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Research Article

Estimation of Total Yearly CO_2 Emissions by Wildfires in Mexico during the Period 1999–2010

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The phenomenon of wildfires became a global environmental problem which demands estimations of their CO_2 emissions. Wildfires have deteriorated the air quality increasingly. Using available information on documented wildfires and a data set of satellite detected hot spots, total yearly emissions of CO_2 in Mexico were estimated for the period 1999–2010. A map of the main vegetation groups was used to calculate total areas for every vegetation type. The yearly number of hot spots per vegetation type was calculated. Estimates of emitted CO_2 in a wildfire were then accomplished by considering parameters such as: forest fuel load, vegetation type, burning efficiency, and mean burned area. The number of wildfires and total affected areas showed an annual variability. The yearly mean of affected area by a single wildfire varied between 0.2 and 0.3 km^2. The total affected area during the period 1999 to 2010 was 86800 km^2 which corresponds to 4.3% of the Mexican territory. Total CO_2 emissions were approximately 112 Tg. The most affected vegetation types were forest and rainforest.

1. Introduction

The enormous growth of the yearly number of forest fires of natural and anthropogenic origin has become a global environmental problem that affects worldwide ecosystems. Maps indicating the position of wildfire's occurrence practically cover a high percentage of the area of affected countries. Since there is a large variability in the characteristics of ecosystems, determined basically by topography, latitude, humidity, atmospheric and oceanic flows, soils, and so forth, the quantification of biomass per unit of area in each type of vegetation became a fundamental issue to estimate the aerosols emissions by wildfires. Biomass burning causes damages to vegetation, injuries to animal species, and land cover changes. The aerosols, produced by forest fires, influence the air quality and they alter the natural geochemical cycles in the atmosphere. Biomass burning significantly affects the ecosystems at functional level [1–3]. Practically in the whole American continent, from Alaska, Canada, until Argentina, occur a large number of wildfires where boreal forest, forest, rain forest, shrub land, grassland, and other vegetation types are devastated. In tropical regions, forest ecosystems are mostly affected by large fuel availability. In Mexico factors such as climate, incidence of hurricanes, topography, and soil bring on conditions for wildfires every year [4, 5]. These fires burn large areas of vegetation causing locally several environmental problems and in relative large distances severe conditions of air pollution [6].

Wildfires have negative impacts on the economy of affected countries. Several countries of Africa and Brazil have reported negative effects for tourism activities due to damages caused by wildfires in the vegetation of ecosystems. Countries such as India, Russia, Asia, Canada, and United States also annually reported economic losses by biomass burning [7]. In Mexico, losses of about US$ 337 million in wood and about US$ 39 million in reforestation costs have been reported for 2003 [7]. To explain this order of magnitude of economic losses in Mexico, it is convenient to analyze the statistics associated with wildfires. Between 1999 and 2010, a maximum number of about 10000 fires were reported and documented annually in Mexico, reaching the affected area values of 3000 km^2 [8]. It means that at these rates of vegetation consumption in 20 years about 3% of the Mexican territory has been devastated by wildfires. However, a large number of wildfires that occur in inhospitable and remote areas are detected only by satellite sensors and they are not documented. The most affected regions are located in the Sierra Madre Oriental and in the southeastern part of Mexico.

There are several factors contributing to initiate the ignition in the established vegetation types. It includes basically human activities and those associated to drought periods [9]. The increase in emissions caused by biomass burning is a global scientific issue due to the generated pollution and to the potential damages associated with the greenhouse effect [2, 10, 11]. Diverse gas emissions by wildfires like carbon dioxide (CO_2), carbon monoxide (CO), NO_x, and water vapor [11–17] which are the result of vegetation burning have been documented worldwide. Kasischke and Penner [18] summarized the results of papers submitted to the meeting sponsored by Global Observation of Forest Cover/Global Observation of Land Dynamics and International Geosphere-Biosphere Program/International Global Atmospheric Chemistry/Biomass Burning Experiment. Chang and Song [19] estimated biomass burning emissions in tropical Asia. They applied burned areas estimated from newly published 1 km L3JRC and 500 m MODIS burned area products (MCD45A1). Relevant for the global warming are those of greenhouse effect like the CO_2 and methane. Another hazardous aspect is that a single wildfire plume of smoke may be transported large distances by wind effect leaving a pollution cloud over inhabited regions. Damoah et al. [20] showed that a plume of smoke from forest fires in Russia traveled over long distances from 10 to 31 of May, 2003. The plume of smoke was observed in several regions of the globe (Canada, Scandinavia, North-Atlantic, Germany, Europe, and Greenland). In this sense, biomass burning may have global implications.

