-CO_2 /ha. This shows that if the closed natural formations are not well managed, they can constitute sources of CO_2 emissions, hence the need for more rigorous monitoring of these lands. It is therefore important to set up a forest management project in which the riparian populations will take an active part because they are the main actors of degradation of the vegetation. In the periphery, cultivated lands constitute the most important source of CO_2 emission with 32.74 t.eq-CO_2 /ha, against only 26.04 t.eq-CO_2 /ha for forest lands. It should be noted that carbon removal is more important in the highly anthropized formations, probably due to the intensity of anthropogenic activities. Overall, the peripheral zone has the highest emission factor evaluated at 87.22 t.eq-CO_2/ha against only 47.37 eq-CO_2/ha for the FR. Examination of Figure 5 shows that in the forest reserve, forest lands present the highest CO_2 emission due to deforestation, i.e. 2545.27 t.eq-CO_2 /ha/year, while the lowest values are recorded within savannah lands, i.e. 1130.52 t.eq-CO_2 /ha/year. The high emission of forest lands could be explained by their fragility and vulnerability to anthropogenic pressures, especially logging activities. In the periphery, cultivated land come first with 24545.42 t.eq-CO_2 /ha/year, while forest lands record the lowest quantities at 19528.10 t.eq-CO_2 /ha/year.

Historical emissions between 2005 and 2020

Historical emissions from deforestation between 2005 and 2020

Figure 5 shows the historical emissions from deforestation between 2005 and 2020. Overall, the peripheral zone presents the highest CO_2 emissions due to deforestation, i.e. 65402.23 t.eq-CO_2/ha/year, against an overall emission of 5106.78 t.eq-CO_2/ha/year for the forest reserve this high emission of the peripheral zone is probably due to the result of the strong anthropic pressure in this zone.

Historical emissions (EH) from degradation between 2005 and 2020

Figure 6 shows the historical emissions from degradation between 2005 and 2020. The examination of figure 6 shows that forest land is the unit that emits the most CO_2 due to degradation in the forest reserve, i.e. 1435.68 t.eq-CO_2/ha/year, against an emission of 637.68 t.eq-CO_2/ha/year for savannah land. On the other hand, in the peripheral zone, cultivated land comes first with 393.94 t.eq-CO_2/ha/year against 313.41 t.eq-CO_2/ha/year for forest land. Overall, the historical CO_2 emissions due to degradation in the forest reserve are more than double those of the peripheral zone, i.e. respectively 2880.53 t.eq-CO_2/ha/year and 1049.67 t.eq-CO_2/ha/year, thus confirming the impact of anthropic pressure in this zone.

Absorptions due to natural recovery between 2005 and 2020

Figure 7 shows the absorptions due to natural recovery between 2005 and 2020. The examination of figure 7 shows that in the forest reserve, forest land has the highest natural recovery removals (326.10 tCO_2eq/ha/year of the forest reserve), while savannah land has the lowest (144.84 t CO_2eq/ha/year). In the peripheral zone, cultivated land present the highest values of CO_2 absorptions due to reconstitution with 1598.48t.eq- CO_2/ha/year against an absorption of 1271.74 t.eq-CO_2/ha/year in forest lands. Globally, the peripheral zone presents a higher CO_2 absorption due to natural reconstitution (4259.22 t.eq-CO_2/ha/year) which could be explained by the conversion of cultivated land into forest land against only 654.28 t.eq-CO2/ha/year for the forest reserve.

