ROAD TRANSPORTATION AND FOREST FIRES IN THE REGION OF ATHENS: AN ACCOUNT OF CARBON FLOWS

CHATZIMPIROS P.[1], **ROUMELIOTI N.**[2], **ZAMBA A.**[2] **and HADJIBIROS K.**[2]

[1] Univ. Paris Diderot, Sorbonne Paris Cité, Institut des Energies de Demain (IED), Paris, France
[2] Department of Water Resources and Environmental Engineering, NTUA, 5, Iroon Polytechniou, 15780, Zografou, Greece
E-mail: k.hadjibiros@hydro.ntua.gr

ABSTRACT

One important component of urban contribution to carbon dioxide atmospheric emissions is transportation. We quantified carbon dioxide (CO_2) emissions from urban road transportation in the center of Athens over a period of five year (2000-2005) and we confront these emissions to the carbon sequestration capacity of regional forests, prior and after the devastating forest fires of 2007 and 2009 in Attica. This comparison of carbon flows points out two complementary aspects of the same socio-environmental issue: persisting sources versus weakening sinks of CO_2 within a mixed (urban and rural) territory. Road transportation emissions are calculated bottom-up using traffic data from in-situ measurements in main road segments. Sequestration capacity of forests is estimated from default literature values on biomass growth rates and satellite images on land cover changes. Over the study period, the per capita CO_2 emissions averaged 0.72 t CO_2/cap/year, which is four times higher than the sequestration capacity of forests before and six times higher after the fires. The imbalance highlights the inadequacy of local carbon sink even before the fires. Although we do not imply that carbon sources and sinks must be balanced locally, comparisons that put urban activities and ecosystem services into common perspective are likely to contribute to local and global environmental sustainability issues. We discuss major socioeconomic factors that may explain differences in per capita CO_2 emissions between our estimates for the centre of Athens and emissions reported for the whole Attica prefecture, where suburban areas are dominant.

Keywords: Road transportation; forest fires; carbon emissions; carbon sequestration; Athens; Attica.

1. Introduction

Human driven alterations of the global carbon (C) cycle mainly originate from fossil fuel combustion and deforestation, both adding carbon dioxide (CO_2) in the atmosphere and oceans. Atmospheric concentration of CO_2 is currently 30% above pre-industrial levels (Steffen *et al*., 2007) as a result of a long term global disequilibrium between carbon emission and sequestration rates. Growing forests and oceans are the main available natural mechanisms for CO_2 sequestration. Yet, oceanic storage is governed by physicochemical processes and biological feedback mechanisms with differential responses to increasing levels of atmospheric CO_2 (Fung *et al*., 2005, Schuster and Watson, 2007, Samiento *et al*., 2004) and many argue that this is likely to weaken future efficiency of the oceanic sink and accelerate climate change (Sabine *et al*., 2004, Schuster and Watson, 2007, McKinley *et al*., 2011). In contrast, forest biomass is a permanent sink for CO_2 as long as forests expand. However, forest growth depends on competition for land among human land uses, such as agriculture, housing and transportation infrastructures, which are land intensive activities and often respond to land scarcity by expanding on proximate forests (FAO, 2009, Lambin *et al*., 2001, Napton *et al*., 2010). Conversion of forests into built-up land and wild forest fires are common examples of land use changes with net releases of CO_2 (Roy, 2003).

We conduct a comparison between CO_2 emissions from the road transportation system in Athens, the capital of Greece, and the reduction of the carbon sequestration capacity of regional forests around Athens. The comparison ties together two aspects of the same socio-environmental issue: emissions from a specific sector of urban activity with changes in suburban areas under human pressure. Although we do not imply that carbon sources and sinks should be balanced locally, comparisons that put urban activities and ecosystem changes into common perspective are likely to promote awareness of city dwellers on local and global environmental issues.

2. Methods and data

2.1. Road transportation and CO_2 emissions

We considered direct and indirect CO_2 emissions from road transportation within the area of Athens prefecture and Piraeus. Athens and Piraeus form a continuous urban tissue with a joint population that exceeds 25 % of population in Greece. We used road traffic data from *in-situ* measurements for the period 2000-2005; these data have already been published in the past (Zamba 2006, Zamba and Hadjibiros 2007).

