



"Gheorghe Asachi" Technical University of Iasi, Romania



ESTIMATING NATIONAL WILDFIRE EMISSIONS FOR THE LAST DECADE IN TURKEY

Faruk Dincer

*TUBITAK Marmara Research Center, Environment and Cleaner Production Institute, 41470, Gebze-Kocaeli, Turkey
E-mail: faruk.dincer@tubitak.gov.tr; Phone: +90 262 677 34 39; Fax: +90 262 641 23 09*

Abstract

Wildfire emissions are a major contributor of atmospheric gaseous and particulate pollutants for local air pollution levels. With respect to wildfires, Turkey faces one of Europe's most severe problems during summer. In this study, a database which holds data for wildfire emissions in Turkey for the last decade (between 2000 and 2009) was established in order to create a wildfire emissions inventory. The emissions of carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), non-methane volatile organic compounds (NMVOC), nitrogen oxides (NO_x), ammonia (NH_3), nitrous oxide (N_2O) sulphur oxides (SO_x), total suspended particulate (TSP), particulate matter $<10 \mu\text{m}$ diameter (PM_{10}) and particulate matter $<2.5 \mu\text{m}$ diameter ($\text{PM}_{2.5}$) are estimated from wildfires in Turkey. European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA) emission factors were used for different biomes of Turkey including temperate forest, Mediterranean forest and steppe. Total emissions from wildfires were estimated as 6,265,180 tons CO_2 , 386,530 tons CO, 18,078 tons CH_4 , 35,901 tons NMVOC, 13,444 tons NO_x , 1,303 tons NH_3 , 414 tons N_2O , 2,690 tons SO_x , 63,974 tons TSP, 41,395 tons PM_{10} and 33,869 tons $\text{PM}_{2.5}$ for the last decade. Comparing the total emissions in Turkey for the year 2000, wildfire emissions constitute 2.78% of CO_2 , 0.27% of PM ($\text{PM}_{10}+\text{PM}_{2.5}$), 0.02% of SO_x , 0.40% NO_x , 2.00% of VOC and 5.32% of CO emissions.

Key words: emission inventory, gaseous pollutants, particulate pollutants, Turkey, wildfire emission

Received: March, 2011; Revised final: February, 2011; Accepted: March, 2012

1. Introduction

Wildfires can produce substantial increases in the concentrations of carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), ozone (O_3) and volatile organic compounds (VOCs) downwind of the fire and significantly affecting global atmospheric chemistry, degrading air quality, and impacting on radiative transfer in the atmosphere (Crutzen et al., 1979; Miranda et al., 2009).

Burning of forests also release high concentrations of aerosols into the atmosphere and result in a severe visibility degradation and harmful effects on human health (Park et al., 2007).

Air pollution is increased due to the direct emissions from fires or by trace species that are generated in the atmosphere from these direct emissions through chemical reactions.

Wildfire emissions can be important for local air pollution levels. According to the CORINAIR-1990 inventory, wildfires contribute 0.2% to the emissions of NO_x , 0.5% to the emissions of nonmethane volatile organic compounds, 0.2% to the emissions of CH_4 , 1.9% to the emissions of CO, 1.2% to the emissions N_2O , and 0.1% to the emissions of NH_3 in Europe (EMEP/EEA, 2009; Kucuk et al., 2012). As these emissions occur on limited areas during short time periods, their impacts are more severe for public health such as respiratory symptoms and illnesses including bronchitis, asthma and upper respiratory infection, impaired lung function, and cardiac diseases (Bowman and Johnston, 2005). In the last two decades, there have been much interest in studying the contribution of wildfires to enhance the production of air pollutants in the atmosphere together with characterise fire emissions

around the globe with many large-scale ground-based and airborne measurement campaigns of biomass burning (Andreae and Merlet 2001; Cinnirella and Pirrone, 2006). Andreae and Merlet (2001) provided separate emission factors for different types of biomass burning such as forest and savanna fires. Wang et al. (2010) showed the concentration levels of PM_{2.5}, carbonaceous species and atmospheric mercury species that were originated after Canadian wildfires on May 31, 2010. Some studies have been carried out on the investigation of environmental results of haze episodes originating from wildfire emissions (Koe et al., 2001; Muraleedharan et al., 2000). Kim et al. (2003) studied the levels of dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) and polycyclic aromatic hydrocarbons (PAHs) in the burnt soil samples in comparison with the results with unburnt soil. The data presented in their study present that PCDD/Fs and PAHs are also formed during wildfires and are then introduced to soil.

More recently, using remote sensing data and fuzzy logic approach became available for active fire, burned area detection, mapping canopy damage and evaluating of land degradation from wildfires (Giglio, 2007; Lentile et al., 2006; Liu et al., 2009; Morton et al., 2011, Meléndez - Pastor et al., 2013). Liu et al. (2009) identified two pollution episodes by ground PM₁₀ measurements and data from multiple satellite remote sensors were integrated with these measurements. The meteorological data was also studied to investigate the impact of Greek wildfires in August 2007 on the air quality in Athens. Singh et al. (2000) analyzed the detailed atmospheric gas/aerosol composition data acquired during the 2008 NASA ARCTAS (Arctic Research of the Composition of the Troposphere from Aircraft and Satellites) airborne campaign performed at high northern latitudes in spring (ARCTAS-A) and summer (ARCTAS-B) and in California in summer (ARCTAS-CARB).

Some studies have been conducted in Turkey regarding to the environmental effects of wildfires on physical, chemical and biological parameters of soil (Camci et al., 2009; Ekinci and Kavdir, 2005). On the other hand several emission estimation studies in Turkey have been conducted recently (Dincer and Elbir, 2007; Elbir and Muezzinoglu, 2004; Muezzinoglu et al., 1998). However, these studies only included emissions from industries, domestic heating and railway vehicles. Emissions from wildfires have not been included in the Turkish emission inventories due to the lack of data.

This study provides estimations about the emissions of carbon dioxide (CO₂), carbon monoxide (CO), methane (CH₄), non-methane volatile organic compounds (NMVOC), nitrogen oxides (NO_x), ammonia (NH₃), nitrous oxide (N₂O) sulphur oxides (SO_x), total suspended particulate (TSP), PM₁₀ and PM_{2.5} from wildfires in Turkey for the period of 2000-2009. The wildfire data (the number of fires and the burnt area) recorded by the General Directorate of Forestry (GDF) and the emission

factors from EMEP/EEA's database were used for the calculation of wildfire emissions for the last decade for the first time in Turkey.

2. Turkey forest resources

The first regular and scientific inventory in order to determine the forest resources was done between 1963-1972. Management plans for all forests were completed in this period. Based on the assessment of 1963 - 1972 inventory results, Turkey had 20,199,296 hectares (ha) forest area covering about 26.1 percent of the country's total land area (GDF, 2009) and based on the forest management plans up to the end of 2009 Turkey has 21,386,200 ha forest area accounting for about 27.5 percent of the country's total land area. According to those inventory results, the forest area has increased about 1,185 thousand ha in the last three decades.

