ROAD TRANSPORT CARBON EMISSIONS AND FOREST SEQUESTRATION CAPACITY IN THE REGION OF ATHENS BEFORE AND AFTER FOREST FIRES

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ABSTRACT

One important component of the urban contribution to carbon dioxide atmospheric emissions is road transport. Carbon dioxide (CO_2) emissions from urban road transport in the centre of Athens recorded over a period of five years (2000–2005) are compared with the carbon sequestration capacity of regional forests, prior to and after the devastating forest fires in Attica in 2007 and 2009, which is the administrative region of Athens. The comparison of carbon flow reveals two complementary aspects of the same socio-environmental issue: persistent sources versus weakening sinks for CO_2 within a mixed (urban and rural) setting. Road transport emissions are calculated bottom-up using traffic data from in-situ measurements along segments of main roads. The sequestration capacity of forests is estimated by combining satellite images of changes in land cover with literature values of biomass growth rates. 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. This imbalance highlights the inadequacy of the local carbon sink. Although there is no biogeochemical need to neutralise carbon budgets locally, defining the CO_2 flows from urban activities and local ecosystems is likely to raise awareness and promote global environmental sustainability. The results are compared with top-down estimates of CO_2 emissions at a regional scale, where suburban areas are dominant, and the differences are discussed in the light of local socioeconomic factors.

Keywords: road transport, peri-urban forests, fires, carbon emissions, carbon sequestration, Athens

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Introduction

Human driven alterations in the global carbon (C) cycle mainly result from the combustion of fossil fuels and deforestation, both of which add carbon dioxide (CO_2) to 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 CO_2 sinks. Oceanic storage is governed by physicochemical processes and biological feedback mechanisms with different responses to increasing levels of atmospheric CO_2 (Samiento et al. 2004; Fung et al. 2005; Schuster and Watson 2007), which many argue is likely to weaken the future capacity of the oceanic sink and, therefore, accelerate climate change (Sabine et al. 2004; Schuster and Watson 2007; McKinley et al. 2011). In contrast, forest biomass allows permanent storage of CO_2. However, forest growth depends on competition for land with human land uses, such as agriculture, housing and transport infrastructure, which are land intensive activities and often respond to land scarcity by expanding into adjacent forests (Lambin et al. 2001; FAO 2009; 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).

In particular, forest fires are a major environmental issue in Greece (Hadjibiros 2001) and many other Mediterranean countries characterized by long periods of dry and hot weather conditions (Papakosta et al. 2014). Pine forests and shrubs, especially at low-altitudes in peri-urban areas (Wildland Urban Interface), are among the most threatened types of vegetation (Chas-Amil et al. 2013; Papakosta et al. 2013). The issue of climate change raises further concerns about a possible increase in the frequency of wildfires (Giannakopoulos et al. 2011).

Typically in the literature, the issue of the capacity of forests to sequester carbon and its reduction due to forest fires are addressed separately from the issue of anthropogenic emissions of specific economic sectors. On the one hand, there is an increasing knowledge of energy consumption and of trends in the emissions from road transport and their possible effects on human health and global climate (He et al. 2005; Chapman 2007; Piecyk and McKinnon 2010). The contribution of transport to global fuel combustion and CO_2 emissions is estimated at 23%. Road traffic is responsible for almost three-quarters of these emissions (IEA 2014; Grote et al. 2016). On the other hand, global scale environmental effects of forest fires, including emissions of carbon, air pollution, biodiversity and climate change dynamics are increasingly being investigated and inte-

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grated into environmental modelling (Amiro et al. 2001; Randerson et al. 2006). However, the quantitative relations between forest fires and CO_2 emissions at the local scale are rarely studied. This study is such a joint analysis of road transport in Athens, the capital of Greece, and the reduction in the carbon sequestration capacity of regional forests around Athens before and after wild fires. This comparison combines two aspects of the same socio-environmental issue: changes in the emissions from a specific sector of urban activity in suburban areas under human pressure. Although carbon sources and sinks are not necessarily balanced locally, comparisons that put specific urban activities and ecosystem changes into a common perspective are likely to promote awareness of city dwellers of local and global environmental issues.

This is a bottom-up study of the CO_2 emissions, which generates data at scales that are not covered by more macro-scale methods that rely on average and aggregated information. We provide in the discussion a comparison of the results obtained at the local scale with the emissions reported in top-down studies and relate the differences to socioeconomic factors influencing mobility.