2.2. Estimation of the carbon sink

The carbon sequestration capacity of growing forests depends on the extent of forest area and on biomass growth rates. We investigate decreases in the sequestration capacity of regional forests around the Greek capital due to fire events that reduced the forest areas. CO_2 sequestration is estimated for the Mounts of Parnitha, Aigaleo, Penteli, Hymettus and for the North-Est mountains of Attiki region before and after the big fires of 2007 and 2009. The dominant tree species in these ecosystems were broadleaves (shrubland) and coniferous species such as Aleppo pines and firs. The growth rate of these species largely determines the sequestration capacity of the entire ecosystems. Therefore, a simple way to assess whether the carbon stock of the whole ecosystem is increasing or decreasing is to compare the frequency of tree destruction to the typical timespan of the main species. Forests before the stage of climax are typically carbon sinks. The growing periods of Aleppo pines and firs are of several decades while the frequency of major fire events in the region varied from a few years to about two decades over the last century (Hadjibiros, 2001). As an example, since 1913, there have been 438 registered fire events on the Mount of Parnitha. These fires have burnt the entire forest at least once, and, some specific parts up to six times (Amorgianiotis, 2007, Karani, 2008). Similarly, according to the official yearly reports of the Greek Ministry of Agriculture, the coniferous forest of Penteli Mountain has been extensively decimated in three big fire events between 1995 and 2000, while Hymettus experienced 59 important fires from 1980 to 1993 and several smaller after. The fire history of the North-Est Mountains of Attiki is similar, though no precise records are available. Based on these evidences, we conclude that the forest ecosystems around Athens were absorptive in both 2007 and 2009.

Upstanding forest areas before the fires were derived from geographical data using the Google Earth application (http://earth.google.com/download-earth-advanced.html) and two other free-access geographic information system applications (GE-Path freeware, version 1.4.4 (http://www.sgrillo.net/googleearth/gepath1_4_4_exec.zip and GEO-UTILITIES online tools, http://geo-news.net/index_geof.html). Fields of interest were enclosed by polygons and measured in terms of land area. Measured vegetation included trees, shrubs and other evergreen sclerophyllous plants. However, no detailed inventory on vegetation land cover was available for those areas.

Burnt forest area was determined from satellite images using Keyhole Markup Language files (.kmz) from relevant websites. Data on burn forest are summarized in Table 1. The European Forest Fire System (EFFIS, http://effis.jrc.ec.europa.eu/current-situation) is a data source where data on burnt forest are provided per vegetation type. However, other data sources provide aggregate data on burnt forest areas without distinction by species, so the calculation of carbon sequestration was based on a uniform sequestration rate (equation 1, IPCC, 2006):

$$C = A * G_w * (1+R) * CF \qquad (1)$$

C is the annual increase in biomass carbon stocks due to forest growth (tons C/yr), A the land area of growing forest (ha), G_w the average annual above-ground biomass growth rate (tons DM/ha/yr), R the ratio of below-ground biomass to above-ground biomass (tons DM below-ground biomass/tons DM above-ground biomass) and CF the fraction of carbon in total dry matter (tons C /tons DM). To express carbon sequestration in terms of carbon dioxide, the results of equation 1 are multiplied by 44/12 (the weight ratio between carbon dioxide and the carbon atom). Values for G_w, R and CF are taken from IPCC (2003), Mokany *et al*. (2006) and Lamlom and Savidge (2006) for vegetation types in Greece. They equal 4.0, 0.4, and 0.5 respectively. Unfortunately, no data on local forest vegetation and growth rates were available.

Table 1: Burnt forest area (2007, 2009) per mountain location in the Attica Prefecture and corresponding data sources.

Regions	Specific location and fire event (year)	Burnt forest area (ha)	Data source
Mount Parnitha	General area (2007)	3 161	Latsoudis, 2007
	Fyli (2009)	89	EFFIS, http://effis.jrc.ec.europa.eu/current-situation
	Magoula (2009)	526	EFFIS, http://effis.jrs.ec.europa.eu/current-situation
Mount Hymettus	Kareas (2007)	13	Tilaphos, http://tilaphos.blogspot.com/2008_01_01_archive.html
	Byronas (2007)	3	Tilaphos, http://tilaphos.blogspot.com/2008_01_01_archive.html
	Kaisariani (2007)	25	Tilaphos, http://tilaphos.blogspot.com/2008_01_01_archive.html
	Papagou (2007)	103	Tilaphos, http://tilaphos.blogspot.com/2008_01_01_archive.html
	Glyfada (2009)	606	EFFIS, http://effis.jrc.ec.europa.eu/current-situation
North-East Attiki region	General area (2009)	13 708	EFFIS, http://effis.jrc.ec.europa.eu/current-situation
Mount Penteli	General area (2007)	860	Tilaphos, http://tilaphos.blogspot.com/2008_01_01_archive.html
Total burnt forest area within Attica (ha)		19 094	

