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Full Length Research Paper

Estimation of domestic and industrial emissions in Côte d'Ivoire (West Africa)

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The domestic and industrial gaseous emissions are estimated in order to complete the high resolution inventory of biogenic and pyrogenic emissions performed over the Côte d'Ivoire (Ivory Coast). In this study, domestic emissions are estimated from the regional population density including rural or urban character, the amount of fuel (wood and charcoal) used per cape per year and emission factors. The population density and the amount of fuel are two key parameters that make up the regional emissivity (0.0081 to 0.0685 kg/m^2 per year), which discriminates the nineteen regions of Côte d'Ivoire into seven groups. Domestic emissions range from 0.016 to 0.1 g/m^2 per year for NO_x, 3.9 to 33 g/m^2 per year for CO and 35.2 to 297 g/m^2 per year for CO_2. Regions with high domestic emissions are located in forest areas and are both producers and consumers of charcoal. Côte d'Ivoire emits 1.6 × 10^7 kg per year of NO_x domestic, 3.8 × 10^9 kg of CO and nine times more CO_2. All these results are consistent with the Emission Database for Global Atmospheric Research (EDGAR). Industrial emissions are not calculated but taken from the EDGAR database to produce a distribution map. These emissions come from the release of major industries (Abidjan, Bouaké and San Pedro) and the manufacture of charcoal. The maximum of industrial emissions is around Abidjan with 10^7 kg per year for CO and 10^6 kg per year for NO_x.

Key words: Côte d'Ivoire, West Africa, domestic, industrial emissions.

INTRODUCTION

Wood is still widely used as an energy source in Africa, where it provides 60% of energy needs and 90% of household energy needs (Hall et al., 1994; Brocard et al., 1996). It is used directly or converted into charcoal. About 50% of these fuels are used for food preparation, 30% as a heat source and 20% for various craft activities (Andreae, 1991). Most of the urban combustion emissions are owed to burning fossil fuels in developed countries. Fossil fuel emissions are also a major source of the air pollution in the urban areas of developing countries. However, in the developing world, the urban regions also have embedded within them numerous, small-scale, loosely regulated combustion sources due to domestic and industrial use of biomass fuel (biofuel) and the burning of garbage and crop residues (Christian et al., 2009). As a result of wide dispersion of houses and their very small size, the estimation of domestic emissions is not particularly easy (Robinson, 1991). After reviewing 40 years of air quality measurements in Mexico city, Raga et al. (2001) concluded that more work was needed on source characterization of non fossil-fuel combustion sources before more effective air pollution mitigation strategies could be implemented.

In Côte d'Ivoire, inventory works of Greenhouse gases (GHG) were realized for 2000 taken as the base year. For that purpose, a national workshop of restoration was organized in September, 2008. The latest revision (1996) guidelines of the Intergovernmental Panel on Climate Change (IPCC) methodology was used with level 1 or level default. Inventories concerned six areas of activities, grouped into five categories: energy, industrial processes and solvent use and other products, agriculture, forestry and waste. The emission inventory covered the following GHGs: carbon oxides (CO_2, CO), methane (CH_4), nitrogen

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Table 1. Emission factors of NO_x, CO and CO_2.

Compounds	Emissions factors of biofuel in g/kg	Sources
NO_x	2	
CO	480	(Bertschi et al., 2003)
CO_2	4337	

oxides (NO_x and N_20), SF_6, volatile organic compounds (NMVOC). Thus, for 2000, total emissions by sector were estimated. As seen, if these national estimations give annual values which contribute on national and international levels to the knowledge of the quantities emitted by sectors, they give no information about their spatial and\or temporal distribution. It is thus, necessary to build a cadastre of emission with a good spatial resolution. It allows realizing specific codes of these emissions which can integrate numerical models of chemistry.

The detailed chemistry of the emissions from these sources has not been available and the degree to which these emissions affect air chemistry in urban regions of the developing world has been difficult to assess (Christian et al., 2009).