Turkey has about 21.4 million ha forest area, about 27.5 percent of the country's land and 99.9% of the forest area is owned by the state (GDF, 2009). The Black Sea, the Mediterranean Sea and Aegean regions are hosted most of the Turkish forests and due to the biodiversity value these forests are natural and semi-natural (Fig. 1). Deciduous forests, that present along northern Turkey, are extensive and relatively continuous at moderate altitudes. Coniferous forests, depending on their species and locations, are found at different elevations from sea level to the timber line.

Forest ecosystems of Turkey include different species due to diverse floristic regions, that are named Euro-Siberian, Mediterranean and Irano-Turanian (Kaya and Raynal, 2001). *Pinus brutia* (calabrian pine), *Pinus nigra* (crimean pine), *Pinus sylvestris* (scotch pine), *Abies* (firs) spp., *Picea orientalis* (eastern spruce), *Cedrus libani* (cedars), *Juniperus* spp., *Quercus* (oaks) spp., *Fagus orientalis* (oriental beech), *Pinus pinea*, *Cupressus sempervirens*, *Pinus halepensis*, *Alnus* spp., *Castanea sativa*, *Carpinus betulus* are the dominant species of Turkish forests. Oaks spread almost in every region of the country depending on its species with 6.4 million ha. Calabrian pine has an area of 5.4 million ha while Crimean pine has 4.2 million ha (GDF, 2009). The most frequent forest tree species existing in Turkey's forest areas is shown in Fig. 2.

Forests of the Euro-Siberian floristic region cover the Black Sea and the Marmara geographical regions, excluding the peninsulas of Gelibolu and Biga. The southern boundary of the region follows the northern slopes of the mountains, extending E-W in direction. The primary vegetation formations of this area are the following; Broad-leaf deciduous and conifer forests, Humid-subhumid coniferous forests, Dry oak and pine forests, The shrub (*pseudosomaquies* and *maquis*) formation (Kaya and Raynal, 2001).

Forest ecosystems of the Mediterranean encompass the coastal belt of the Marmara Sea, the western portion of the Anatolian and the Mediterranean geographical regions. The elevation of

the ecosystem ranges from sea level to up to 4000 m. The primary vegetation formations of this area are as follows; Shrub (maquis and garrigue) formation, Lower (Eu- or Thermo) Mediterranean belt forests, Aegean mountain (Oro-) forests, Mediterranean (Oro-) mountain forests (Kaya and Raynal, 2001).

Forest ecosystems of the Irano-Turanian region encompass all parts of the inner, eastern and southeastern Anatolian geographic area. Forests are present at the edge of plains and in tectonic depressions. Most basins support steppe vegetation. Dry black pine, oak, juniper forests also exist in this region (Kaya and Raynal, 2001).

The GDF, acting as an independent body under the Ministry of Forestry and Water Affairs in Turkey, is responsible for the management of Turkey's forest resources which are in a very fragile ecosystem with very rich biological diversity. The GDF has twenty seven Regional Forest Directorates for the management of forest resources (Adana, Adapazari, Amasya, Ankara, Antalya, Artvin, Balikesir, Bolu, Bursa, Canakkale, Denizli, Elazig, Erzurum, Eskisehir, Giresun, Isparta, Istanbul, Izmir, Kahramanmaraş, Kastamonu, Mersin, Mugla, Trabzon, Zonguldak, Kutahya, Konya, Sinop).

3. Wildfires data in Turkey

Wildfires are appearing to be the major reason that damages the presence of forests in our country and the case is the same for some other countries in the world (Pausas and Vallejo, 1999; USGAO, 2004). Turkey is located in Mediterranean climate region. The forests usually located at the coastal band areas are under severe risks of fire threats. The coastal band of 1,700 km begins at Eastern Mediterranean coasts and covers all Aegean and Marmara costs. The area covering 160 km depth of the coastal band is fire sensitive region. Twelve million ha of forests, which are 58% of whole forest

area, is located in this region and under fire risk (GDF, 2009).

Wildfire statistics have been kept in Turkey since 1937. According to these statistics 86,769 wildfires occurred and 1,617,701 ha of forest area was burned until 2009 since 1937. The average annual number of wildfires and burned areas between 1937 and 2009 were 1205 and 22,468 ha, respectively.

The burnt area in ha from wildfires is illustrated in Table 1 with respect to the Regional Forest Directorates of GDF. The biome characteristics of the Directorates are also shown in the table. These biomes are classified as; (1) Temperate forest (Euro-Siberian floristic region), (2) Mediterranean forest (Mediterranean floristic region) and (3) Steppe (Irano-Turanian floristic region). The average area burnt annually during the period 2000–2009 was approximately 11,046 ha, which was 17% less than in the previous decade (1990–1999).

The historical trend for the wildfires data for the period of 1937–2009 in Turkey are derived from GDF official website (Fig. 3) (www.ogm.gov.tr). In the past decade (2000–2009), the average annual number of wildfires throughout Turkey has exceeded 2,000 which is 5% more than recorded during the previous decade (1990–1999). During the previous decade the average annual number of wildfires throughout Turkey was 1,989 and the average area burnt annually was approximately 12,906 ha. The mean area burnt per fire event decreased from 73 ha during the decade 1950–1959 to 38 ha (1980–1989) and 16 ha (1990–1999). During the period 2000–2009, the mean area burnt per fire decreased to 5 ha. Changes may be attributed to variable meteorological conditions and differences in extensive dry conditions during summer. In addition, a downward trend in the total area burnt per year has been noticed during the presented decades. It is depicted that, during the year 2008, the area burnt was the largest of the last decade.