It is difficult to quantify the amount of emitted pollutants into the atmosphere by wildfires, due to multiple factors involved in the ignition [2, 21]. However, there are methods to estimate the amount of produced pollutant in a wildfire by considering some parameters such as forest fuel load, vegetation type, burning efficiency, and burned area. This may represent an advantage for potential pollutant estimations in a wildfire event but may represent a problem when there is not enough information for all parameters. Nevertheless, other sources of data can be included such as satellite images, laboratory data, and field measurements [22].

Despite the complexity to quantify emitted pollutants by wildfires, different methodologies have been applied to estimate values and ranges of CO_2 emissions from biomass burning in different parts of the world. An estimation of CO_2 emissions in Greece yielded an order of magnitude of 2.2 Tg (1 Tg = 106 Ton) [21]. Calculations of emitted CO_2 by wildfires in the State of California, USA, deliver an approximated value of 6 Tg [13]. CO_2 emissions by wildfires in USA in the period 2002–2006 varied in the range 80–213 Tg [23]. An evaluation carried out for Russia and North America on CO_2 emissions by wildfires produced an order of magnitude varying between 828 and 1103 Tg [24]. A global estimation of CO_2 emissions by wildfires in 1994 yielded an approximated value of 5716 Tg

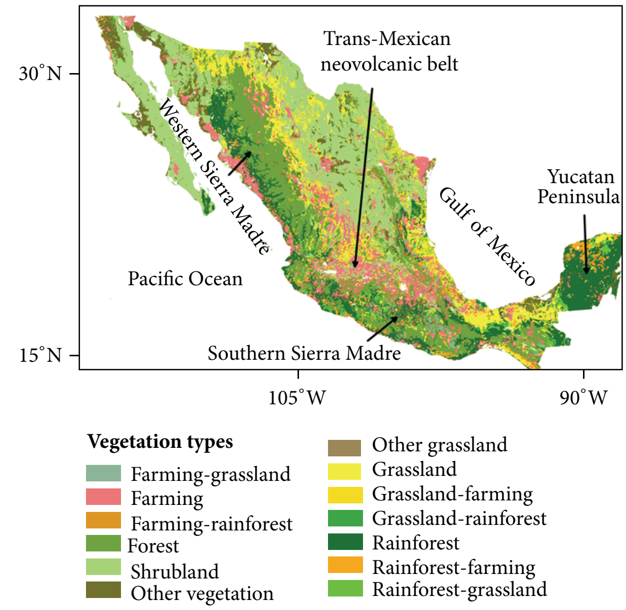

FIGURE 1: Main vegetation groups in Mexico. Groups of vegetation are displayed according to the floristic characteristic and vegetative development. The principal mountain chains and the peninsula of Yucatan are also indicated.

[17]. All these estimated quantities on CO_2 emissions by wildfires have implications on the chemical composition of the atmosphere. Thus it is essential to calculate CO_2 emissions in other regions of the world to understand the influence of this phenomenon, since it alters the carbon biogeochemical cycle and favors the global climate change by greenhouse effects [25–27]. In this research, we present estimations of the total CO_2 emissions by wildfires occurred in Mexico in the period from 1999 to 2010. The calculations are based on satellite information on fire hot spots, land cover, vegetation types, and other sources of information about wildfires.

2. Materials and Methods

Figure 1 shows the main vegetation groups in Mexico, according to the classification given by the National Institute for Statistics, Geography, and Informatics [28]. Different types of vegetation were grouped based on ecological floristic and physiognomic affinities. In the classification system performed by INEGI, was considered the development of vegetation by their degree of disturbance both by natural and anthropogenic causes. Mexico occupies an area of about 1964375 km^2. From this area, about 2.5% is superficial water (lakes, dams, and rivers). As a first step, the corresponding total area of each type of vegetation was calculated applying GIS (Geographical Information System). In Table 1, it is shown that shrubland occupies the largest area in Mexico with about 25.98% of the total area of Mexico. It is followed by forest with 17.51%, rainforest 14.24%, farming 13.52%, and grassland with 13.25%. These five types of vegetation embrace 84.5% of the total area. Although they were contemplated

TABLE 1: Available and calculated information on the considered ecosystems [29]. This data set was applied to estimate CO_2 emissions.