The purpose of this paper is to complete the cadastre of emission established for Côte d'Ivoire, where pyrogenic (Bouo, 2007; Kouamé et al., 2010) and biogenic (Bouo et al., 2010) sources were considered. We suggest estimating the domestic emission flux based on the population number, its distribution on the Ivorian territory, emission factors, etc. Also, Côte d'Ivoire since 1999 is facing a social, political and military crisis, which has an undeniable impact on domestic emissions. The most recent general census of population and housing was conducted in 1998. They are the reasons of the choice of 2000 as relevant year to estimate the flows of domestic emissions. An update will be made when a new population census will be made and the country will be more stable. The assessment of CO and NO_x domestic emissions is carried out according to the rural or urban population. These emissions are caused by using wood or charcoal as a source of energy in households. In this paper, we are pursuing the following objectives:

1. Assess the CO and NO_x emissions from domestic sources;
2. Compare the annual emissions from various sources for these two compounds;
3. Compare our estimates with databases: Emission Database for Global Atmospheric Research (EDGAR, http://arch.rivm.nl/env/int/coredata/edgar/) and Global Emission Inventory Activity (GEIA, http://www.rivm.nl/geia/).

For this, we estimated domestic emissions. Industrial emissions are from the EDGAR database (1995).

Domestic emissions

Côte d'Ivoire has 15.3 million inhabitants in 1998 for an area of 322462 km^2 (density of 47.4 inhabitants/km^2). The spatial distribution of population by region is drawn from the work of Zanou and Nyankawindemera (2001). The country is administratively divided into nineteen regions which are subdivided into eighty three departments, including two districts (Abidjan and Yamoussoukro). The urbanization rate is 42.5% in 998 (source: Institut National de la Statistique (INS), http://www.ins.ci/stats/ Tableaux/ Tab06.htm).

In 1997, approximately 87% of Ivorian households used firewood or charcoal at a rate of 2 kg of coal or 4.6 kg of firewood a day (Ministère du Logement, du Cadre de vie et de l'Environnement, 1997). Wood fuels remain until again the main fuel of Ivorian households: 70 to 80% of the total household energy still result from wood fuels (Rapport UNCCD, 2002). Moreover, the consumption of butane gas is concentrated in urban and suburban areas. Abidjan concentrates alone, 75% of overall consumption of butane gas. Populations in rural areas use exclusively, in general, wood for fuel.

Experiments, such as CHARCOAL/DECAFE-92 and FIREWOOD/DECAFE-94 carried out in Côte d'Ivoire have provided a set of detailed emission data. The emission factors for NO_x, CO and CO_2 from domestic fires reported in Table 1 are from this study (Bertschi et al., 2003). From these different works, we know domestic emissions depending on population density and the emission factor of biofuel per cape. Besides, we take into account the type of population (rural and/or urban).

METHOD OF ESTIMATION

We evaluate domestic emissions in each administrative region in distinguishing two types of regions: rural and urban. The administrative regions of rural type have a population less than 7% of the total population (that is, a population not exceeding one million seventy-one thousand inhabitants). In these regions, 70% of the population use wood or charcoal as an energy source with 1000 kg of biofuel per cape per year (Delmas et al., 1995). In urban areas (population greater than 7% of the total population), 30% of the population use wood or charcoal as energy source, a rate of 800 kg of biofuel per cape per year from household (Brocard et al., 1996). Emissions of other compounds (CO or CO_2, for example) can be deducted from the emissions of NO_x using the relationship of proportionality between emission factors (Akeredolu and Isichei, 1991). Finally, we can formulate domestic emissions in each administrative region. The next formula permits to traduce the quantity of biofuel (kg per cape per year) in emission flux (g/m^2 per year):

$$\mathbf{E}_{\mathbf{dom}}(\mathbf{X}) = \frac{\mathbf{k} \times \mathbf{H} \times \mathbf{Q} \times \mathbf{C(X)}}{\mathbf{S}} \quad (1)$$

Table 2. Domestic emissions in the 19 administrative regions of Côte d'Ivoire (NO_x, CO and CO_2 emissions).