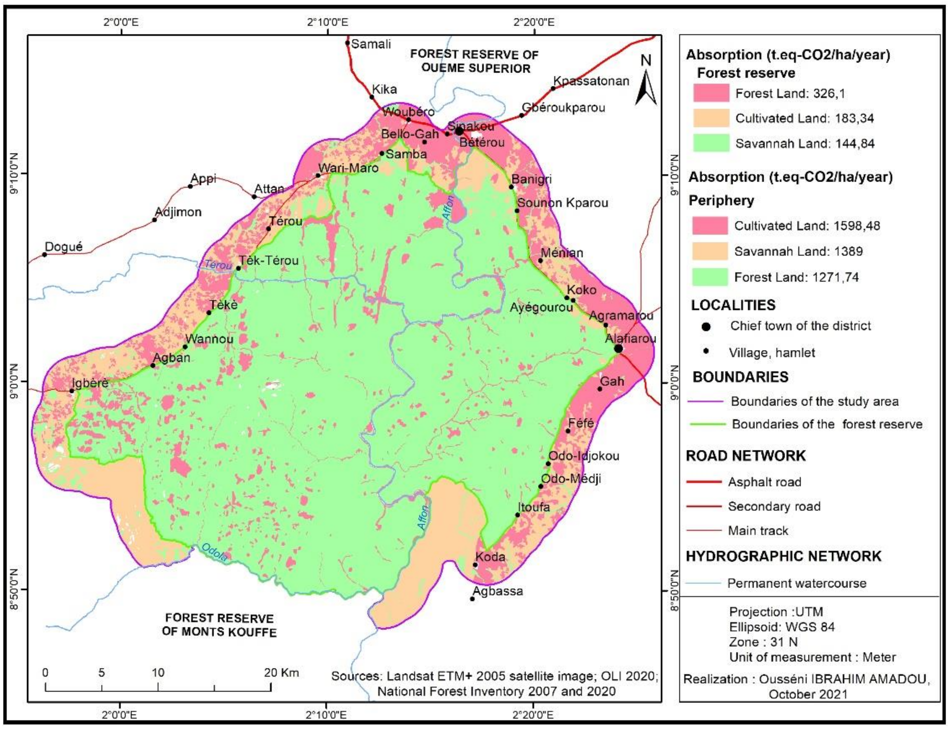

Fig. 7: Absorptions from natural recovery in Wari-Maro forest reserve and its periphery.

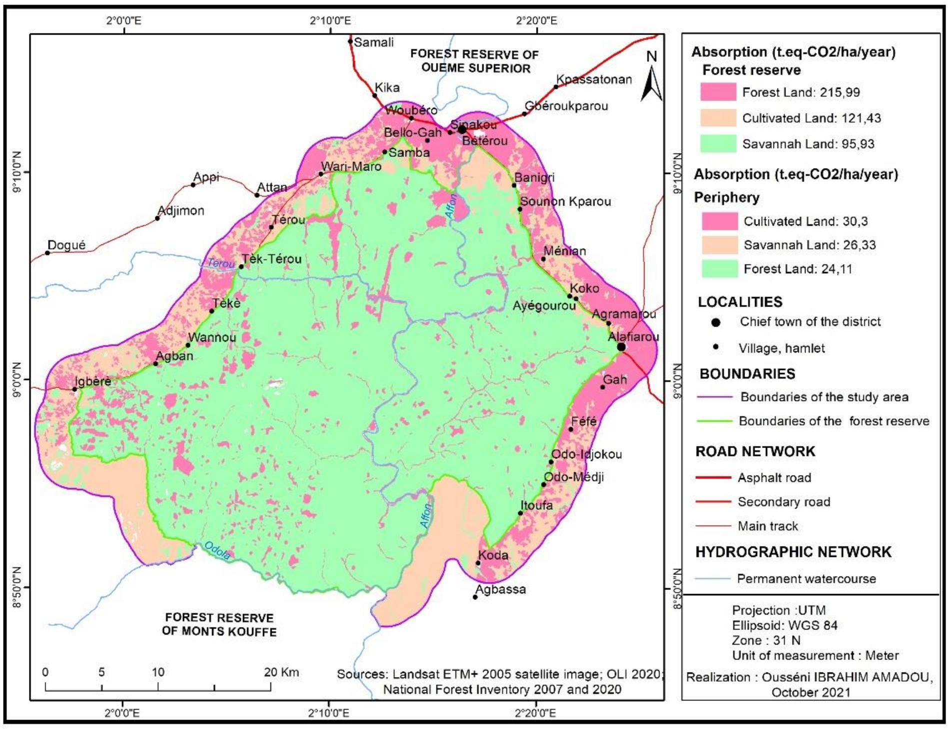

Fig. 8: Absorptions from improvements Wari-Maro forest reserve and its periphery.