Vegetation type	Percentage of total area (%)	Biomass load (ton/km^2)	Burning efficiencies
Rainforest	14.24	5000–55000	0.2
Forest	17.51	5000–10000	0.3
Farming	13.52	500–10000	0.4
Grassland	13.25	150–550	0.96
Schrubland	25.98	50–200	0.95
Grassland-farming	1.24	350–5275	0.68
Rainforest-grassland	1.45	2575–27775	0.58
Farming-rainforest	1.16	2750–32500	0.30
Other vegetations	7.1	325	0.95

in the calculation, the rest of the vegetation types embrace percentages of 1-2%.

Although in Mexico thousands of wildfires are documented annually by the National Forest Commission (CONAFOR), there are enormous inaccessible regions where a large number of wildfires occur. The information given by CONAFOR considers only total number of documented wildfires and total affected areas per federal state of the country. The total number of documented wildfires and total affected areas per year for the whole country are given in Figure 2(a). Since the geographical information per federal state is not coincident with the geography of the ecosystems, yearly averaged affected areas per fire for the considered period (1999–2010) were calculated from the available data for the whole country. An alternative to fill the lack of information about all wildfires that occur in Mexico is by using satellite data. For this purpose, daily records of detected hot spots in Mexico for the period 1999–2010 were applied. The data set was obtained from reports issued by the National Commission for Knowledge and Use of Biodiversity (CONABIO). This data are obtained by CONABIO from MODIS (Moderate resolution Imaging Spectroradiometer) and from NOAA-AVHRR (National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer). The data set is the result of statistical analysis and verification of a real incidence of wildfires. From the original data set of hot spots, about 6% of them were eliminated [30]. Figure 2(b) shows the number of hot spots per year in the studied period. The yearly hot spots variability is due to climate factors, to anthropogenic activities, and to satellite feasibility [6, 30, 31]. Although the position of the hot spots is known, information on affected area is not available. For this reason, we applied yearly averaged affected areas from the documented wildfires. We summarize the followed methodology to estimate the emissions of CO_2 by wildfires in Mexico in the period from 1999 to 2010.

(a) A vegetation type map for México was used. This database was updated in 2005 by the National Institute for Statistics Geography and Informatics (INEGI).

(b) Historical records of documented forest fires were applied to estimate yearly means (1999–2010) of affected areas for the whole country. The data set was obtained from reports made by the National Forest Commission (CONAFOR).

(c) Daily records on the position of hot spots for the period 1999–2010 were applied (CONABIO).

(d) Applying a GIS approach, the total occupied area in the whole country by every vegetation type was established. Since the position of all hot spots is known, the total number of hot spots per vegetation type was then determined.

(e) After the statistical analysis and verification about the certainty that the applied hot spots are real wildfires [29], the corresponding yearly mean of affected area was assigned to every hot spot.

(f) Information on biomass load and biomass burning efficiencies for six types of vegetation was collected [29] (Table 1). For other combined vegetation types, average values for biomass load and burning efficiencies were calculated from the original components.

(g) The estimation of CO2 emissions was carried out as follows: the equation proposal by Seiler and Crutzen [32], actualized by Levine [29], was applied:

$$CO_2(x, y) = \beta C(x, y), \tag{1}$$

where $CO_2(x, y)$ is the amount of carbon dioxide in Mg (1 Mg = 1 Ton) emitted by each forest fire (hot spot). (x, y) means the position (longitude, latitude) of the wildfire. $\beta = 0.90$ is the fraction of emitted CO_2 for tropical vegetation [29]. The variable $C(x, y)$ is written in the form $C(x, y) = \alpha \cdot M(x, y)$, where $M(x, y) = ABE$ (A = burned area in km^2, B = burned biomass load in Mg/km^2, and E = burning efficiency). $\alpha = 0.45$ is the percentage of carbon contained in the biomass [29]. From points a-6, all required information was available to estimate the CO_2 emissions by wildfires in Mexico into the atmosphere (Table 1).