Region	Chief town	Population	F (Kg/m^2 per year)	NO_x (g/m^2 per year)	CO (g/m^2 per year)	CO_2 (g/m^2 per year)	Groups
Lagunes	Abidjan	3610800	0.0685	0.137	32.9	297.0	1
Marahoué	Bouaflé	566100	0.0564	0.113	27.1	244.5	2
Sud-Comoé	Aboisso	397800	0.0495	0.099	23.8	214.7	3
Haut-Sassandra	Daloa	1025100	0.0464	0.093	22.3	201.2	
Montagnes	Man	1009800	0.0457	0.091	21.9	198.2	
Sud-Bandama	Divo	642600	0.0457	0.091	21.9	198.2	
Fromager	Gagnoa	535500	0.0444	0.089	21.3	192.7	
Lacs	Yamoussoukro	504900	0.0419	0.084	20.1	181.7	
Agnéby	Agboville	535500	0.0381	0.076	18.3	165.2	4
Moyen-Comoé	Abengourou	367200	0.0366	0.073	17.5	158.6	
Moyen Cavally	Guiglo	459000	0.0228	0.046	11.0	99.1	5
N'Zi Comoé	Dimbokro	688500	0.0228	0.046	11.0	99.1	
Savanes	Korhogo	994500	0.0165	0.033	7.9	71.6	6
Bafing	Touba	153000	0.0152	0.030	7.3	66.1	
Zanzan	Bondoukou	765000	0.0152	0.030	7.3	66.1	
Bas-Sassandra	San-Pedro	1224000	0.0116	0.023	5.6	50.3	
Worodougou	Séguéla	397800	0.0116	0.023	5.6	50.5	
Vallée du Bandama	Bouaké	1178100	0.0087	0.017	4.2	37.9	7
Denguélé	Odiénné	244800	0.0081	0.016	3.9	35.2	

where $E_{dom}(X)$ is the domestic emission of compound X in g/m^2 per year, k represents the coefficient adjustment between urban and rural zones (k set to 70% for a rural zone and 30% for urban zone), H is the population number, S is the area in m^{-2} of the region, Q is the amount of biofuel per cape per year according to the zone and C(X) is the emission factor in g/kg of biofuel for the compound X. The parameters k, H, Q and S depend on the region. We combine these four parameters to define a coefficient F which is a regional flow of emissions:

$$\mathbf{F} = \frac{\mathbf{k} \times \mathbf{H} \times \mathbf{Q}}{\mathbf{S}} \qquad (2)$$

This coefficient represents the regional emissivity and reflects the capacity of a region to be issued. F performs the spatial distribution of domestic emissions. It allows describing them, and the emission factor differentiates the compounds emitted.

RESULTS

Table 2 gives F values and domestic emissions (NO_x, CO and CO_2) from 19 administrative regions of Côte d'Ivoire. They can be classified into seven groups according to F (Figure 1). The first group is characterized by F exceeding 0.06 kg/m^2 per year, and includes the region of Lagunes with Abidjan as capital. The region of Marahoué ($0.05 < F < 0.06$ kg/m^2 per year) with Bouaflé as administrative centre, composes the second group (Table 2 and Figure 1). Six administrative regions constitute the third group characterized by regional flow of emissions between 0.04 and 0.05 kg/m^2 per year, namely: Sud-Comoé, Haut-Sassandra, Sud-Bandama, Montagnes, Fromager and Lacs. The fourth group is marked by emissions between 0.03 and 0.04 kg/m^2 per year. Two administrative regions constitute this group: Agnéby and Moyen-Comoé. The fifth group ($0.02 < F < 0.03$ kg/m^2 per year), gathered around the value of 0.0228 kg/m^2 per year, is composed of the regions of Moyen-Cavally and N'zi Comoé. The sixth group ($0.01 < F < 0.02$ kg/m^2 per year) consists of regions of Savanes, Bafing, Zanzan, Worodougou and Bas-Sassandra. Finally, the seventh group, consisting of the Bandama Valley and Denguélé and is characterized by flow not exceeding 0.01 kg/m^2 per year.