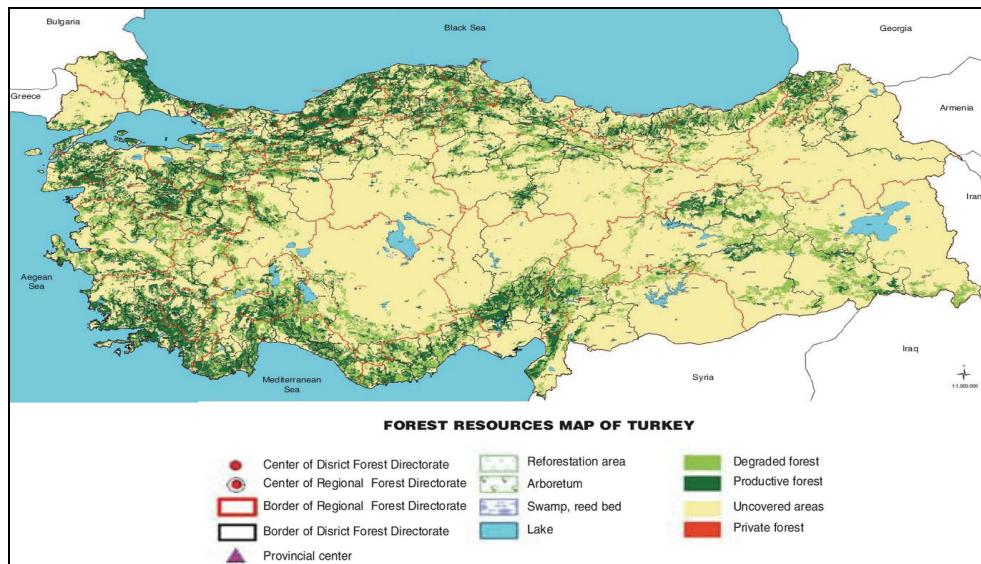


Fig. 1. Forest resources map of Turkey

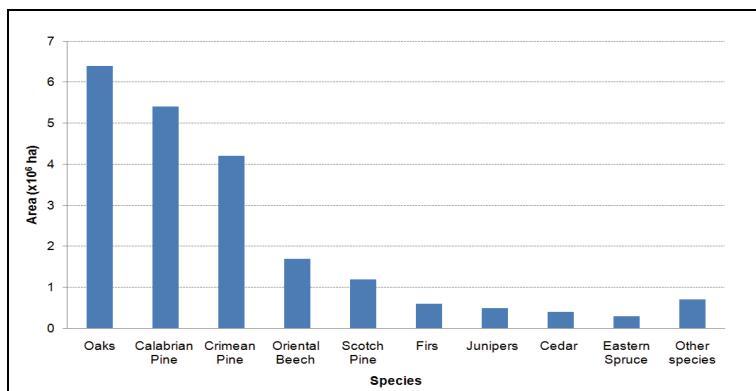


Fig. 2. Distribution of forest areas by main tree species

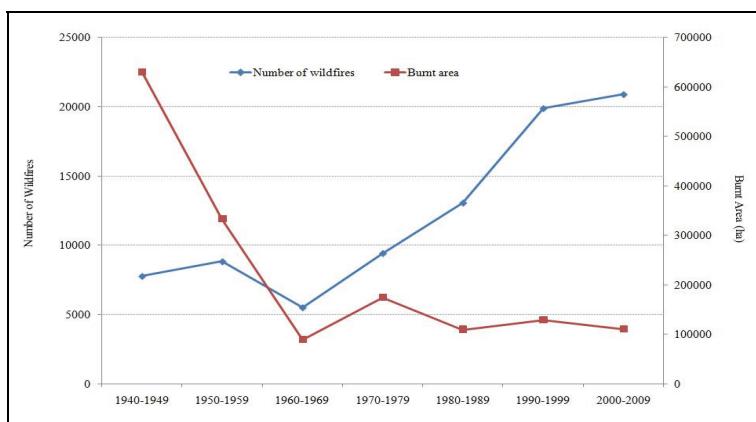


Fig. 3. Historical trend of wildfires in Turkey (1940-2009)

Table 1. Burnt area (ha) data for the period of 2000 – 2009 in Turkey

| Forest Directorates | YEARS | | | | | | | | | | Σ of 10 Years |
|----------------------|--------------|--------------|-------------|-------------|-------------|-------------|-------------|-------------|--------------|--------------|----------------------|
| | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | |
| Temperate forest | ADAPAZARI | 358 | 361 | 53 | 176 | 77 | 25 | 170 | 321 | 192 | 358 |
| | AMASYA | 139 | 281 | 97 | 176 | 108 | 32 | 93 | 413 | 46 | 85 |
| | ARTVİN | 7 | 6 | 62 | 9 | 4 | 9 | 7 | 6 | 34 | - |
| | BOLU | 188 | 65 | 26 | 400 | 19 | 18 | 284 | 80 | 29 | 1121 |
| | GİRESUN | 108 | 54 | 26 | 59 | 22 | 18 | 10 | 33 | 51 | 11 |
| | İSTANBUL | 1649 | 237 | 34 | 207 | 145 | 32 | 67 | 263 | 96 | 90 |
| | KASTAMONU | 106 | 122 | 66 | 221 | 32 | 18 | 137 | 233 | 29 | 5 |
| | SİNOP | 156 | 170 | 69 | 25 | 11 | 35 | 30 | 78 | 54 | 21 |
| | TRABZON | 213 | 95 | 76 | 114 | 73 | 58 | 10 | 40 | 324 | 46 |
| | ZONGULDAK | 95 | 120 | 68 | 836 | 36 | 63 | 101 | 373 | 56 | 14 |
| | BALIKESİR | 2200 | 497 | 3634 | 254 | 275 | 260 | 257 | 442 | 150 | 253 |
| | BURSA | 2732 | 928 | 115 | 161 | 105 | 11 | 159 | 386 | 54 | 452 |
| Mediterranean forest | ELAZIĞ | 204 | 478 | 221 | 197 | 217 | 115 | 104 | 338 | 859 | 210 |
| | ERZURUM | 263 | 45 | 2 | 9 | 50 | 2 | 65 | 28 | 14 | 0 |
| | ESKİSEHİR | 73 | 673 | 2 | 50 | 38 | 11 | 66 | 107 | 24 | 70 |
| | ADANA | 3478 | 211 | 109 | 215 | 397 | 94 | 443 | 704 | 415 | 183 |
| | ANTALYA | 3854 | 183 | 450 | 824 | 509 | 404 | 515 | 2093 | 17026 | 469 |
| | ÇANAKKALE | 3844 | 118 | 21 | 439 | 689 | 8 | 45 | 101 | 1824 | 76 |
| | DENİZLİ | 1687 | 92 | 173 | 55 | 181 | 47 | 61 | 369 | 71 | 88 |
| | ISPARTA | 50 | 63 | 32 | 31 | 48 | 10 | 49 | 55 | 61 | 38 |
| | İZMİR | 2952 | 1020 | 308 | 622 | 976 | 438 | 579 | 963 | 1790 | 1603 |
| | K.MARAŞ | 126 | 391 | 165 | 74 | 119 | 93 | 45 | 949 | 710 | 78 |
| Steppe | MERSİN | 97 | 95 | 421 | 112 | 24 | 14 | 29 | 1053 | 5080 | 80 |
| | MUĞLA | 1451 | 526 | 2072 | 1194 | 258 | 945 | 3416 | 1531 | 665 | 260 |
| | ANKARA | 209 | 290 | 22 | 140 | 173 | 42 | 314 | 80 | 63 | 65 |
| | KONYA | 66 | 189 | 21 | 22 | 39 | 12 | 132 | 42 | 17 | 88 |
| | KÜTAHYA | 47 | 84 | 168 | 26 | 251 | 8 | 574 | 581 | 15 | 25 |
| | TOTAL | 26352 | 7394 | 8513 | 6648 | 4876 | 2822 | 7762 | 11662 | 29749 | 4680 |
| | | | | | | | | | | | 110458 |

4. Methods

Emissions from wildfires depend on (1) the duration and intensity of the fire, (2) the total area burnt by the fire, and (3) the type and amount of vegetation that is burnt (EMEP/EEA, 2009).