3. Results and Discussion

Although the distribution of hot spots was determined for all types of vegetation and for every year applying a GIS process, this procedure is documented in Figures 3(a) and 3(b) for two

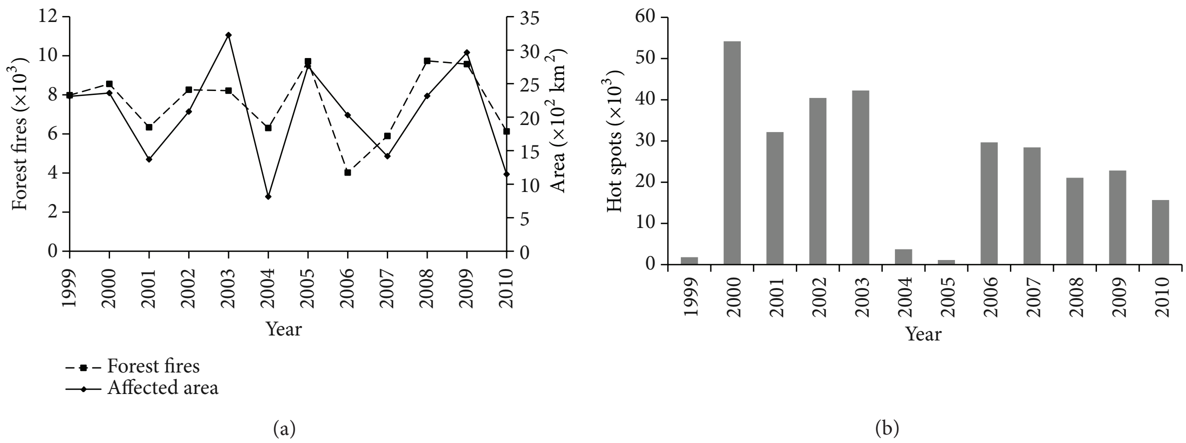

Figure 2: Documented number of forest fires and total affected area (CONAFOR) (a); reported number of hot spots (CONABIO) (b).

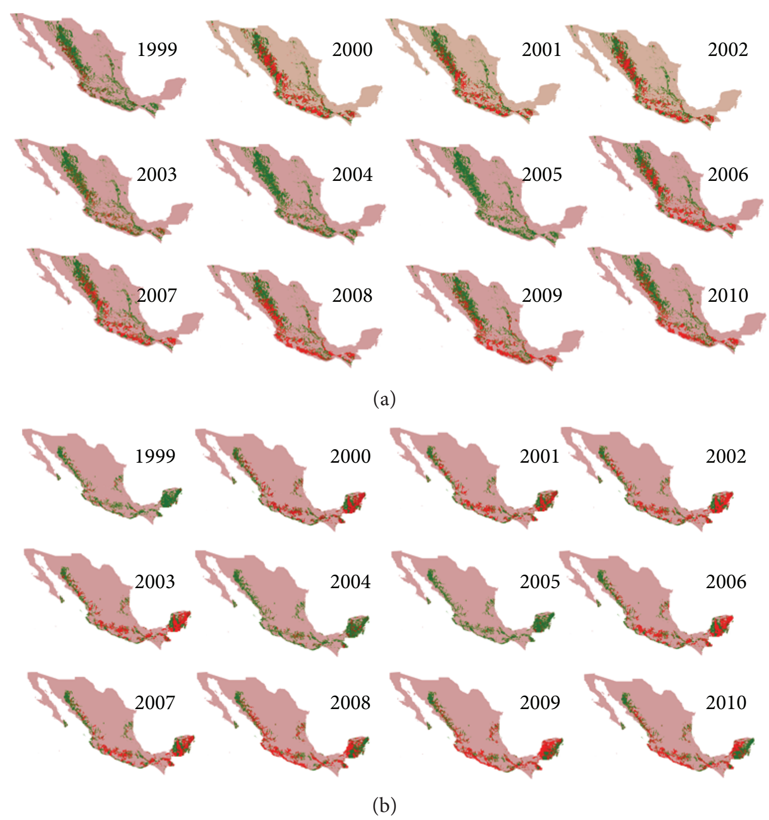

Figure 3: Incidence of wildfires in forest (a) and in rainforest (b). Green areas represent the polygon of the vegetation type and the red points symbolize the hot spots.