The annual domestic emissions are between 0.016 to 0.137 g/m^2 per year for NO_x, 3.9 to 33 g/m^2 per year for CO and 35.2 to 297 g/m^2 per year for CO_2. The maxima are located in the Lagunes region (South) in rainforest, and minima in Worodougou (North West) in Sudanese

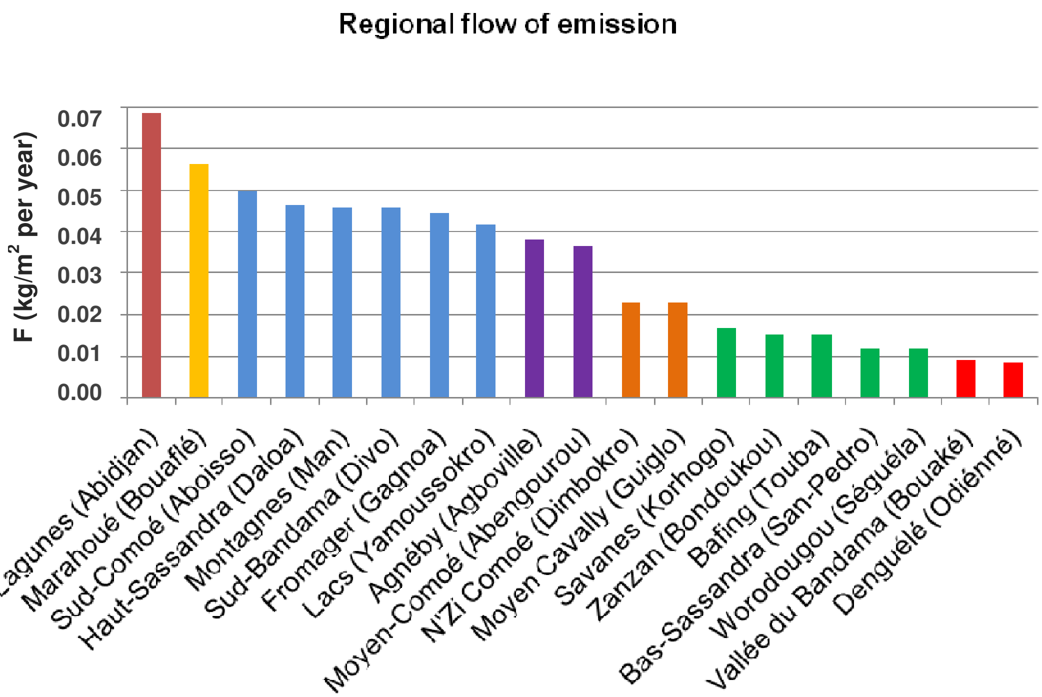

Figure 1. Regional emissivity in Côte d'Ivoire.

savanna (Figure 2). The strongest domestic emission flow is noted in regions (groups 1 to 3) which are located in forest areas, except the region of Bas-Sassandra (group 6). These regions are areas of charcoal production and consumption. The total of the domestic emissions gives 1.6×10^7 kg per year of NO_x, 3.8×10^9 kg per year of CO and 3.43×10^{10} kg per year for CO_2. Estimates of domestic emissions are consistent with the EDGAR database (Table 3).

Industrial emissions

From the global data base of the EDGAR (1995), we were able to establish Figure 3. It shows, with a resolution of 1° × 1°, the distribution of industrial emissions for CO and NO_x. In these emissions are taken into account (very roughly), the release of main industries (area of Abidjan, Bouaké and San Pedro), but also emissions from the manufacture of charcoal which are more dispersed in the part of Southern Cote d'Ivoire. The maximum lies around Abidjan with 10^7 kg per year of CO and 10^6 kg per year of NO_x.