This paper is organized as follows. Section 2 describes the methods for estimating road CO_2 emissions and the sequestration capacity of regional forests. Section 3 presents the results and provides a quantitative ratio for the emission and absorption rates. Section 4 focuses on differences between bottom-up and top-down studies of road CO_2 emissions and discusses possible explanatory socio-economic factors and the local environmental effects of fires. Finally, a short conclusion summarizes the findings of the paper.

Methods and Data

Road Transportation and CO_2 Emissions

We consider the direct and indirect emissions of CO_2 (Chi and Stone 2005) from road transport within the area of the Athens prefecture and Piraeus. The population in this continuous urban area makes up more than 25% of the population in Greece. The average population density in this area is 7,638 inhab/km².

Direct emissions are those from the combustion of fuel by the road transport system, which depends on the distances travelled, fleet composition, fuel use per vehicle category and fuel emission factors. Indirect emissions are those associated with the construction and maintenance of roads, manufacturing, servicing and scrapping of vehicles (Jonsson 2007) and drilling for, refining and distribution of fuels (Lane 2006). Indirect emissions may be accounted for in terms of the percentage of the direct emissions. This paper calculates direct emissions for the period 2000–2005 based on *in situ* measurements of traffic volumes (Zamba 2006; Zamba and Hadjibiros 2007). Indirect CO_2 emissions associated with the construction and maintenance of the roads are assumed to be equal to 40% of the direct emissions (Jonsson 2007).

Traffic data was collected for 16 main roads (Fig. 1, red lines) on which the traffic is typical of that of Athens. These roads are in the so-called 'greater ring' of Athens, which is the center of the social and cultural activities of the Greek capital (Fig. 1, black lines). The annual distances travelled, fuel consumption and CO_2 emissions calculated for this area are extrapolated to all roads in the greater ring of Athens based on geometrical data derived from road maps.

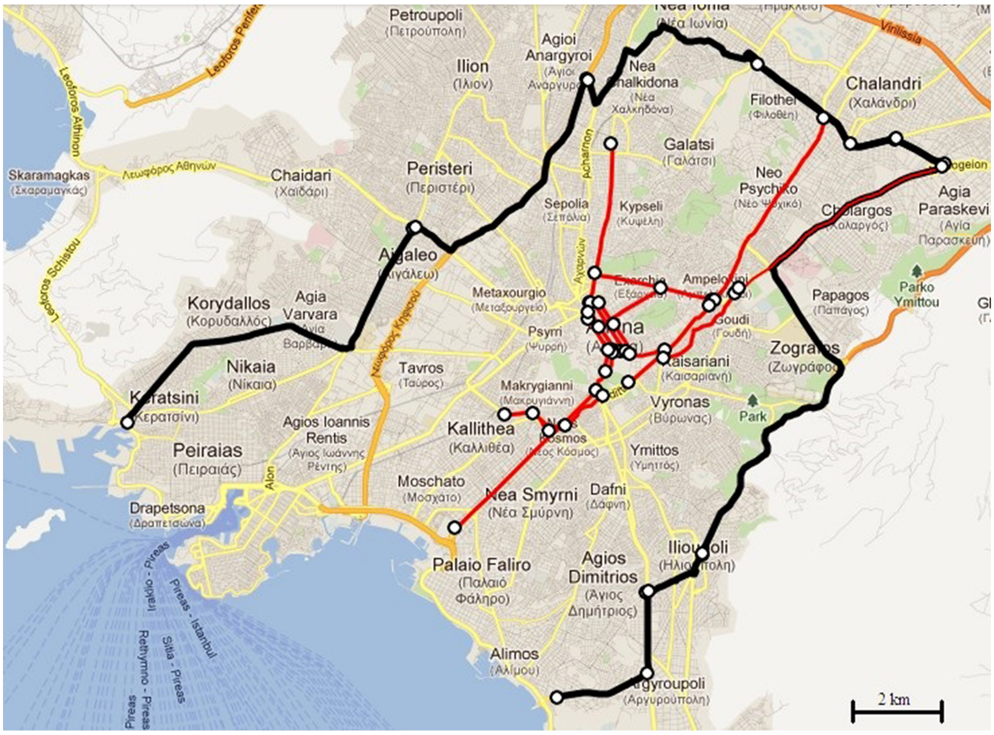

Fig. 1 The "greater ring" (black perimeter) in Athens and the 16 main roads (red lines) for which data on road traffic was collected. Source: Google Maps.

