

Net Ecosystem Carbon Exchange (NEE) of the Island of Pianosa

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Abstract

The overall gas exchange occurring between Mediterranean ecosystems and the atmosphere has been rarely quantified experimentally, but due to the occurrence of prolonged summer drought that limits gas exchange, the potential carbon (C) sink of Mediterranean ecosystems is generally considered low. Net Ecosystem C Exchange (NEE) was measured for a period of 12 months in the Island of Pianosa (Central Italy) using the eddy covariance technique. The Island is partly covered by macchia vegetation and by abandoned agricultural land and it is ideal for flux measurements due to its flat topography and for the absence of anthropogenic C sources. C-flux measurements made between April 2002 and March 2003 showed that the Island of Pianosa was a net sink of C during a 12 months period accumulating 2.64 t C ha⁻¹ per year. Such a sink was less than what has been reported for evergreen forest in the region, but it is larger than what is generally estimated for drought limited ecosystems. The analysis of seasonal changes in the C-flux revealed that phenology and temperature were likely limiting C uptake during the winter months, while drought was limiting during the summer months. The potential C sink that could be provided by the entire island was finally calculated as the difference between the C stock contained at present in the Island's ecosystems and that contained in the areas covered by the Mediterranean macchia.

Introduction

Mediterranean ecosystems (MTEs) are well adapted to the typical climate of the region and water availability is considered the main driver for growth and C accumulation (Rambal & Debussche, 1995; Bottner *et al.*, 1995; Rambal, 2001). Several observations have shown that the typical growth patterns of Mediterranean vegetation involve significant C uptake by photosynthesis in the Spring and Autumn months with very limited C uptake during the summer drought. Such a pattern, which is closely linked to growth limitations imposed by water availability in the summer, and temperature limitations in the winter, is tightly coupled with the typical Mediterranean climate where mild springs and autumns predominate and the winter months are only rarely very cold (Brunetti *et al.*, 2000; Dunkeloh & Jacobeit, 2003; Brunetti *et al.*, 2004). The Net Ecosystem C Exchange (NEE) (Table 1), i.e. the net uptake of C from the atmosphere of typical MTEs has been rarely assessed and it is generally considered very low (Falge *et al.*,

2002). Accordingly, the contribution of MTEs to the global terrestrial C cycle remains almost unknown.

As clearly shown elsewhere in this volume (Colom *et al.*, this issue), the Island of Pianosa represents a typical example of a MTE as its surface is a mosaic of different ecosystems that include both natural patches and areas where anthropogenic disturbances have been predominating. Historical sources (Baraldi *et al.*, this issue) report that agriculture was introduced in the island more than 150 years ago. Cultivated area likely reached its maximum expansion after the second world war, when more than two thousands people were living on the island. Decreasing population, over the last twenty years, caused, a progressive abandonment of agriculture that was finally completely abandoned in 1998, when the Island became a protected area and the number of inhabitants was suddenly reduced to a few units. This land use history has many analogies to what happened in the rest of the Mediterranean region. The relative small fraction of undisturbed land in Pianosa is not far from what is observed in many areas of

Table_01 – Acronyms for gas exchange parameters. Definitions according to Curtis *et al.*, 2002

Acronym		Definition
GPP	Gross Primary Productivity	gain of C from autotrophic organisms
NEP	Net Ecosystem Production	rate of C accumulation in an ecosystem defined as difference between Gross Primary Productivity and Ecosystem respiration
NPP	Net Primary Productivity	rate of C accumulation in an ecosystem defined as difference between Gross Primary Productivity and autotrophic respiration
NEE	Net Ecosystem CO ₂ Exchange	conceptually NEE and NEP are equivalent in that both constitute the difference between GPP and total ecosystem respiration, methodologically, however, they are independent, having unrelated measurement errors
R _{eco}	Ecosystem respiration	loss of C due to autotrophic and eterotrophic respiration

the Mediterranean basin and recent land abandonment is a rather common feature of the entire region. This observation suggested that the NEE of the entire island could be considered a reliable indicator of what may happen over a much larger fraction of the Mediterranean region and can be in any case representative of a much larger fraction of the land area of continental Italy.

This paper provides an estimate of the annual NEE of Pianosa over the period April 2002 to March 2003. NEE was measured by integrating C flux measurements that were made using an eddy covariance system that was installed in Pianosa in early 2002. The role of phenology, temperature and drought in limiting C uptake during winter and summer months is discussed.