In this study, gaseous and particulate matter emissions from forest fires in Turkey are quantified. The pollutants studied are the main products of forest fires: CO₂, CO, CH₄, NMVOC, NO_x, NH₃, N₂O, SO_x, TSP, PM₁₀ and PM_{2.5}. The estimation of the burnt biomass is rather complicated as it depends on many parameters. The burning material is inhomogeneous, adding complexity to the emission estimates. Forest fire fuels include all the materials that can be affected by a fire such as shrubs, trees, leaves, branches, barks, and all the organic matter that is present in the upper layers of the ground (Lazaridis et al., 2008). In particular, the amount of the dry biomass burnt (M in kilograms) is estimated after Seiler and Crutzen (1980) (Eq. 1):

$$M = A \times B \times \alpha \times \beta \quad (1)$$

where A is area burnt in m²; B is average total biomass of fuel material per unit area in kg/m²; α is fraction of biomass above the surface; β is burning efficiency (fraction burnt) of the above-ground biomass. The coefficients α and β depend on the type of the ecosystem (dimensionless). The average total biomass of fuel material values of the relevant biomes are based on the studies of Seiler and Crutzen (1980) and the ' α ' and ' β ' fractions (Table 2) are derived from the Spanish Corinair 1990–1993 inventories (Murillo 1994).

The quantity of carbon emitted (in kilograms) is estimated as (Eq. 2):

$$C = 0.45 \times M \quad (2)$$

where 0.45 is the mean mass fraction of carbon in dry biomass (with mass M in kilograms) and is considered independent of the type of biomass.

For calculation of the gas emissions in this paper, the product of the EMEP/EEA emission factors (kg/ha), and the GDF burned area (A) are used to calculate annual emissions (Eq. 3):

$$E(x) = A_{temperate} * EF_{temperate}(x) + A_{Mediterranean} * EF_{Mediterranean}(x) + A_{steppe} * EF_{steppe}(x) \quad (3)$$

where x = CO, CH₄, etc.

Many publications (Akagi et al., 2011; Alves et al., 2011; Andreae and Merlet, 2001; McMeeking et al., 2009) have demonstrated that emission factors vary widely, depending on fuel types, combustion phase (smouldering versus flaming), area burnt, fuel loadings, fuel consumption and types of vegetation. In these publications emission factors are given in gram species per kilogram dry matter burned or kg species per ton dry matter burned. The wildfire data recorded by GDF do not include the above mentioned variables. The number of fires and the burnt area in ha were achievable with respect to biome types of forest in Turkey so the emission factors that were given by EMEP/EEA (2009) and EMEP/CORINAIR (2006) database were used in emission estimation calculations (Table 3).

5. Results and discussion

The emissions of gaseous and particulate matter pollutants were estimated using the emission methodology presented above. For the period of 2000–2009, emissions amounted to 6,265,180 tons CO₂, 386,530 tons CO, 18,078 tons CH₄, 35,901 tons NMVOC, 13,444 tons NO_x, 1,304 tons NH₃, 414 tons N₂O, 2,690 tons SO_x, 63,974 tons TSP, 41,395 tons PM₁₀ and 33,869 tons PM_{2.5}.

Table 2. Biome characteristics for wildfire emission calculations

| Biome | B = Biomass (kg/m ²) | α = Above ground fraction biomass | β = Burning efficiency |
|----------------------|----------------------------------|--|------------------------------|
| Temperate forest | 35 | 0.75 | 0.2 |
| Mediterranean forest | 15 | 0.75 | 0.25 |
| Steppe | 2 | 0.36 | 0.5 |

Table 3. Emission factors for different biomes

| Pollutant | Temperate forest | Mediterranean forest | Steppe | Unit |
|-------------------|------------------|----------------------|--------|------------------------------------|
| CO | 5400 | 2900 | 373 | kg ha ⁻¹ area burned |
| CH ₄ | 354 | 95 | 24 | |
| NMVOC | 500 | 270 | 34 | |
| NO _x | 190 | 100 | 13 | |
| NH ₃ | 43 | 23 | 3 | |
| N ₂ O | 6 | 3 | 0.7 | |
| SO _x | 38 | 20 | 3 | |
| TSP | | 17 | | |
| PM ₁₀ | | 11 | | g kg ⁻¹ wood burned |
| PM _{2.5} | | 9 | | |

There is clearly a decreasing trend in all the emissions during 2000 to 2005 (Table 4). For the period of 2005-2008, an upward trend is noticed. The highest emissions are observed in 2000 and 2008, while the lowest emissions occurred in 2005 (Table 4).

Comparing the wildfire emissions estimated in this study for the year 2000 to the total amount of emissions estimated for air pollutants sector in Turkey for the year 2000, it can be stated that the wildfire emissions constitute 2.78% of CO₂ (TSI, 2012), 0.27% of PM, 0.02% of SO_x, 0.40% NO_x, 2.00% of VOC and 5.32% of CO emissions (Muezzinoglu et al., 1998).

Being in Mediterranean region, the forests at the coastal bands are fire sensitive. The distribution of emissions according to biome type of forests are presented in Fig. 4. High proportions of gaseous emissions are released from Mediterranean wildfires with respect to Temperate and Steppe wildfires (Fig. 4). Mediterranean wildfire emissions comprise 57% of CO, NO_x, SO_x, NMVOC, NH₃ and 55% of N₂O emissions. Temperate wildfire emissions cause high particulate emissions with respect to Mediterranean and Steppe wildfires. Temperate wildfire emissions comprise 46% of TSP, PM₁₀ and PM_{2.5} of the total emissions.

Estimations about the wildfire emissions calculated here are compared with those reported by the previous studies (Table 5). Not only estimates of gaseous pollutants emissions but also estimates of particulate emissions in Turkey are higher than emission estimates of Greece and Italy for the years 2000 and 2001. Emission estimates of CO₂, CO, CH₄ and NO_x in Portugal were much lower than Turkey's emission estimates from wildfires between 2000 - 2004. Emission estimates of Southern Europe countries including Spain, Portugal, Italy, Greece and Mediterranean France are higher than Turkey's emission estimates for the year 2003. Gaseous pollutants emission estimates of Canada are almost similar to Turkey's estimates while particulate emission estimates are lower in Turkey. Both estimates of gaseous Pollutant emissions and estimates of particulate pollutants emissions of USA are higher than the emission estimates of Turkey.