of the most important vegetation types for CO_2 emissions, that is, for forest and rainforest. The principal incidence of wildfires (red points) in forest (Figure 3(a)) occurs on the western side of Mexico, along the Western Sierra Madre, Southern Sierra Madre, Trans-Mexican Neovolcanic Belt, and Sierra Madre of Chiapas. In contrast, wildfires in rainforest occur dominantly in the Peninsula of Yucatan and along the coastal plains of the Gulf of Mexico and Pacific Ocean (Figure 3(b)). The number of wildfires in each vegetation type varies from year to year and the incidence of wildfires in different types of vegetation is not necessarily correlated. For example, in 2003 occurred relatively few wildfires in forest but in rainforest the incidence of wildfires was especially high. Even within the same type of vegetation, the distribution of wildfires strongly changes from year to year. It seems that climatic factors like rainfall, humidity, drought periods, and hurricanes influence regionally the potential incidence of wildfires. These climatic factors are reflected in parameters

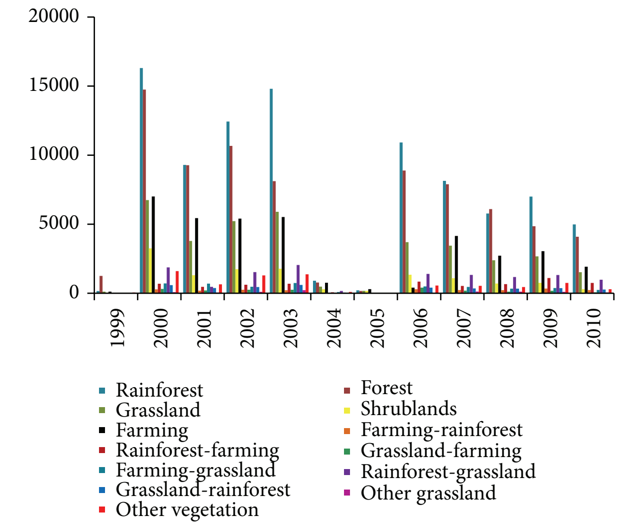

FIGURE 4: Time series of the yearly number of hot spots (wildfires) per vegetation type.

like normalized difference vegetation index (NDVI), relative humidity, relative green maps, fuel availability, and others which are applied to predict conditions for incidence of wildfires and to explain its regional variability. In the Peninsula of Yucatan, in the years 1999, 2004, and 2005, the number of wildfires was small compared with the rest of the years where the density of wildfires was always very high. This analysis reveals the importance of separating the incidence of wildfires in each type of vegetation. This kind of analysis could also provide strategies to prevent the occurrence of wildfires or to be prepared for a possible large incidence of fires. Another important aspect to be analyzed in the question of wildfires is its occurrence in the different types of vegetation. Once the polygons for all considered vegetation types were determined (see Figure 3 for forest and rain forest), the number of hot spots in each type of vegetation was calculated. In order to complete the discussion on the incidence of wildfires in the different types of vegetation, a histogram of yearly accumulated number of hot spots in every vegetation type is given in Figure 4. Although the variability in the number of hot spots seems to be correlated for all vegetation types, there are large changes in the number of hot spots for each vegetation type. For example, for rainforest, the number of hot spots varied from about 16 000 in the year 2000 to only a few hundred in 2005. It is also of interest to remark that there are years with a large number of wildfires in all vegetation types and years where the number of wildfires decreases dramatically. In the period of time considered (1999–2010), a recurrent minimum in the number of wildfires seems to occur every 5-6 years. In years with a minimum number of detected hot spots, there are even vegetation types without any incidence of wildfires.