Comparison of annual emissions from various sources for key components

When evaluating emissions over a year and for each region, the annual domestic emissions are included in an interval of 0.016 to 0.1 g/m^2 per year for NO_x and 3.9 to 33 g/m^2 per for CO (Figure 2 and Table 3). The annual biomass burning emissions are between 0.04 and 0.08 g/m^2 per for NO_x and range from 1.5 to 3 g/m^2 per for CO (Table 3), while the annual biogenic emissions are approximately 0.04 to 0.16 g/m^2 per for NO (Bouo et al., 2010). The database of Global Emission Inventory Activity (GEIA, 1990) gives values of about 0.09 g/m^2 per for NO (Table 3). If we estimate an annual average, the maximum ones emissions of NO_x domestic and biomass burning emissions have the same order of magnitude, while we have a coefficient of 10 between CO biomass burning and domestic emissions (Table 3). The maximum of biogenic emissions are slightly higher than those biomass burning and domestic emissions. All these emissions are spatially and temporally expressed differently. For all of the Côte d'Ivoire (Table 4), emissions from biomass burning are the same magnitude as domestic emissions for NO (2.3×10^7 kg per year against 1.6×10^7 kg per year), but they are lower (5 times less) for CO (7.5×10^8 kg per year against 3.8×10^9 kg per year).

The domestic and biogenic emissions are continuous all year long and are distributed throughout the territory, while biomass burning emissions last only 3 months and cause strong damage in the air quality (important value of ozone, NO_x and carbonaceous aerosols), since they release alone practically in two months as much as the domestic emissions throughout the year. For industrial emissions from the EDGAR database (1995), we have values equal to 10^6 kg per year or 0.1 g/m^2 per year of NO_x and 5×10^7 kg per year or 5 g/m^2 per year of CO in the area of Abidjan. For NO_x, they are almost the same