Inter-annual variability in burnt area was high during the study period, ranging from over 25,000 ha in 2000 and 2008, to a low of 2,800 ha in 2005, i.e. one order of magnitude (Table 1). Burnt area decreased a little, from a total of 129,508 ha during the previous decade (1990 – 1999) to 110,458 ha in the past decade (2000 – 2009) (Fig. 3). A similar study was conducted by Rosa et al. (2011) that aimed to estimate atmospheric emissions from wildfires over the period 1990-2008 in Portugal. Inter-annual variability in their studies was very high, over 400,000 ha in 2003, to a low of 9,000 ha in 2008. Within this large annual variability, Rosa et al. (2011) found that CO₂ was the gas with larger quantities emitted in 2003 with a value of 5,083,000 tons. In this study CO₂ was also found with large quantities emitted. In 2000, CO₂ emissions occurred 1,558,698 tons with its maximum value. In 2003, CO₂ emissions were 424,638 tons, which is over 10-fold lower from Portugal emissions.

Barbosa et al. (2009) conducted a study on the number of forest fires and burned area distribution as retrieved by European Forest Fire Information System (EFFIS) database. Atmospheric emission estimates of CO₂ and other trace gases were done for the 2000-2005 period in which burned area maps were used together with fuel load and burning efficiency figures. Emission factors were also used to estimate trace gas and aerosol emissions produced by wildfires. The emission estimates from wildfires in the EU countries (19 countries) as well as Croaita, Switzerland, Norway and Turkey (CSNT) were presented in the study. Table 6 depicts the emission estimates of these countries as well as Turkey's emission estimates that are found in this study. Turkey's emission estimates comprise 21% - 88% of CO₂, 33% - 123% of CO, 34% - 173% of CH₄, 23% - 106% of NO_x, 4% - 109% of PM₁₀ and 29% - 89% of PM_{2.5} emissions. The difference between the ratios especially over 100% may be due to the calculation methodology of the studies.

The mean value and the upper and lower limit of the 95% confidence interval for CO₂, CO, CH₄, NMVOC, NO_x and SO_x emission distributions are shown in Fig. 5.

Table 4. Annual wildfire emissions estimates for the period of 2000-2009, t y⁻¹

| Pollutant | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | Total |
|-------------------|---------|--------|--------|--------|--------|--------|--------|--------|---------|--------|---------|
| CO ₂ | 1558698 | 493866 | 576894 | 424638 | 263634 | 164236 | 389026 | 646428 | 1464978 | 282780 | 6265180 |
| CO | 96835 | 30350 | 35532 | 26039 | 16000 | 9795 | 23832 | 39896 | 91062 | 17190 | 386530 |
| CH ₄ | 4680 | 1733 | 1972 | 1368 | 744 | 447 | 1069 | 1871 | 3341 | 853 | 18078 |
| NMVOC | 8992 | 2814 | 3295 | 2416 | 1486 | 910 | 2214 | 3705 | 8473 | 1596 | 35901 |
| NO _x | 3371 | 1062 | 1243 | 909 | 556 | 340 | 828 | 1388 | 3148 | 599 | 13444 |
| NH ₃ | 365 | 178 | 196 | 124 | 52 | 30 | 67 | 135 | 87 | 70 | 1304 |
| N ₂ O | 104 | 33 | 39 | 28 | 17 | 10 | 26 | 43 | 95 | 19 | 414 |
| SO _x | 674 | 213 | 249 | 182 | 111 | 68 | 166 | 278 | 630 | 120 | 2690 |
| TSP | 15999 | 5040 | 5878 | 4308 | 2663 | 1619 | 3981 | 6618 | 15022 | 2846 | 63974 |
| PM ₁₀ | 10352 | 3261 | 3804 | 2788 | 1723 | 1048 | 2576 | 4282 | 9720 | 1842 | 41395 |
| PM _{2.5} | 8470 | 2668 | 3112 | 2281 | 1410 | 857 | 2108 | 3504 | 7953 | 1507 | 33869 |

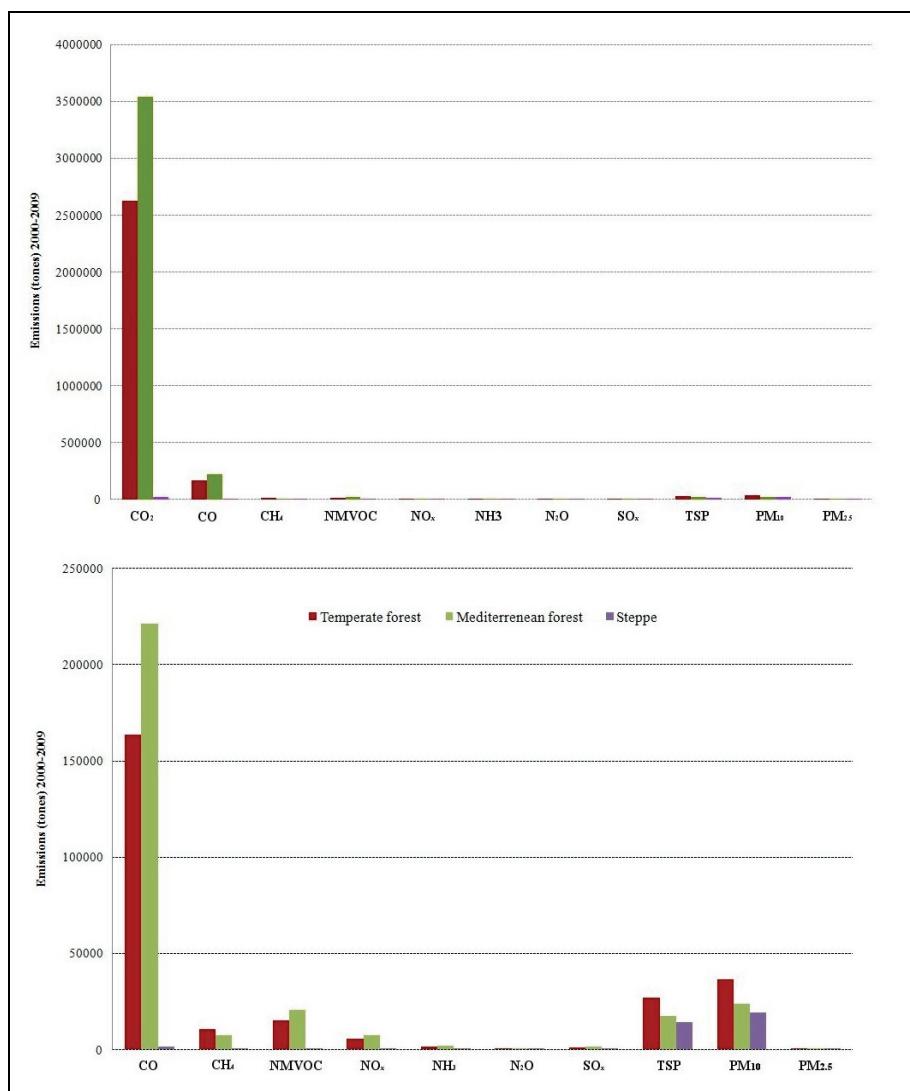


Fig. 4. Wildfire emissions for the period of 2000-2009 with respect to biome types