Once the total yearly number of wildfires was determined for every type of vegetation, the corresponding yearly mean of affected area was then applied. In Figure 5(a), yearly means of affected areas, calculated from the total documented wildfires by the National Forest Commission, are displayed. Due to the scarce regional information about affected areas by every wildfire, we had to calculate a yearly mean affected area for the whole country. With the information on yearly mean affected area and with the yearly number of wildfires, it was possible to estimate the yearly affected area for every type of vegetation and the total yearly affected area. Comparison of yearly mean affected area and total yearly affected area considering all wildfires in all types of vegetation indicates that these two variables are occasionally positively and sometimes negatively correlated (Figures 5(a) and 5(b)). In 2004, a small yearly mean affected area coincided with a small total affected area by all wildfires. On the contrary, in 2005, a relative large yearly mean affected area is negatively correlated with a very small total affected area. The number of hot spots in 2005 was the smallest in the considered period. Considering that the CONAFOR documented in this year about 9000 wildfires, it is obvious that there were problems with the detection or availability of hot spots for CONABIO. In the years 2003 and 2006, a positive correlation takes place; that is, large yearly means affected areas coincide with large total affected areas considering all wildfires. From this analysis on affected areas, for example, large yearly mean affected areas and very small total yearly affected areas, the importance of regionally well-documented wildfires acquires relevance. The total yearly affected area seems to have a large variability, whereas the yearly mean affected area per wildfire remains dominantly in the same order of magnitude, about 0.2-0.3 km^2. The total affected area during the period 1999 to 2010 was approximately 86800 km^2 which corresponds to about 4.3% of the Mexican territory.

By applying (1) and using the number of wildfires, yearly means of affected areas, the biomass load, and burning efficiencies for each vegetation type, the total yearly emissions of CO_2 into the atmosphere by wildfires were estimated. It is important to mention that due to the wide variety of vegetations in Mexico, there is still insufficient information about total forest fuel per area for each type of vegetation. However, we consider that the collected information about biomass load and burning efficiencies could yield a good order of magnitude of total yearly emissions of CO_2. The total yearly emissions of CO_2, T_E were then calculated from the sum of all emissions. To analyze the role played by every type of vegetation in the total yearly emissions (T_E), time series of the percentage of emissions of CO_2 for every type of vegetation is given in Figure 6. Whereas for rainforest, forest, and grassland, their percentages in the total emissions remain largely the same, and there are other vegetation types with a growing influence like grassland-rainforest, rainforest-farming, and rainforest-grassland. The principal problem in Mexico related to wildfires is in rainforest regions where about 50–60% of the total emissions of CO_2 to the atmosphere occur. It is followed by forest regions with about 20% of the total emissions. The emissions by the vegetation type rainforest-farming grew from about 2% in 1999 to 7% in 2010, and this could be a warn signal for the CONAFOR. Although the percentages of emissions by farming areas show some oscillations, they remain approximately between 6 and 10%. Other vegetation types, farming-grassland, and shrubland reach values around 1%. Although the available

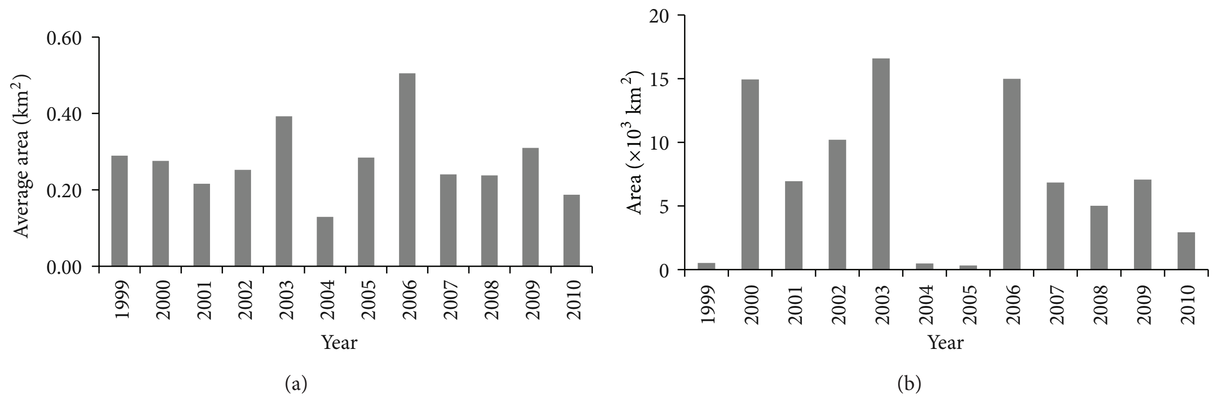

Figure 5: Mean affected area per fire obtained from documented wildfires (CONAFOR) (a) and total affected area considering all reported hot spots in all vegetation types (CONABIO) (b).