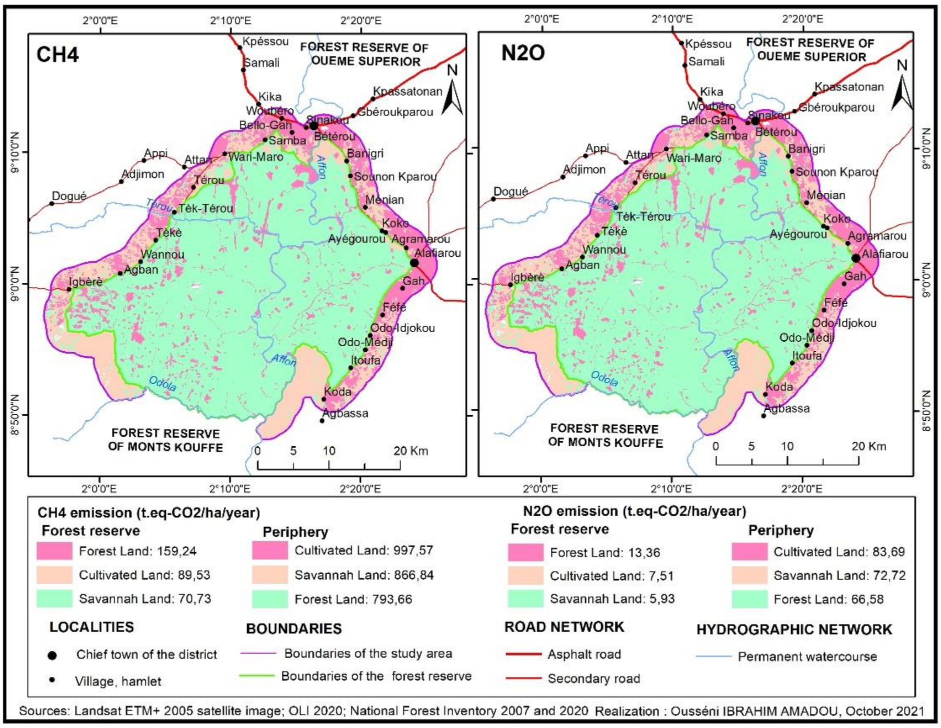

Fig. 9: CH_4 and N_2O emissions in CO_2 equivalent Wari-Maro forest reserve and its periphery.

Absorptions due to improvements between 2005 and 2020

Figure 8 shows the absorptions due to improvements between 2005 and 2020. Examination of figure 8 shows that in the forest reserve, forest land absorbs up to 215.99 t.eq-CO_2ha/year against only 95.93 t.eq-CO_2/ha/year for savannah land. In the periphery, cultivated land absorbs the highest quantities, i.e. 30.3 t.eq-CO_2ha/year against 24.11 t.eq-CO_2/ha/year for forest land. Overall, the forest reserve absorbs more CO_2 due to improvements (433.35 t.eq-CO_2/ha/year) against only 80.74 t.eq-CO_2/ha/year for the peripheral zone, which could be explained by the implementation of management projects limiting the impact of activities in the forest reserve.

Estimated CH_4 and N_2O emissions in CO_2 equivalent between 2005 and 2020

The CH_4 and N_2O emissions in CO_2 equivalent generated by agricultural production, livestock and land management activities are presented in Figure 9. Examination of Figure 9 shows that both CH_4 and N_2O increase progressively from the forest reserve to the periphery. In the forest reserve, the highest values of CH_4 (159.24 t.CO_2eq/ha/year) and N_2O (13.36 t.CO_2eq/ha/year) are recorded in the forest lands while the lowest values 70.73 t.CO_2eq/ha/year and 5.93 t CO_2eq/ha/year are recorded in the savannah land in the periphery, the highest values of CH_4 (997.57 t.eq-CO_2/ha/year) and N_2O (83.69 t.eq-CO_2/ha/year) are recorded in cultivated land while the lowest values 793.66 t.eq-CO_2/ha/year and 66.58 t.eq-CO_2/ha/year are recorded in forest lands. Overall, the peripheral zone has a much higher potential to emit CH_4 and N_2O than the CF, probably due to the extent of agricultural and livestock activities.

Discussion and Conclusion

The use of remote sensing data and forest inventory data allowed the estimation of activity data, emission factors and historical GHG emissions in the FRWM and its periphery. The different treatments and analyses allowed us to observe that in the forest reserve, forest lands present the highest CO_2 emission due to deforestation, i.e. 2545.27 t.eq-CO_2/ha/year, while the lowest values are recorded within savannah lands, i.e. 1130.52 t.eq- CO2 /ha/year.

The high emission of forest lands could be explained by their fragility and vulnerability to anthropogenic pressures, especially logging activities. In the periphery, cultivated land comes first with 24545.42 t.eq-CO_2/ha/year, against 19528.10 t.eq-CO_2/ha/year for forest land. Globally, the peripheral zone presents the highest CO_2 emissions due to deforestation, i.e. 65402.23 t.eq-CO_2/ha/year against a global emission of 5106.78 t.eq-CO_2/ha/year for the forest reserve. This high emission of the peripheral zone is probably due to the result of the strong anthropic pressure in this area.