Materials and Methods

An eddy-covariance flux tower has been installed, during winter 2002, in the proximity of the geometric centre of the island (Lat. 42° 35' 07.7" N, Long. 10° 04' 44.5" E) (Figure 1) to assess the overall mass and energy exchange of the entire island. The site of Pianosa contributes to Fluxnet (<http://www.fluxnet.ornl.gov/>), a world wide network of more than 252 micrometeorological tower sites that use eddy covariance to measure the exchange of mass and energy of terrestrial ecosystems. The tower is a walk-up scaffold of 13 m height with an additional mast of 2 m height where the instruments are installed. The eddy covariance system consists of commercially available instrumentation: a 3 axis symmetrical sonic anemometer (Metek Usa-1, Metek GmbH, Elmshorn, Germany), an open path infra-red gas analyser (IRGALi 7500, Li-COR, Lincoln, Nebraska, USA) and sensors to measure net radiation (Q7 Rebs, USA), PAR (Kippen & Zonen), soil temperature (thermocouple J-type), soil water content (Delta-T Theta probe) and soil heat flux. The data from the fast sensors are recorded at a frequency of 20Hz by a PC while those from the slow sensors are recorded half-hourly on a data logger (Campbell, CR7X). Ecosystem fluxes of CO₂, H₂O, momentum, sensible and latent heat are calculated at half-hourly intervals according to the Euroflux methodology (Aubinet *et al.*, 2000; Baldocchi, 2003).

In order to obtain daily, monthly and annually integrated balances a gap-filling procedure has been applied. Gap filling was made for all the missing data in the series and when the value of u^* was falling below a given minimum threshold.

The quantification of eddy covariance measurements owing to a lack of turbulent transport is a major issue in the eddy flux community (Goulden *et al.*, 1996; Moncrieff *et al.*, 1996; Aubinet *et al.*, 2000; Falge *et al.*, 2001, Carrara *et al.*, 2003; Staebler & Fitzjarrald, 2004) and the despite the awareness



Figure 1 – The eddy covariance tower installed on Pianosa Island

of the problems in accurately determining night-time fluxes, no general consensus has been reached for correcting the flux (Falge *et al.*, 2001).

The analytical procedures used for gap filling was made using the beta-version of the Flux data gap-filling and flux-partitioning procedure, provided by Markus Reichstein from Bayreuth University (Germany). The details of such procedure are described in Reichstein *et al.*, (2005 submitted). In brief, the procedure identifies three different conditions: i) only the data of direct interest are missing, but all the meteorological data are available; ii) also air temperature or vapour pressure deficit (VPD) is missing, but radiation is available; iii) also radiation data is missing. In the first case, the missing value is replaced by the average value under similar meteorological conditions within a time-window of seven days. Similar meteorological conditions are present when global radiation (R_g), air temperature (T_{air}) and VPD do not deviate by more than 50 W m^{-2} , $2.5 \text{ }^\circ\text{C}$, and 5.0 hPa respectively. If no similar meteorological conditions are present within the time window, the averaging window is increased by fourteen days. In case ii) the same approach is taken, but similar meteorological conditions can only be defined via R_g deviation less than 50 W m^{-2} and window size is not increased. In case iii) the missing value is replaced by the average value at the same time of the day. If after these steps the values could not be filled, the procedure is repeated with increased window sizes until the value can be filled.

For as concern the flux-partitioning procedure only the data not gap-filled has been used, and all original data flagged with a quality indicator >1 (e.g., with non-turbulent

conditions) are dismissed. Night-time data was selected using a global radiation threshold of 20 W m^{-2} (night below that threshold), cross-checked against sunrise and sunset data derived from the local time and standard sun-geometrical routines, and defined as ecosystem respiration (R_{eco}). Then the data set is split into consecutive periods of length x (days), and for each period it is checked where there are more than six data points available and whether the temperature range is more than 5°C , since only under these conditions reasonable regressions of R_{eco} versus temperature can be expected (x is a parameter of the algorithm and currently set to 10 days). For each of those periods where the criteria are met, the Lloyd & Taylor (1994) regression model is fitted to the scatter of ecosystem respiration (R_{eco}) versus either soil or air temperature (T).

The Cheng-I Hsieh *et al.* (2000) model was applied for footprint estimation (Fig.2) of the flux tower. Finn *et al.* (1996) examined the performances of Eulerian and Lagrangian models for estimating footprint, concluding that while the Eulerian model are easier to implement, they should use with caution over rough surfaces; Leclerc & Thurtell (1990) first applied a Lagrangian particle trajectory model and found a very consistent underestimates of the fetch when the observations were made above smooth surfaces and in stable conditions. The model used in this study is one of the existing models that explicitly describes the relationship between footprint, observation height, surface roughness, and atmospheric stability, integrating a dimensional analysis in conjunction with the Lagrangian stochastic dispersion model of the Thomson (1987).