3. Results

The weighted average fuel consumption of vehicles is 0.0903 L/km and corresponding CO_2 emissions 219 g CO_2/km and 0.72 t CO_2/cap/year (Zamba and Hadjibiros, 2007). Table 2 shows total traveled distances, energy use, direct and indirect CO_2 emissions and the corresponding area for carbon sequestration (the energy footprint) in hectares. We observe that traffic volumes remained practically unchanged in the period from 2000 to 2005. This reflects traffic saturation conditions in the center of Athens by that time and probably until 2009 which is the year of the outbreak of the Greek financial crisis, after which traffic volume decreased.

Table 2: Travel distances, energy use, carbon emissions and energy footprint of road transportation in Athens

Year	Total annual vehicle travel distance (10^6 km)	Energy use for vehicle propulsion (TJ)	Direct CO_2 emissions (kt)	Indirect CO_2 emissions (kt)	Total CO_2 emissions (kt)	Total energy footprint (kha)
2000	7267	22971	1446	587	2033	198.0
2001	7265	22964	1446	586	2032	197.9
2002	7268	22973	1446	587	2033	198.0
2003	7146	22589	1422	577	1999	194.7
2004	7236	22871	1440	584	2024	197.1
2005	7129	22533	1419	575	1994	194.2
Average	**7218**	**22817**	**1437**	**583**	**2019**	**196.7**

Table 3: Changes in carbon sequestration capacity (kt/yr) in forests around Athens between 2006 and 2009. Reduction of absorption is denoted by "-".

Forest area (ha)		Annual C absorption (kt/yr)	Annual CO_2 absorption (t/yr)
Burnt	19,094	- 53	- 196
Remaining	33,593	94	345
Total	52,687	148	541