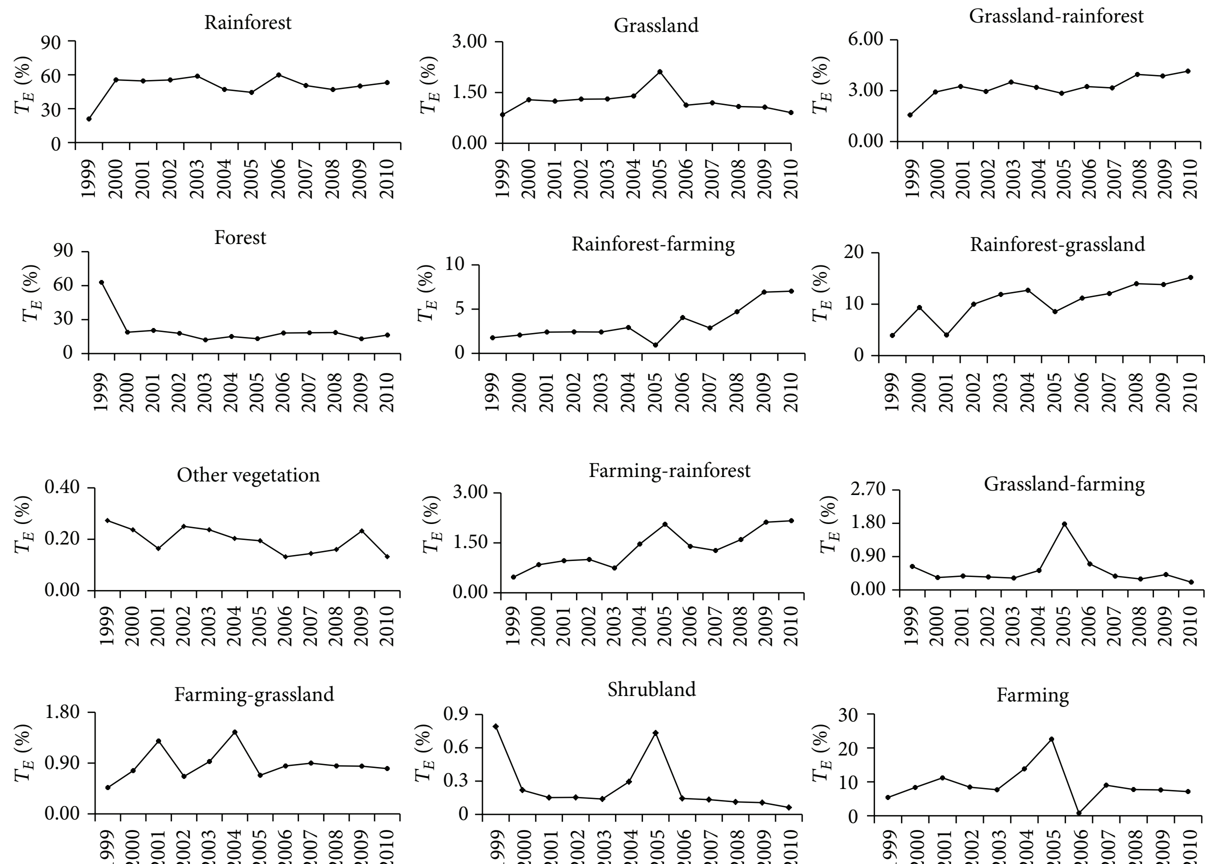

Figure 6: Time series of the percentages of each vegetation type in relation to the total yearly emissions. The considered period is from 1999 to 2010.

information is scarce, we think that this analysis reveals very well what is happening in the; therefore it could be relevant to the design of firefighting strategies.