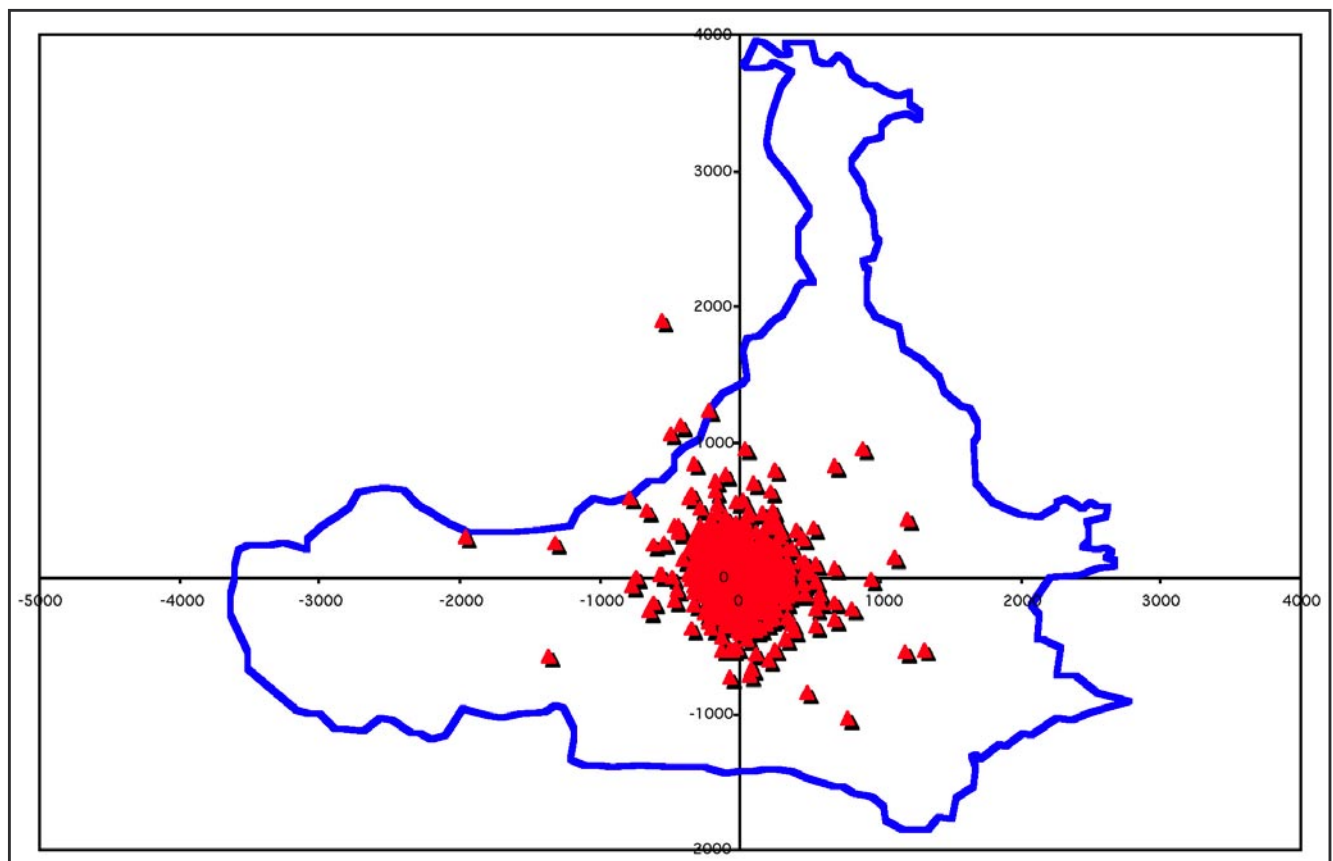


Figure 2- Footprint analysis of the daytime fluxes on Pianosa Island. Red points indicate the peak location of the footprint who contribute to the 90% of fluxes from March 2002 to March 2003.