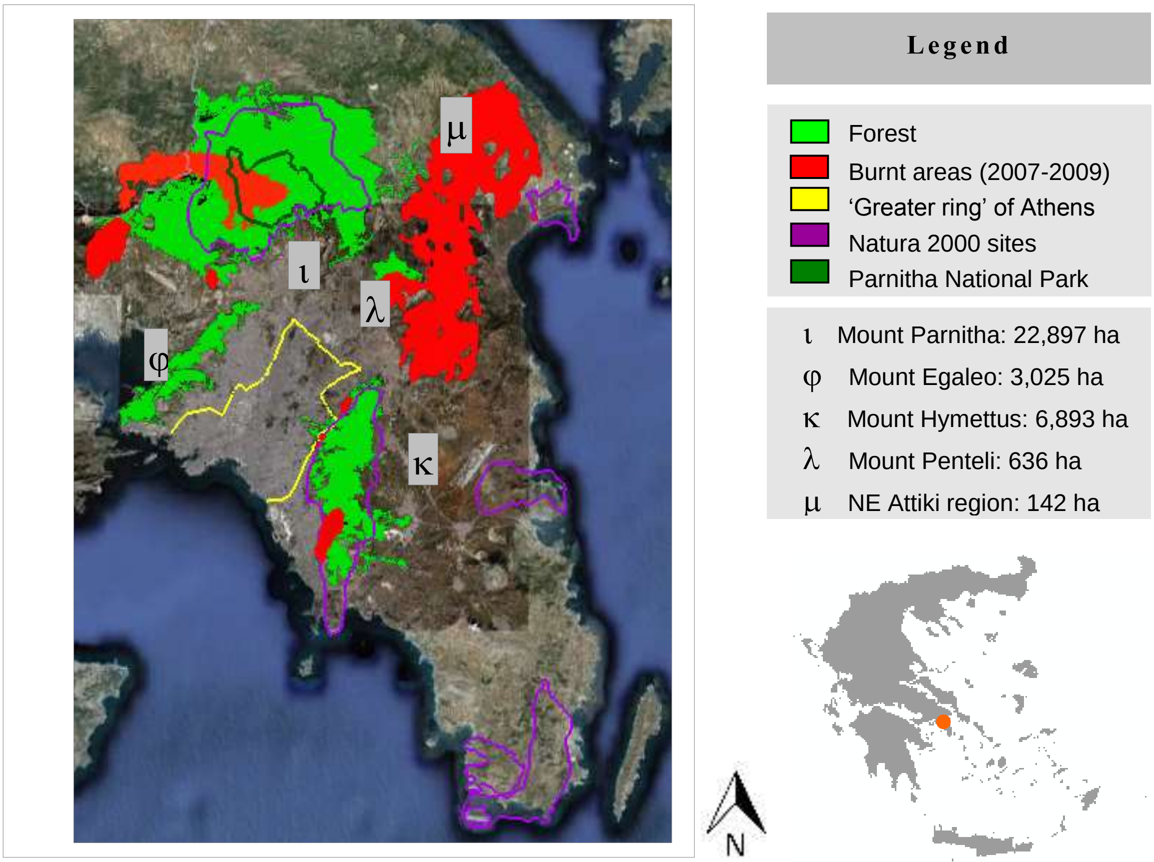

Figure 1: Burnt (red) and remaining forest (green) in Attica region after the 2007 and 2009 fires.

The fires of 2007 and 2009 burned down almost 40% of the forest area within the Attica Prefecture (Table 3). Figure 1 gives an overview of the burnt sites (red color) and of the remaining standing forest (green color). As indicated in Figure 1, significant parts of the burnt area were 'Natura 2000' zones and/or parts of the National Park of Parnitha. By comparing carbon emissions and sequestration (Tables 2 and 3) we obtain that the sequestration capacity of forests was about four times lower than the road CO_2 emissions before the fires and about six times lower after.

4. Discussion and conclusions

Our analysis shows that the sequestration of CO_2 relating to fuel combustion of vehicles and to the construction and maintenance of the road system in the prefecture of Athens and in the adjacent city of Piraeus - together hosting 2.9 million people and spreading over 370 km^2- requires an area of growing forest of about 12 times bigger than the urban area itself. In other words, the sequestration of the emissions from 1 hectare of road system requires about 100 hectares of forest. This ratio has probable decreased, since 2009, as a result of the economic crisis which reduced the road traffic intensity.

Our approach is bottom-up and the results can be put in perspective with top-down estimates of emissions at the national and regional scales. The comparison can reveal sub-regional heterogeneity in road traffic and emissions.

CO_2 emissions from road transportation at the national scale in Greece were 15.7 Mt in 2000 and 18.22 Mt in 2005 (OECD/IDF, 2010). Of these emissions, about 46 %, so 7.2 Mt in 2000 and 8.4 Mt in 2005, are allocated to road transportation in the administrative region of Attica, where Athens and Piraeus belong, and where total recorded population is 3.8 million people. If we downscale this figure proportionally to population in the study area, the share of Athens and Piraeus in Attica's emissions is 5.5 Mt in 2000 (~1.9 t/cap/year) and 6.3 Mt in 2005 (~2.5 t/cap/year) which is roughly 3 times higher than the emissions calculated in this study for Athens and Piraeus (~0.72 t/cap/year). The difference can be explained by factors like population density, public transportation services and other socioeconomic factors that we discuss below.
With respect to population density, discrepancies between Athens and suburban areas are very significant. Population density in the whole Attica region - including Athens and Piraeus- is about 990 cap/km^2, while if Athens and Piraeus are excluded, the figure drops to 270 cap/km^2, so almost 30 times lower than the population density in the study area (7 638 cap/km^2). This is very significant with respect to emissions because fuel consumption in road transportation decreases exponentially with urban density (Newman and Kenworthy, 1999). Regarding public transportation services, the gap between Athens and Attica is also very significant. Public transportation networks quickly become scarce with distance from Athens with concomitant dependency on private cars for leisure, home-to-work rides and household food and materials supply. Railway services connecting Athens and Piraeus to the suburbs located outside the study area are indeed very scarce. Subsequently, the attractiveness of the city of Athens generates mobility in suburban areas that is almost exclusively sustained by the use of private cars. Indeed, the Attica region hosts 35 % of the national population while it accounts for 46 % of all road transportation emissions (OECD/IDF, 2010), most of which are from the suburbs. Two additional socioeconomic factors are likely to contribute to the observed sub-regional discrepancies in the CO_2 emissions per capita. First, everyday long-distance car driving by Athenian workers to surrounding industrial and tertiary sector zones. Second, frequent family weekend trips to middle-distance country-houses. In both cases, the corresponding emissions stem mainly from Athenians who live within the study area but mostly drive outside of it. The traffic data that we used in the calculations do not capture the "suburban" fraction of these trips. We estimate the corresponding "off-zone" emissions by focusing on the main drivers. The first driver is home-to-work-trips. These trips are significant because almost half of the industrial activity of Greece locates in Attica (ROPA, 2007) and in particular in zones that are distant from Athens: in the north, the industrial zones of Kryoneri and Oinofita respectively locate at about 25 and 55 km from the north edge of Athens, in the west, the sites of Thriasio and Elefsina with petrol refineries and shipyards at 15 km, and in the east, the plain of Mesogeia, with significant