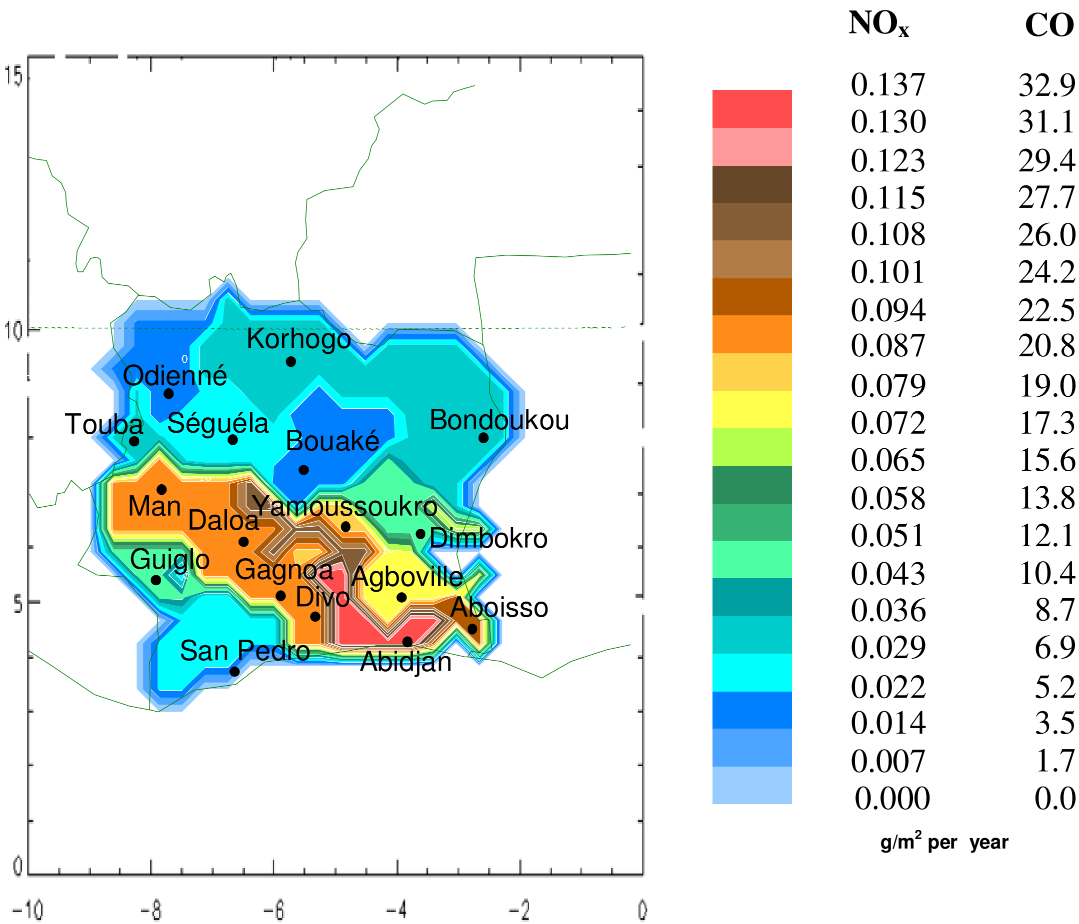

Figure 2. Annual domestic emissions of NO_x and CO in Côte d'Ivoire.

Table 3. Comparison of emissions (biomass burning, domestic, industrial and biogenic).

Emissions (g/m^2 per year)	NO_x	NO	CO	Sources
Biofuel/Domestic	0.016 - 0.1	-	3.9 - 33	This work
	0.01 - 0.1	-	1 - 50	EDGAR
Industrial	0.1	-	1	EDGAR
Biogenic	-	0.09	-	GEIA
	-	0.04 - 0.16	-	Bouo et al. (2010)
Biomass burning	10^{-5} - 1	-	0.1 - 10	EDGAR
	0.04 - 0.08	-	1.5 - 3	Bouo et al. (2010)

order of magnitude as the domestic emissions on the same site (0.1 g/m^2 per year of NO_x and 33 g/m^2 per year of CO). We note nevertheless that CO domestic emissions are, any time, 7 times higher than industrial emissions. The domestic emissions must be taken into account.

Conclusion

We evaluated the carbon oxides (CO and CO_2) and nitrogen (NO_x) emissions from domestic and industrial sources. The domestic emissions were estimated for each of the nineteen administrative regions of Ivory Coast,