3.1. Total Emissions of CO_2. We have carried out a careful analysis on the distribution of wildfires in the different ecosystems and we have discussed about the relative importance of the vegetation types in the emissions of CO_2 to the atmosphere. It allowed for obtaining information on the tendencies in the incidence of wildfires in the vegetation types. It was possible to determine total affected areas separately, that is, in every vegetation type and for every year in the considered period. The principal aim of this research work was to estimate the total emissions of CO_2 considering the incidence of the wildfires for the main groups of vegetation in Mexico. In Figure 6, the percentage of yearly emissions of CO_2 for every ecosystem was displayed. It provided relevant

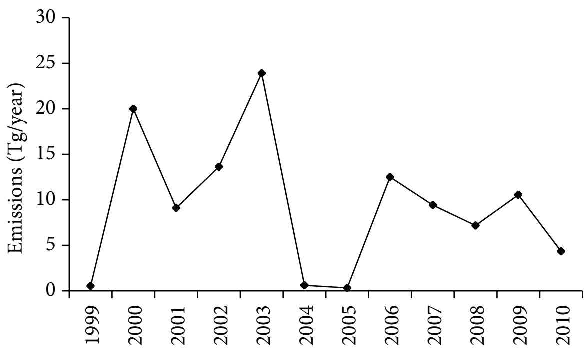

Figure 7: Total yearly emissions of CO_2 in Mexico during the period 1999 to 2010 considering all vegetation types.

evidence about the tendencies related to the emissions by wildfires in every type of vegetation. We consider that the knowledge about the tendency of damages of vegetation types by wildfires is very important to establish policies to protect threatened areas. In Figure 7, the time series of the yearly total emission of CO_2 by wildfires during the period 1999–2010 in Mexico is given. The total emission of CO_2 for this period is 112 Tg and the annual mean is 9.3 Tg with a standard deviation of 7.5 Tg. The estimated quantities in this work are relevant because it gives an idea about the tons of CO_2 emitted into the atmosphere and its impact on the greenhouse effect. The most affected regions due to these emissions are located in the southern part and in the peninsula of Yucatan. It corresponds to areas with forest and rainforest (see Figure 3). The results reflect the magnitude of the problem of air pollution, principally in the months with major presence of wildfires which regularly occur from January to May, although in some years it extends until August [6]. It is important to mention that the presented results may have uncertainties in the estimation of total yearly emissions of CO_2, due to the lack of information or due to the form in which available data were applied. The documentary sources provide only the available information but it is not the required, and it is incomplete. However, the results are relevant because they provide a quantitative idea about the emissions of CO_2 generated by forest fires that occur in Mexico every year. We are aware that currently there is a degree of uncertainty about the magnitude of CO_2 emissions by biomass burning. The same occurs with the pollution affecting the air quality in urban areas near regions with a high incidence of forest fires with the corresponding CO_2 emissions. The difficulties that we found to estimate the CO_2 emissions by wildfires in Mexico have been with approximations ridded, but the principal barrier was that wildfires are not well documented. Finally in Table 2, we compare the results obtained in this work with other estimations realized in different parts of de world and with different methodology.

Table 2: Reported values of CO_2 emissions by forest fires in different parts of the world.

CO_2 emissions in Tg	Site
2.2	Greece [21]
6	California (USA) [13]
112	This work—Mexico (1999–2010)
147	USA [23]
966	Russia North America [24]
5716	Global [17]

4. Conclusions

Using available data like documented wildfires, the position of satellite-detected hot spots, biomass load for every type of vegetation, and biomass burning efficiencies, important information on yearly variability and distribution of wildfires was obtained. We found that emissions of carbon dioxide (CO_2) due to wildfires represent a problem that affects predominantly the vegetation types: rainforest, forest, grassland, and farming in Mexico. The total CO_2 emissions to the atmosphere during the period 1999 to 2010 were of the order of 112 Tg, with a yearly mean emission of about 9.3 Tg. According to our results, the emissions of CO_2 to the atmosphere by wildfires are in the order of magnitude of those reported in other studies realized in different parts of the world. In the same period, an area of approximately 86800 km^2 was affected by the wildfires. The analysis on the incidence of wildfires in different types of vegetation revealed interesting aspects about the relative importance of each ecosystem. We found that the relative significance of forest and rainforest in the question of wildfires remained approximately constant in the period 1999–2010. In contrast, the relative importance of rainforest-farming and rainforest-grassland is continuously growing. Since there are in Mexico vast inaccessible regions where also a large number of wildfires occur, our estimations acquire importance because the whole Mexican territory was considered through the detected hot spots in the calculation of total yearly emissions of CO_2. We are aware that there is a lot of work to be in a position where better estimations for the emissions of CO_2 can be carried out, but we consider our results as an important first step in that direction.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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