manufacturing activity at 25 km. Many of the employees in these sites are Athenians whose combined trips measure thousands of km every day. Regarding weekend trips, hundreds of thousands of Athenian families own secondary residences in the countryside, mainly in the north, east and south coastlines of Attica but also in Evvoia (the big peninsula in the North of Attica) and on the northern Peloponnese. In order to reach these sites from Athens, half of the Attica must be crossed. We can roughly estimate that, prior to the economic crisis, one third of the population of Athens, so 300 000 families do so twice per month, which are about 7.5 million family trips per year. Given Attica's geography, average travel distance per family and weekend exceeds 150 km which results in annual CO_2 emissions of 300 Mt, or 20 % more than those within the study area.

The comparison between anthropogenic CO_2 emissions and the sequestration capacity of regional forests shows that before the strong fires of 2007 and 2009, emissions outnumbered the regional carbon sinks. These latter reduced about 40 % by the fires, which highlights the growing inadequacy of local carbon sequestration capacity. Of course, our estimates present significant uncertainties; the results on carbon sequestration are based on default values from literature (the values of the parameters Gw and R are not specific to the region of Attica); in addition, assumptions were made on the vegetation land cover; we were not able to overcome such simplifications because no more detailed ecological data were available for the study area.

Nonetheless, the list of ecological impacts of the fires extends beyond the global consequences in relation to direct and post-fire releases of green-house gases. Major local consequences include the weakening capacity of suburban ecosystems to provide ecosystem services to local population including flood control, local climate regulation, prevention of soil erosion, recreation activities etc. as well as impacts on biodiversity. The mountains around Athens are rich in plant and animal species. We discuss some impacts on biodiversity and possible actions for future forest preservation. Especially on the Mount of Parnitha, the impacts on biodiversity are significant and some of them may be irreversible. The Parnitha Mount was granted, since 1961, the status of National Park because it hosted a great variety of flora and fauna species including endemic or endangered plants, birds, reptiles, insects, amphibians and mammals (Amorgianiotis and Aplada, 2007, Latsoudis, 2007). A well-known protected species is the red deer which population in Parnitha was the largest and one of the last in Greece. According to post-fire *in-situ* observations, more than 10 % of the deer population was estimated to have perished in the fire while further population decline is expected since about two thirds of the summer biotope of the deer had been decimated (Latsoudis, 2007). The Mount of Parnitha was also rich in birds and plant species. Recorded bird species totalled 132, out of which about 90 are protected and 6 are rare (Amorgianiotis, 1997, Karani, 2008). Some argue that the recovery of these species is doubtful even if the forest fully regenerates (WWF, 2009). Concerning the vegetal diversity of Parnitha, 1100 plant species were recorded in the burnt areas, out of which 92 are endemic in Greece and two (*Campanula celsii parnesia* and *Silene oligantha parnesia*) are endemic in Parnitha (Sfikas, 1985, Aplada *et al*., 2007). Long-term effects on biodiversity are however particularly difficult to assess and depend on soil protection measures against erosion and grazing as well as on meteorological factors such as succession of temperature and humidity conditions which are critical parameters for ecosystem regeneration during several years after the fires. The fate of some endangered species also depends on the recovery of other species on which they depend for food and shelter. Fire guard controls and National Parks are tools for conservation and protection of natural capital. Since those tools failed in fulfilling forest protection, additional protective mechanisms are needed, especially in the context of climate change which increases extreme forest fire risk occurrence (Giannakopoulos *et al*., 2011). A thorough identification and mapping of the remaining natural areas in terms of biodiversity, land cover and indigenous species can significantly contribute to this direction. On the one hand, it can help raising awareness of individuals and, on the other hand, it can provide basic information to adapt protection measures to the specificities of the ecosystem. To do so, inventories must be regularly updated in order to monitor changes in vegetation and plant diversity, identify causes and carry out relevant actions. The absence of basic knowledge may be a major threat against natural ecosystems, since it results to loose protection measures if not to total negligence.

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