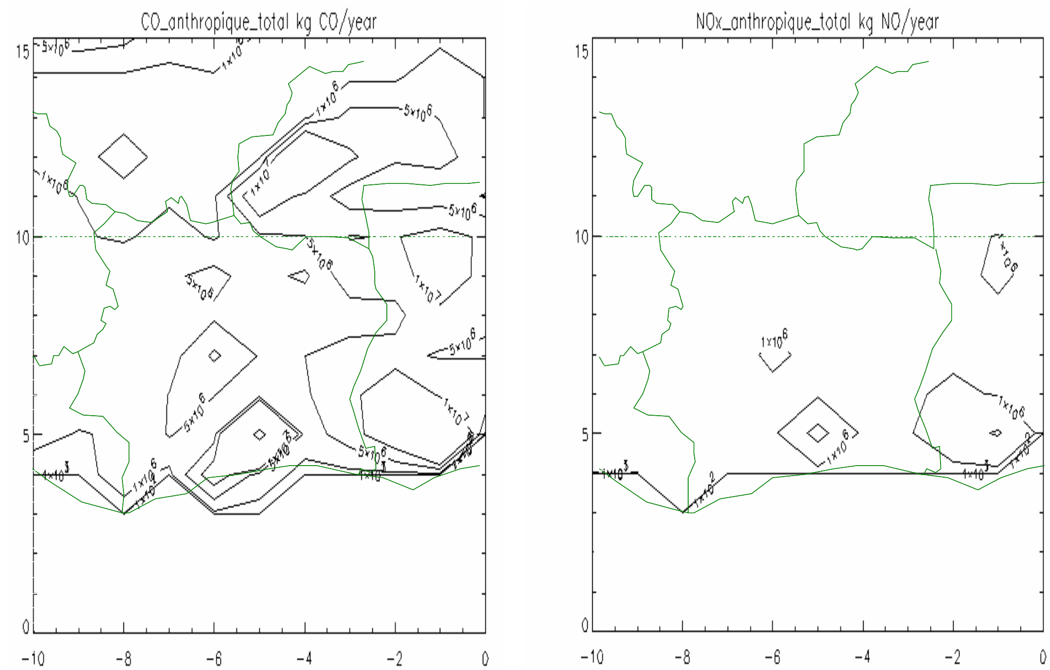

Figure 3. Annual industrial emissions of NO_x and CO in Côte d'Ivoire (Database EDGAR (1995)).

Table 4. Comparison of total emissions over Côte d'Ivoire (domestic, biomass burning and biogenic emissions of NO, NO_x and CO).

Emissions (kg per year)	NO_x	NO	CO
Domestic	1.6×10^7	-	3.8×10^9
Biomass burning	2.3×10^7	1.9×10^7	7.5×10^8
Biogenic from soil	-	3.5×10^7	-

from the number of inhabitant with the consideration of the rural or urban character of the region, the quantity of fuel (wood and charcoal) used per cape per year and emission factors. We raised the importance of the regional emissivity and the factors of emission which are two major parameters in the evaluation of the domestic emissions. The discrimination of nineteen Ivory Coast regions was realized, thanks to the regional emissivity which was defined by the regional density of population and the quantity of fuel used per cape per year. Seven groups of region were distinguished according to this emissivity, the values of which varied from 0.0081 to 0.0685 kg/m^2 per year. The domestic emission flux that resulted, ranging from 0.016 to 0.1 g/m^2 per year for NO_x, 3.9 to 33 g/m^2 per year for CO and 35.2 to 297 g/m^2 per year for CO_2, with maxima in the Lagunes (in forest areas) and minima in the region of Worodougou (in savanna). They were stronger in the forest than in savannas. The total of the domestic emissions gave 1.6×10^7 kg per year of NO_x, 3.8×10^9 kg per year of CO and 3.43×10^{10} kg per year of CO_2. We noted a good agreement between these estimations and the EDGAR database (1995). The industrial emissions, given by the EDGAR database, were restored on a map. We were able to observe there that the regions of Abidjan, Bouaké and San Pedro were installed the main industries, where regions with strong industrial emissions, with Abidjan as key region (10^7 kg per year of CO and 10^6 kg per year of NO_x). The comparison between the emissions of various sources showed that the domestic emissions (3.8×10^9 kg per year) were 5 times higher than the biomass burning emissions (7.5×10^8 kg per year) for the CO, while they were the same order of magnitude for the NOx. On the other hand, the biogenic emissions were twice superior to the domestic emissions for NO. The domestic source thus, had a considerable contribution with regard to the other sources.

This study completes the cadastre of emissions proposed by Bouo (2007) for Côte d'Ivoire where the biogenic and pyrogenic sources were considered. We therefore built a database that can be used to emission codes in numerical simulation models. Also, it is important to know the spatial distribution of emissions, which depends on two major parameters, namely the emissivity of a zone (region, city or village) and the emission factor of the emitted compound. One can thus, identify regions with strong emissions to act locally for the reduction of greenhouse gas emissions and combat desertification.

The study can help in decision making, ensuring proper orientation of awareness programs, policies to combat desertification and the reduction of greenhouse gas emissions.

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