Estimates of the Carbon Sink

The carbon sequestration capacity of growing forests depends on the area of forest and biomass growth rate. The area classified as forest covers about 43% of the area in Attica. Changes in the sequestration capacity of the forests on Mounts Parnitha, Aigaleo, Penteli, Hymettus and the North-East mountains (Fig. 2) were determined before and after the big fires of 2007 and 2009. The dominant tree species in these ecosystems were broadleaved (shrubland) and coniferous trees such as Aleppo pines and firs. The growth rate of these species largely determines the sequestration capacity of the entire ecosystem. Therefore, a simple way to assess whether the carbon stock of the whole ecosystem is increasing or decreasing is to compare the frequency with which trees are destroyed to the typical growth timespan of the main species. Forests before reaching the climax stage are typically carbon sinks. The growing periods of Aleppo pines and firs are 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, 438 fires have been recorded on Mount Parnitha. These fires destroyed the entire forest at least once, and, specific parts of it up to six times (Amorgianiotis 2007; Karani 2008). Similarly, according to the Greek Ministry of Agriculture, the coniferous forest on Mount Penteli was decimated by three big fires between 1995 and 2000, while Mount Hymettus experienced 59 important fires from 1980 to 1993 and several smaller fires later. The fire history of the North-East Mountains in Attica is similar, though there are no precise records. This evidence support the hypothesis that the forest ecosystems around Athens were mostly far from climax and therefore absorptive in both 2007 and 2009.

The areas of forest 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). Areas of interest were enclosed by polygons and measured in terms of land area. The measured vegetation included trees, shrubs and other evergreen sclerophyllous plants. However, there is no detailed inventory of the vegetation covering these areas. Burnt forest area was determined from satellite images using Keyhole Markup Language files (.kmz) from relevant websites. Data on burnt forests are taken from Latsoudis (2007), Tilaphos (2008) and EFFIS (2009). Data from EFFIS include type of vegetation, whereas other data sources only provide aggregate data.

The carbon sequestration capacity was calculated using a uniform sequestration rate and equation (1) (IPCC 2006):

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

where C is the annual increase in biomass of carbon due to forest growth (tons C/year), A the area of land covered by growing forest (ha), G_w the average annual above-ground biomass growth rate (tons DM/ha/year), 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 predictions 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 (respectively; 4.0, 0.4 and 0.5) are taken from IPCC (2003), Mokany et al. (2006) and Lamlom and Savidge (2006) for vegetation in Greece.

Results

Total distance travelled, energy use, direct and indirect CO_2 emissions and the corresponding areas of forest for carbon sequestration (the energy footprint) in hectares from 2000 to 2005 are detailed in Chatzimpiros et al. (2015) based on data from Zamba and Hadjibiros (2007). The weighted average fuel consumption of vehicles is 0.09 l/km and corresponding CO_2 emissions 219 g CO_2/km; the annual per capita CO_2 emissions average 0.72 t CO_2/cap/year and the total required sequestration area is about 200×10^3 ha. Table 1 shows

Table 1 Distances travelled, energy use, carbon emissions and the carbon sequestration requirements of road transport in Athens.

Year	Total annual distance travelled by vehicles (10^9 km)	Energy used for vehicle propulsion (PJ)	Direct CO_2 emissions (Mt)	Indirect CO_2 emissions (Mt)	Total CO_2 emissions (Mt)	Total area of forest (kha) required for sequestration
2000	7.3	23.0	1.4	0.6	2.0	198.0
2001	7.3	23.0	1.4	0.6	2.0	197.9
2002	7.3	23.0	1.4	0.6	2.0	198.0
2003	7.1	23.0	1.4	0.6	2.0	194.7
2004	7.2	22.9	1.4	0.6	2.0	197.1
2005	7.1	22.5	1.4	0.6	2.0	194.2
Average	**7.2**	**22.8**	**1.4**	**0.6**	**2.0**	**196.7**

total distance travelled, energy use, direct and indirect CO_2 emissions and the corresponding area for carbon sequestration in hectares.

The fires of 2007 and 2009 destroyed almost 40% of the forest biomass in the Attica region (Table 2). Fig. 2 gives an overview of the burnt sites (red colour) and of the remaining standing forest (green colour). Significant parts of the burnt area were 'Natura 2000' zones or belonged to the National Park of Parnitha. Comparing carbon emissions and sequestration revealed that the sequestration capacity of forests was about four times lower than the road CO_2 emissions before and about six times after the fires. There was, therefore, a significant imbalance and decrease over time because of the fires, in the CO_2 sequestration capacity of the regional forests compared to the road CO_2 emissions.