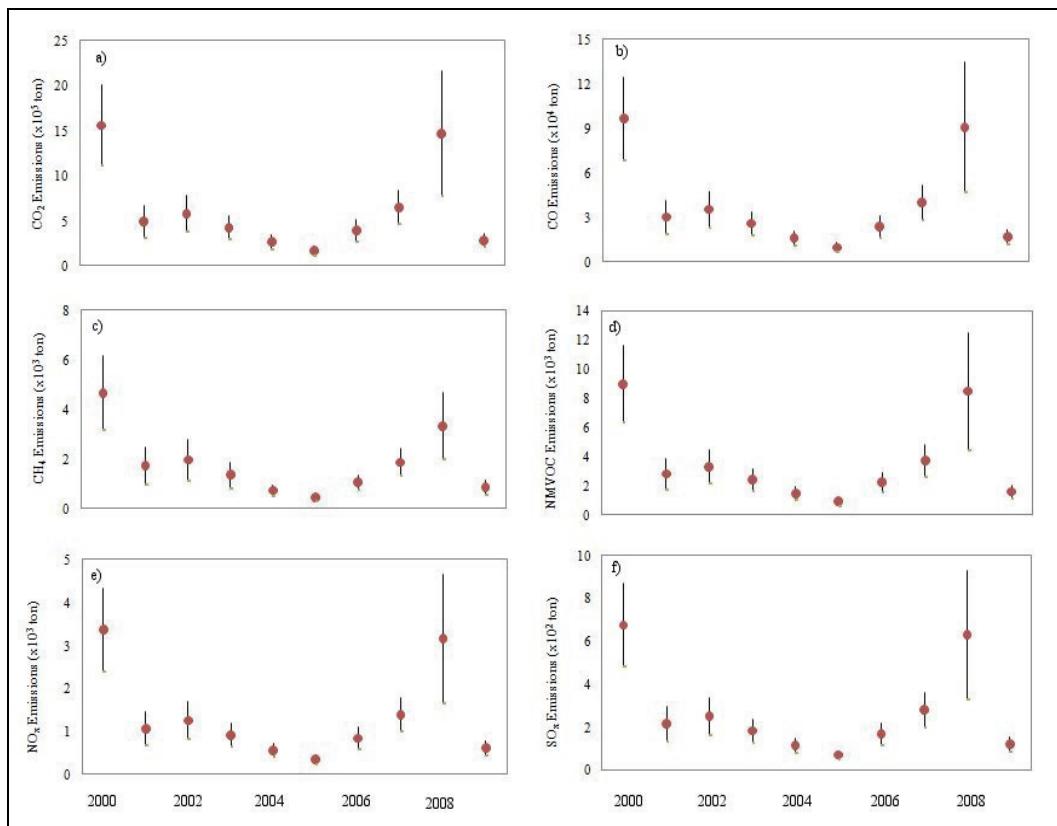
Table 5. Comparison of annual wildfire emission estimates ($t \text{ ha}^{-1}$) for selected countries

| Region/ Country | Year | CO_2 | CO | CH_4 | $NMVOC$ | NO_x | NH_3 | N_2O | SO_x | TSP | PM_{10} | $PM_{2.5}$ | Reference |
|--------------------|------|---------|--------|--------|---------|--------|--------|--------|--------|-------|-----------|------------|---|
| Greece | 2000 | 22.202 | 1.591 | 0.109 | 0.143 | 0.055 | 0.012 | 0.003 | 0.011 | 0.129 | 0.116 | - | Lazaridis et al. (2008) |
| Portugal | | 13.784 | 0.815 | 0.034 | - | 0.025 | - | - | - | - | - | - | Rosa et al. (2011) |
| Turkey | | 59.149 | 3.675 | 0.178 | 0.341 | 0.128 | 0.014 | 0.004 | 0.026 | 0.607 | 0.393 | 0.321 | This study |
| Italy | 2001 | 12.440 | 0.607 | - | 0.077 | 0.034 | - | - | - | - | - | - | Miranda et al. (2009) |
| Portugal | | 14.305 | 0.876 | 0.040 | - | 0.021 | - | - | - | - | - | - | Rosa et al. (2011) |
| Turkey | | 66.793 | 4.105 | 0.234 | 0.381 | 0.144 | - | - | - | - | - | - | This study |
| Portugal | 2002 | 15.272 | 0.804 | 0.040 | - | 0.025 | - | - | - | - | - | - | Rosa et al. (2011) |
| Turkey | | 67.766 | 4.174 | 0.204 | - | 0.146 | - | - | - | - | - | - | This study |
| Southern Europe | 2003 | - | 19.868 | - | 6.030 | 6.314 | 2.444 | - | 4.240 | - | - | - | Miranda et al. (2009) |
| Portugal | | 11.980 | 0.752 | 0.034 | - | 0.022 | - | - | - | - | - | - | Rosa et al. (2011) |
| Turkey | | 63.875 | 3.917 | 0.600 | 0.363 | 0.137 | 0.019 | - | 0.027 | - | - | - | This study |
| USA | 2004 | 108.813 | 6.052 | 0.306 | 0.397 | 0.131 | 0.058 | - | 0.049 | - | 0.825 | 0.734 | Wiedinmyer et al. (2006) NOAA (2004 ^a) |
| Canada | | 69.262 | 3.875 | 0.195 | 0.153 | 0.043 | 0.018 | - | 0.015 | - | 0.549 | 0.488 | Wiedinmyer et al. (2006) Johnston (2004 ^a) |
| Portugal | | 10.036 | 0.695 | 0.027 | - | 0.015 | - | - | - | - | - | - | Rosa et al. (2011) |
| Turkey | | 54.067 | 3.281 | 0.153 | 0.305 | 0.114 | 0.011 | - | 0.023 | - | 0.353 | 0.289 | This study |

^a burnt area in ha is taken from these references

Table 6. Emission estimates from forest fires in Croatia, Switzerland, Norway, Turkey (CSNT) and Turkey, t y^{-1}