Speaking of CO_2 emissions due to degradation, forest land is the unit that emits the most CO_2 in the forest reserve, i.e. 1435.68 t.eq-CO_2/ha/year, against an emission of 637.68 t.eq-CO_2/ha/year for savannah land. On the other hand, in the periphery, cultivated land comes first with 393.94 t.eq-CO_2/ha/year against 313.41 t.eq-CO_2/ha/year for forest land. Overall, historical CO_2 emissions due to degradation in the forest reserve are more than double those of the peripheral zone, i.e., 2880.53 t.eq-CO_2/ha/year and 1049.67 t.eq-CO_2/ha/year respectively, thus confirming the impact of anthropogenic pressure in this zone. Issifou Moumouni (2020), obtains 23,769.03 t.eq-CO_2/year in gallery forest and riparian formations, followed by tree and shrub savannahs with an annual emission of about 8,149.48 t.eq-CO_2/year.

It also notes that gallery forests and riparian formations, which constitute the primary driving force of CO_2 emissions due to deforestation, are fragile units that are vulnerable to anthropogenic pressures in the basin, especially in the terroirs where they are not protected areas. In the cotton basin of northeastern Benin, Toko Imorou et al. (2018) obtain 592.23 t.eq-CO_2/ha for tree and shrub savannah compared to 1573.74 t.eq-CO_2/ha for gallery forests. The total CO_2 emissions of the protected areas are estimated at 2.23 Mt.eq-CO_2/ha, i.e. 0.02 Mt.eq-CO_2/ha/year against a global emission of 21.04 Mt.eq-CO_2/ha, i.e. 0.21 Mt.eq-CO_2/ha/year in the terroirs. The high gas emission due to deforestation at the terroir level is the result of the high demographic pressure on the land. For Ouattara (2017), the historical gross average emissions from forests over the period 2000-2015 in the Southern Region of Ivory Coast are estimated to be 3,268,931 t.CO_2/year ± 531,654 t.CO_2/year. This difference could be explained by the fact that several carbon pools were taken into account when estimating GHG emissions in the area.

The absorptions due to natural recovery in the periphery are higher (4259.22 t.eq-CO_2/ha/year) than those in the FC (654.28 t.eq-CO_2/ha/year). The high CO_2 uptake in the periphery is explained by the conversion of cropland to forest land. On the other hand, within the forest reserve, the proportion of cultivated land is very low, which minimizes the impact of its conversion into forest land on the absorptions. Speaking of removals due to improvement, the forest reserve absorbs more CO_2 (433.35 t.eq-CO_2/ha/year) against only 80.74 t.eq-CO_2/ha/year for the peripheral zone, which could be explained by the implementation of management projects limiting the impact of agricultural activities in the CF. In the middle Sota basin, removals due to natural replenishment are of the order of 494.95 t.eq-CO_2/ha/year and those related to improvements are of the order of 13,628 t.eq-CO_2/ha/year (Issifou Moumouni, 2020).

Methane (CH_4) and nitrous oxide (N_2O) are also accounted for in the GHG emissions balance in the forest reserve and its periphery. Both CH_4 and N_2O increase progressively from the forest reserve (319.492 t.eq-CO2/ha/year and 26.803 t.eq-CO_2/ha/year) to the periphery (2658.08 t.eq-CO_2/ha/year and 222.99 t.eq-CO_2/ha/year) which could be due to the importance of pastoral activities. Toko Imorou et al. (2018) estimated these two gases respectively at 59,026.03 t.eq-CO_2/ha/year in protected areas, 492,009 t.eq-CO_2/ha/year in the territory of the cotton basin. For N_2O, the protected areas emit 795,568.16 t.eq-CO_2/ha/year against 6,631,434.20 t.eq-CO_2/ha/year for the territory of the cotton basin of northeast Benin. The results obtained by Toko Imorou et al. (2018) differ from ours in terms of CO_2, CH_4 and N_2O emission values probably due to the allometric equation used to calculate biomass and carbon and then to the fact that they are two different geographical areas.

In accordance with the IPCC methodological guide and good inventory practice guidelines, activity data from land use changes and CO_2 equivalent emission factors from the forest inventory were used to calculate historical emissions from deforestation and degradation in the Wari-Maro forest reserve and its periphery. The peripheral zone has the highest CO_2 emissions due to deforestation. On the other hand, historical CO_2 emissions due to degradation in the forest reserve are more than double those of the peripheral zone. Absorptions due to natural recovery in the periphery are higher than those in the forest reserve. At the end of this research, it appears that GHG emission mitigation actions must be undertaken directly in areas as vulnerable to climate change as the FRWM in order for Benin to benefit from carbon credits or the green climate fund.

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