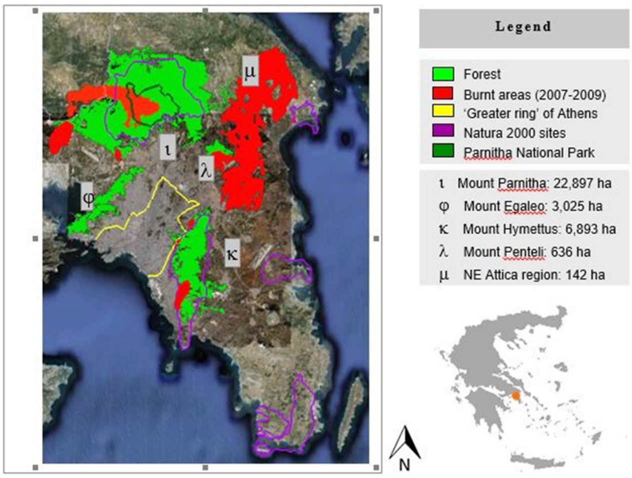

Fig. 2 Burnt (red) and remaining forest (green) in the Attica region after the 2007 and 2009 fires.

Table 2 Changes in carbon sequestration (kt/yr) by forests around Athens between 2006 and 2009.

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

Reduction in absorption is denoted by "−".

Discussion

The sequestration of CO_2 resulting from fuel combustion by vehicles and the construction and maintenance of the road system in the prefecture of Athens and adjacent city of Piraeus, which together host 2.9 million people and cover an area of over 370 km², requires an area of growing forest of about 12 times bigger than the urban area itself. Given that 8 hectares of urban area contain about 1 hectare of road network (Zamba 2006), the sequestration of the emissions from 1 hectare of road requires about 100 hectares of forest. During this study, total annual distances travelled remained practically unchanged at around 7.2×10^9 km. This reflects the traffic saturation conditions in the center of Athens, which is a common problem in densely populated cities surrounded by large suburbs with little public transport. However, since 2009, which is the year of the start of the Greek financial crisis, traffic volumes have decreased due to a slow-down in the Greek economy. Accordingly, the calculated emission to sequestration ratio has probably also slightly decreased since 2009. This is an interesting example of an improvement in traffic conditions, with subsequent decrease in environmental degradation without the application of specific road traffic control strategies (Papageorgiou et al. 2003).

The comparison at the local scale of CO_2 emissions from a specific sector with the sequestration potential of forests (and its possible reduction due to fire or changes in land use) is barely addressed in the literature, although the challenge for environmental protection and climate action largely rely on local awareness and behaviour. Such comparisons require bottom-up approaches based on inventories of local data that may deviate from more macro-scale estimates. Deviations can be attributed to heterogeneity and specificities of distinct spatial zones (Wang et al. 2009). The results of this paper are put into perspective in terms of top-down estimates of emissions at national and regional scales. The comparison reveals sub-regional discrepancies in road traffic and emissions. At the national scale in Greece, road CO_2 emissions are estimated at 15.7 Mt in 2000 and 18.22 Mt in 2005 (OECD/IDF 2010). Of these emissions, about 46%, 7.2 Mt in 2000 and 8.4 Mt in 2005, are allocated to Attica. If we downscale this figure proportionally in terms of the population in the study area, the share of Athens and Piraeus in Attica's emissions would be 5.5 Mt in 2000 (~1.9 t/cap/year) and 6.3 Mt in 2005 (~2.5 t/cap/year), which is almost 3 times higher than the emissions calculated in this study (~0.72 t/cap/year). This difference could be partly related to the effects of local driving patterns (series of accelerations, decelerations and frequent stops) on fuel consumption (Tzirakis et al. 2006). Moreover, there are major infrastructural and socioeconomic differences between Athens and its administrative region that imply that a simple population-based downscaling of emissions would be problematic. The differences in emissions in relation to socioeconomic factors influencing mobility are discussed below.

The population density in the whole Attica region is about 990 cap/km². If Athens and Piraeus are excluded, the figure drops to 270 cap/km², against 7 638 cap/km² in the study area. This 30-fold difference is very significant with respect to road CO_2 emissions because fuel consumption decreases exponentially with urban density (Newman and Kenworthy 1999). In addition, the public transport network in Athens is much denser than in the rest of Attica. As a consequence, the dependency on private cars for leisure, home-to-work rides and household food and materials supply is much higher in Attica than in the city of Athens and Piraeus. Moreover, assuming that the attractiveness of the city of Athens generates mobility in the broader Attica region, this mobility is almost exclusively sustained by the use of private cars.