| <i>Region/ Country</i> | <i>Year</i> | <i>CO₂</i> | <i>CO</i> | <i>CH₄</i> | <i>NO_x</i> | <i>PM₁₀</i> | <i>PM_{2.5}</i> |
|----------------------------|-------------|-----------------------|-----------|-----------------------|-----------------------|------------------------|-------------------------|
| CSNT | 2000 | 2600000 | 107000 | 6000 | 6000 | 12000 | 10000 |
| Turkey | | 1558698 | 96835 | 4680 | 3371 | 10352 | 8470 |
| Turkey/CSNT (%) | | 60 | 90 | 78 | 56 | 86 | 85 |
| CSNT | 2001 | 800000 | 31000 | 1000 | 1000 | 3000 | 3000 |
| Turkey | | 493866 | 30350 | 1733 | 1062 | 3261 | 2668 |
| Turkey/CSNT (%) | | 62 | 98 | 173 | 106 | 109 | 89 |
| CSNT | 2002 | 1700000 | 72000 | 4000 | 4000 | 8000 | 8000 |
| Turkey | | 576894 | 35532 | 1972 | 1243 | 3804 | 3112 |
| Turkey/CSNT (%) | | 34 | 49 | 49 | 31 | 48 | 39 |
| CSNT | 2003 | 2000000 | 78000 | 4000 | 4000 | 10000 | 8000 |
| Turkey | | 424638 | 26039 | 1368 | 909 | 2788 | 2281 |
| Turkey/CSNT (%) | | 21 | 33 | 34 | 23 | 28 | 29 |
| CSNT | 2004 | 300000 | 13000 | 1000 | 1000 | 1000 | 1000 |
| Turkey | | 263634 | 16000 | 744 | 556 | 1723 | 1410 |
| Turkey/CSNT (%) | | 88 | 123 | 74 | 56 | 172 | 141 |
| CSNT | 2005 | 600000 | 22000 | 1000 | 1000 | 29000 | 2000 |
| Turkey | | 164236 | 9795 | 447 | 340 | 1048 | 857 |
| Turkey/CSNT (%) | | 27 | 45 | 45 | 34 | 4 | 43 |

**Fig. 5.** Uncertainty analysis of (a) CO₂, (b) CO, (c) CH₄, (d) NMVOC, (e) NO_x and (f) SO_x emissions from wildfires in Turkey between 2000 - 2009

Uncertainty in emission estimations data are characterised by the mean and standard deviation of the data, assuming a normal distribution. Results of the uncertainty analysis for the entire time series reveal a very high inter-annual variability, which reflects annual area burnt. The remaining five distributions not shown in Fig. 5 (NH₃, N₂O, TSP, PM₁₀ and PM_{2.5}) present the same emission patterns, clearly linked to the annual variability in burnt area.

6. Conclusions

In this study a database of the wildfire emissions in Turkey has been created for the years 2000-2009. The emission estimations relied on burnt area data and emission factors that are given in databases. During the last decade a downward trend in the wildfire emissions has been noticed between 2000 and 2005, while an upward trend has been noticed between 2005 and 2009.

The estimation of wildfire emissions of gaseous and particulate pollutants (CO_2 , CO , CH_4 , NMVOC, NO_x , NH_3 , N_2O , SO_x , TSP, PM_{10} and $\text{PM}_{2.5}$) in Turkey is presented for the first time. The estimated emissions are; 6,265,180 tons CO_2 , 386,530 tons CO , 18,078 tons CH_4 , 35,901 tons NMVOC, 13,444 tons NO_x , 1,304 tons NH_3 , 414 tons N_2O , 2,690 tons SO_x , 63,974 tons TSP, 41,395 tons PM_{10} and 33,869 tons $\text{PM}_{2.5}$ for the period of 2000-2009.

Results show that the estimated emissions from wildfires in Turkey are relatively low as compared to national emission inventory results. Among the air pollutants from wildfire emissions, CO emissions from wildfires had the highest contribution (5.32%) to the total CO emissions according to emission inventory of Turkey in 2000.

Comprehensive studies will be necessary to show how wildfires and air quality issues can be linked. The quantification of wildfires' contribution to air pollution episodes is a fundamental stage of the development of plans and programs for determining management strategies for air quality. The application of numerical air quality modeling systems is also an added value when evaluating and assessing air quality levels in areas affected by wildfires.

Further studies must also be done in order to find correlations between these estimates with the other studies that will be done in Turkey that includes biomass values, emission and combustion factors of Turkish forests with the combination of burnt area maps and land cover maps.

Acknowledgement

The author is thankful to the Ministry of Environment and Forest – General Directorate of Forestry (GDF) for the burnt area and number of fire database and TUBITAK Marmara Research Center Environment and Cleaner Production Institute for encouraging the author to write this manuscript.

References

- Akagi S.K., Yokelson R.J., Wiedinmyer C., Alvarado M.J., Reid J.S., Karl T., Crounse J.D., Wennberg P.O., (2011), Emission factors for open and domestic biomass burning for use in atmospheric models, *Atmospheric Chemistry and Physics*, **11**, 4039-4072.
- Alves C., Vicente A., Nunes T., Gonçalves C., Fernandes A.P., Mirante F., Tarelho L., Sanchez la Campa A.M., Querol X., Caseiro A., Monteiro C., Evtyugina M., Pio C., (2011), Summer 2009 wildfires in Portugal: emission of trace gases and aerosol composition, *Atmospheric Environment*, **45**, 641-649.
- Andreae M.O., Merlet P., (2001), Emission of trace gases and aerosols from biomass burning, *Global Biogeochemical Cycles*, **15**, 955-966.
- Barbosa P., Camia A., Kucera J., Liberta G., Palumbo I., San-Miguel-Ayanz J., Schmuck G., (2009), *Assessment of Forest Fire Impacts and Emissions in the European Union Based on the European Forest Fire Information System*, In: *Developments in Environmental Sciences*, Bytnerowicz A., Arbaugh M., Riebau A., Andersen C. (Eds.), Elsevier, 197-208.
- Bowman D.M.J.S., Johnston F.H., (2005), Wildfire smoke, fire management, and human health, *EcoHealth*, **2**, 76-80.
- Camci Cetin S., Ekinci H., Kavdir Y., Yuksel O., (2009), Using soil urease enzyme activity as soil quality indicator for reflecting fire influence in forest ecosystem, *Fresenius Environmental Bulletin*, **18**, 1184-1191.
- Cinnirella S., Pirrone N., (2006), Spatial and temporal distributions of mercury emissions from forest fires in Mediterranean region and Russian federation, *Atmospheric Environment*, **40**, 7346-7361.
- Crutzen P.J., Heidt L.E., Krasnec J.P., Pollock W.H., Seiler W., (1979), Biomass burning as a source of atmospheric gases CO , H_2 , N_2O , NO , CH_3Cl and COS , *Nature*, **282**, 253-256.
- Dincer F., Elbir T., (2007), Estimating national exhaust emissions from railway vehicles in Turkey, *Science of the Total Environment*, **374**, 127-134.
- Ekinci H., Kavdir Y., (2005), Changes in soil quality parameters after a wildfire in Gelibolu (Gallipoli) National Park, Turkey, *Fresenius Environmental Bulletin*, **14**, 1184-1191.
- EMEP/CORINAIR, (2006), EMEP/CORINAIR Emission Inventory Guidebook – 2006, Technical report No 11/2006 Group 11: Other sources and sinks, Copenhagen, On line at: http://www.eea.europa.eu/publications/EMEPCORIN_AIR4.
- EMEP/EEA, (2009), EMEP/EEA Air Pollutant Emission Inventory Guidebook 2009, Technical guidance to prepare national emission inventories, Part B, 11.B Forest fires, Copenhagen, On line at: <http://www.eea.europa.eu/publications/emep-eea-emission-inventory-guidebook-2009>.
- Elbir T., Muezzinoglu A., (2004), Estimation of emission strengths of primary air pollutants in the city of Izmir, Turkey, *Atmospheric Environment*, **38**, 1851-1857.
- GDF, (2009), State of Turkey's Forests. Esta Ltd., Ankara, On line at: <http://web.ogm.gov.tr/languages/English/dokumanlar/Publications/stateofforests.pdf>.
- Giglio L., (2007), Characterization of the tropical diurnal fire cycle using VIRS and MODIS observations, *Remote Sensing of Environment*, **108**, 407-421.
- Johnston T., (2004), Canadian report 2004, Canadian Interagency Forest Fire Center, On line at: <http://www.fire.uni-freiburg.de/inventory/database/Canada-Fire-Report-2004.pdf>.
- Kaya Z., Raynal D.J., (2001), Biodiversity and conservation of Turkish forests, *Biological Conservation*, **97**, 131-141.
- Kim E.J., Oh J.E., Chang Y.S., (2003), Effects of forest fire on the level and distribution of PCDD/Fs and PAHs in soil, *Science of the Total Environment*, **311**, 177-189.
- Koe L.C.C., Arellano A.F.Jr., McGregor J.L., (2001), Investigating the haze transport from 1997 biomass burning in Southeast Asia: its impact upon Singapore, *Atmospheric Environment*, **35**, 2723-2734.
- Kucuk O., Bilgili E., Bulut S., Fernandes P.M., (2012), Rates of surface fire spread in a young calabrian pine (*Pinus brutia* Ten.) plantation, *Environmental Engineering and Management Journal*, **11**, 1475-1480.
- Lazaridis M., Latos M., Aleksandropoulou V., Hov Ø., Papayannis A., Tørseth K., (2008), Contribution of forest fire emissions to atmospheric pollution in