Results and Discussion

The sum of latent (LE), sensible (H) and soil heat fluxes measured by the eddy covariance system over the entire study period in the Island of Pianosa accounted for 77% of the net radiation measured by net radiometers (Fig. 3). Incomplete energy balance closure in eddy covariance is not uncommon and it is often attributed to a different footprint of the tower compared to that of the net radiometers or to flux losses due to insufficient time resolution of the sensors (Mahrt, 1998; Kustas *et al.*, 1998; Twine *et al.*, 2000; Wilson & Baldocchi 2000). Differences in scale of areas for net radiation and flux footprint has been discussed in details by Schmid (1997). The source area of a net radiometer is constant and depends on the sensor height while the spatial dimension of the flux footprint is not fixed in space but depends on atmospheric conditions. In practice, the source areas for a net radiometer and eddy covariance flux footprint never match (Wilson *et al.*, 2002) and such imbalance is likely to be very pronounced in a complex ecosystem like that of Pianosa. This possibly explains the incomplete energy balance closure that was observed. The footprint of the flux measurement calculated with the Cheng-I H *et al.* (2000) model extended over areas covered by both abandoned agricultural land and shrubland while the net radiometer footprint was confined to the abandoned agricultural land patch where the tower was mounted. The fraction of abandoned agricultural land was approximately 58% of the footprint area, with the remaining fraction covered mostly by the Mediterranean macchia. The relative abundance of those two land uses in the footprint area compares well with the relative land use frequency over the entire island (Colom *et al.*, this issue), thus supporting the assumption that the fluxes measured by the eddy covariance tower were representative of the entire island surface.

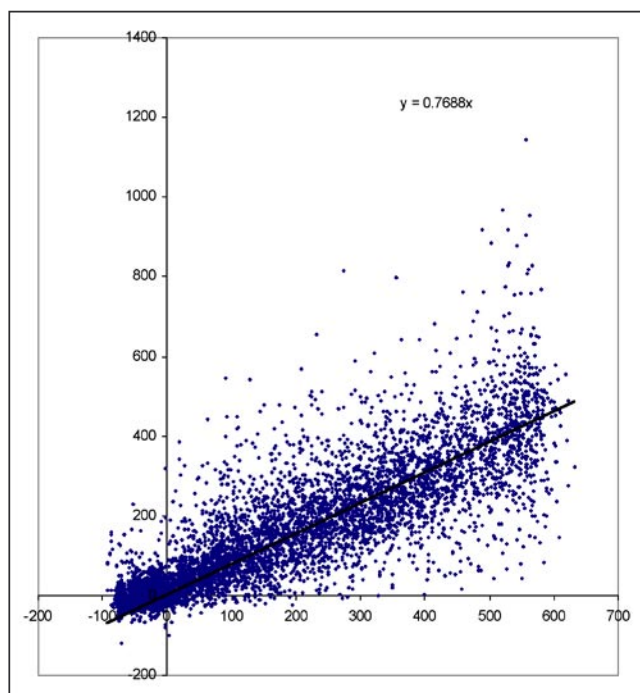


Figure 3 – Energy Balance of Pianosa Island, from March 2002 to March 2003. On X axis are reported the Net radiation measured by net radiometers installed on the eddy covariance tower (Wm^{-2}), on Y axis are reported the sum of latent, sensible and soil heat fluxes measured by the tower (Wm^{-2}). Solid line represent the regression line of the data shown (closure at 77 %), grey line represent 100% of the closed energy balance.

The Island of Pianosa was, in the twelve-months period considered here, a net sink for atmospheric CO_2 . Island's NEE was, during this period, equivalent to $2.64 t C ha^{-1}$. Sink activity was the highest during the spring and the autumn months while the island became a net source of C in the central part of the summer period (Table 2). NEE during January and December was very close to zero. Such pronounced seasonality in NEE was clearly associated to temperature and radiation limitations of photosynthesis during winter and part of the spring and autumn, while water availability was limiting C uptake in the summer. A significant negative correlation between NEE and soil temperature was observed over the period November 2002 - May 2003 ($r^2=0.35$, Fig. 4) while a positive correlation between NEE and the Bowen ratio was found during for the period June - October 2002 ($r^2=0.56$, Fig. 5). The Bowen ratio (i.e. the ratio between H and LE fluxes) is a reliable aridity index as it partitions the incoming solar energy into the relative fractions used for evaporation and for warming the air. Drought necessarily occurs when H largely prevails over LE or when the Bowen ratio becomes large (Hunt *et al.*, 2002).

Temperature limitations to photosynthesis are well documented in the literature (Bernacchi *et al.*, 2001; Long & Bernacchi, 2003; Zhu *et al.*, 2004), but in real situations, where NEE is measured over a seasonal course, other factors like sun radiation, day length and phenology co-vary with temperature and may have a role in limiting NEE during the winter, spring and autumn months. Air and soil temperature are well correlated to global radiation at mid latitudes, while day length does have an effect on the phenology of several plant species (Loskutov, 2001).