Two additional socioeconomic factors are likely to explain the observed difference. The first is everyday long-distance car driving by Athenian workers to surrounding industrial and tertiary sector zones. The second is frequent family weekend trips to middle-distance country-houses. In both cases, the corresponding emissions mainly result from Athenians living within the study area but mostly driving outside it. The "suburban" share of their trips therefore contributes to the emissions for Attica, which are not included in our measurements.

The corresponding "off-zone" emissions can be estimated by focusing on the main drivers. One main driver is home-to-work-trips, which are quite significant. Almost half of the industrial activity of Greece is located 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 are about 25 and 55 km from the Northern edge of Athens, in the West are 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 at these sites are Athenians whose combined daily trips amount to thousands of kilometres.

Regarding weekend trips, hundreds of thousands of Athenian families own secondary residences in the countryside, mainly along 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 Attica must be crossed. It can be roughly estimated that, prior to the economic crisis, one third of the population of Athens, about 300 000 families, owned countryside houses and made such trips twice per month. This amounts to about 7.5 million family trips per year. Given Attica's geography, average travel distance per family per weekend exceeds 150 km, resulting in annual CO_2 emissions of about 300 Mt, which is 20% of the emissions calculated for the study area. The above assumptions are certainly rough, but reflect the order of magnitude of regional road emissions generated by Athenians. They also provide insights into the factors that need to be accounted for in order to downscale road emissions in heterogeneous areas.

Although there is no detailed information, it is probable that because of the increase in unemployment, long-distance car driving by Athenian workers to surrounding industrial and tertiary sector zones significantly declined after the 2009 crisis. In addition, the frequency of family weekend trips also probably decreased after 2009; such changes may be considered as "positive" consequences of the economic crisis in reducing CO_2 emissions, although the recent decrease in the price of fuel may act in the opposite direction.

The list of the ecological effects of fires extends far beyond the global consequences in relation to greenhouse gas emissions. Major local consequences include the weakening capacity of suburban ecosystems to provide ecosystem services to the local population, such as flood control, regulation of local climate, prevention of soil erosion, recreation activities, etc. They also include effects on biodiversity. The mountains around Athens are rich in plant and animal species. Especially Mount Parnitha, where the effects on biodiversity are significant and possibly irreversible. In 1961 Mount Parnitha became a National Park because it hosted a great variety of flora and fauna 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 of which the population on Mount Parnitha is the largest and one of the last in Greece. According to post-fire *in-situ* estimates, more than 10% of the deer perished in the fire and a further decline in abundance is expected as about two thirds of the summer biotope of the deer was destroyed (Latsoudis 2007). Mount Parnitha was also rich in species of birds and plants. A total of 132 species of birds are recorded of which about 90 are protected and 6 are rare (Amorgianiotis 1997; Karani 2008). The recovery of these species is doubtful even if the forest fully regenerates (WWF 2009). Concerning plant diversity on Mount Parnitha, 1100 species of plant are recorded for the area destroyed by fire, out of which 92 are endemic to Greece and two (*Campanula celsii parnesia* and *Silene oligantha parnesia*) are endemic to Mount Parnitha (Sfikas 1985; Aplada et al. 2007). Long-term effects on biodiversity are, however, particularly difficult to assess as they partly depend on protecting soil against erosion and grazing, and on a succession of years after the fires when the temperature and humidity conditions are favourable for ecosystem regeneration. 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 means of conserving and protecting natural capital. Since they failed to protect the forests, additional protective measures are needed, especially in the context of climate change, which increases the risk of forest fires occurring (Giannakopoulos et al. 2011). The identification and mapping of the remaining natural areas in terms of biodiversity, land cover and indigenous species is important as it can help raise awareness of individuals of climate change and biodiversity issues and provide basic information needed to implement measures for protecting or reinstating the ecosystem. The 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 to natural ecosystems, since it results in poor or no protection measures.

Conclusions

The comparison of road traffic CO_2 emissions with the sequestration capacity of regional forests in Attica reveals that even before the fires in 2007 and 2009, emissions were greater than the regional carbon sinks. The latter were reduced about 40% by the fires, which highlights an increasing inadequacy of the local carbon sequestration capacity. Protection measures are required to deal with local causes that generate global environmental issues. This analysis also provides an estimate of road CO_2 emissions at an urban scale, for which previously there was no official data. This brings regional official statistics into line with more local measurements and connects the deviations to specific socioeconomic factors. We also conclude that the lack of specific inventories and identification of the remaining ecosystems in terms of ecological value may contribute to their further destruction, because of poor or no protection measures.

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