- Greece, *Air Quality, Atmosphere & Health*, **1**, 143-158.
- Lentile L.B., Holden Z.A., Smith A.M.S., Falkowski M.J., Hudak A.T., Morgan P., Lewis S.A., Gessler P.E., Benson N.C., (2006), Remote sensing techniques to assess active fire characteristics and post-fire effects. *International Journal of Wildland Fire*, **15**, 319-345.
- Liu Y., Kahn R.A., Chaloulakou A., Kourakis P., (2009), Analysis of the impact of the forest fires in August 2007 on air quality of Athens using multi-sensor aerosol remote sensing data, meteorology and surface observations, *Atmospheric Environment*, **43**, 3310-3318.
- McMeeking G.R., Kreidenweis S.M., Baker S., Carrico C.M., Chow J.C., Collett J.L.Jr., Hao W.M., Holden A.S., Kirchstetter T.W., Malm W.C., Moosmüller H., Sullivan A.P., Wold C.E., (2009), Emissions of trace gases and aerosols during the open combustion of biomass in the laboratory, *Journal of Geophysical Research*, doi:10.1029/2009JD011836.
- Meléndez-Pastor I., Navarro-Pedreño J., Koch M., Gómez,I., Hernández E.I., (2013), Evaluation of land degradation after forest fire with a fuzzy logic model, *Environmental Engineering and Management Journal*, **12**, 2087-2096.
- Miranda A.I., Marchi E., Ferretti M., Millan M.M., (2009), *Forest Fires and Air Quality Issues in Southern Europe*, In: *Developments in Environmental Sciences*, Bytnerowicz A., Arbaugh M., Riebau A., Andersen C. (Eds.), 8, Elsevier, Amsterdam, 209-231.
- Morton D.G., DeFries R.S., Nagol J., Souza Jr. C.M., Kasischke E.S., Hurt G.C., Dubayah R., (2011), Mapping canopy damage from understory fires in Amazon forests using annual time series of Landsat and MODIS data, *Remote Sensing of Environment*, **115**, 1706-1720.
- Muezzinoglu A., Elbir T., Bayram A., (1998), Inventory of emissions from major air pollutant categories in Turkey, *Environmental Engineering Policy*, **1**, 109-116.
- Muraleedharan T.R., Radojevic M., Waugh A., Caruana A., (2000), Chemical characterisation of the haze in Brunei Darussalam during the 1998 episode, *Atmospheric Environment*, **34**, 2725-2731.
- Murillo R.J.C., (1994), The carbon budget of the Spanish forests, *Biogeochemistry*, **25**, 197-217.
- NOAA, (2004), NOAA National Climatic Data Center, State of the Climate: Wildfires for Annual 2004, published online December 2004, On line at: <http://www.ncdc.noaa.gov/sotc/fire/2004/13>.
- Park R.J., Jacob D.J., Logan J.A., (2007), Fire and biofuel contributions to annual mean aerosol mass concentrations in the United States, *Atmospheric Environment*, **41**, 7389-7400.
- Pausas J.G., Vallejo V.R., (1999), *The Role of Fire in European Mediterranean Ecosystems*, In: *Remote Sensing of Large Wildfires in the European Mediterranean Basin*, Chuvieco E. (Ed.), Springer-Verlag, 3-16.
- Rosa I.M.D., Pereira J.M.C., Tarantola S., (2011), Atmospheric emissions from vegetation fires in Portugal (1990-2008): estimates, uncertainty analysis, and sensitivity analysis, *Atmospheric Chemistry and Physics*, **11**, 2625-2640.
- Seiler W., Crutzen P.J., (1980), Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning, *Climatic Change*, **2**, 207-247.
- Singh H.B., Anderson B.E., Brune W.H., Cai C., Cohen R.C., Crawford J.H., Cubison M.J., Czech E.P., Emmons L., Fuelberg H.E., Huey G., Jacob D.J., Jimenez J.L., Kaduwela A., Kondo Y., Mao J., Olson J.R., Sachse G.W., Vay S.A., Weinheimer A., Wennberg P.O., Wisthaler A., (2010), Pollution influences on atmospheric composition and chemistry at high northern latitudes: Boreal and California forest fire emissions, *Atmospheric Environment*, **44**, 4553-4564.
- TSI, (2012), Greenhouse gases emission inventory, 1990-2010, Report No: 10829, Turkish Statistical Institute, Ankara, Turkey.
- USGAO, (2004), Environmental effects of wildland fire, Report No: GAO-04-705, United States General Accounting Office, Washington DC.
- Wang Y., Huang J., Zananski T.J., Hopke P.K., Holsen T.M., (2010), Impacts of the Canadian Forest Fires on Atmospheric Mercury and Carbonaceous Particles in Northern New York, *Environmental Science & Technology*, **44**, 8435-8440.
- Wiedinmyer C., Quayle B., Geron C., Belote A., McKenzie D., Zhang X., O'Neill S., Wynne K.K., (2006), Estimating emissions from fires in North America for air quality modeling, *Atmospheric Environment*, **40**, 3419-3432.