As it may occur for several annual grasses, the duration of the flowering, maturation and the subsequent senescence phases are concomitantly controlled by daylength and tem-

Table_02 – Total NEE (Net Ecosystem C Exchange) on monthly basis expressed as tonnes of C and CO_2 per hectares of the Pianosa Island

Year	Month	tCha ⁻¹	tCO ₂ ha ⁻¹
		Total	Total
2002	Jan	ND	ND
2002	Feb	ND	ND
2002	Mar	-0.17	-0.63
2002	Apr	-0.63	-2.31
2002	May	-0.41	-1.50
2002	Jun	-0.02	-0.06
2002	Jul	0.10	0.35
2002	Aug	0.31	1.15
2002	Sep	-0.14	-0.50
2002	Oct	-0.42	-1.55
2002	Nov	-0.26	-0.97
2002	Dec	-0.09	-0.33
2003	Jan	-0.05	-0.19
2003	Feb	-0.20	-0.73
2003	Mar	-0.66	-2.43
TOTAL		-2.64	-9.70

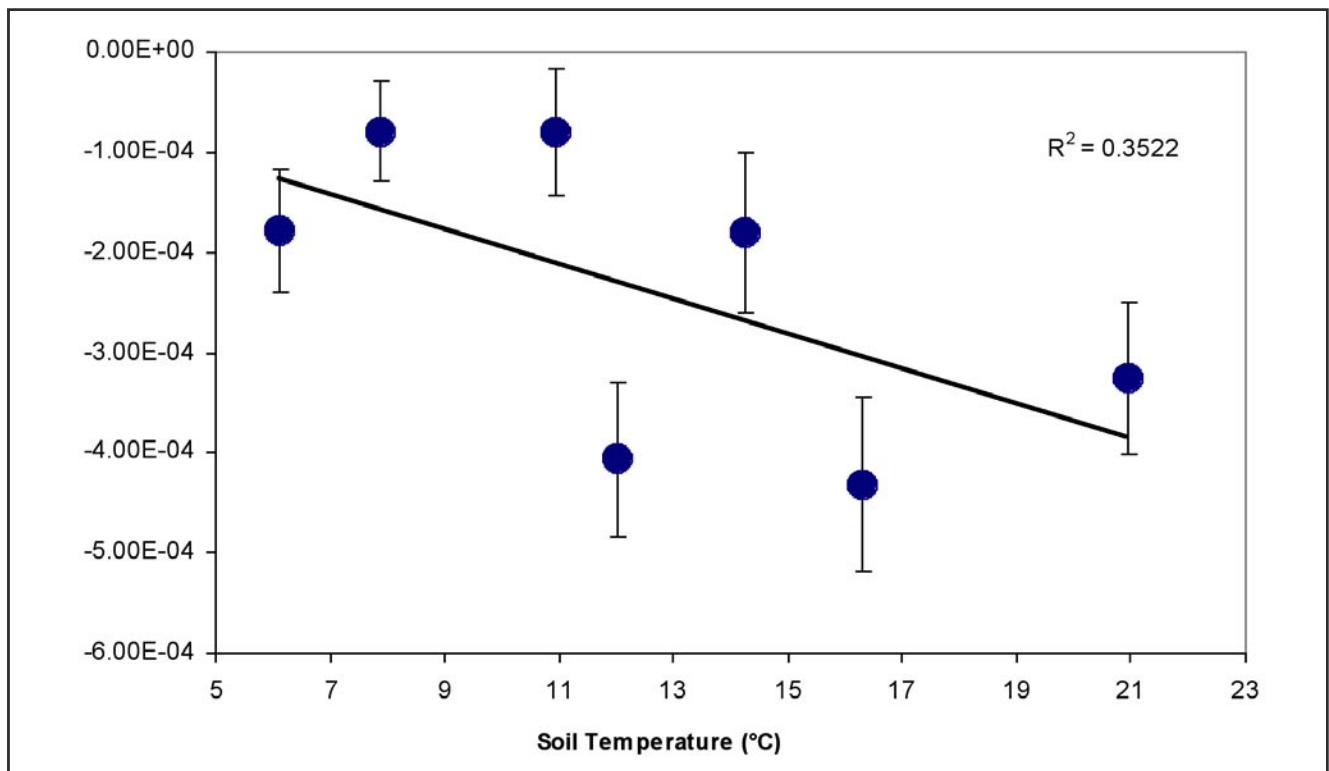


Figure 4 – Average of NEE (Net Ecosystem C Exchange) on monthly basis expressed as tCha⁻¹ vs Soil temperature (°C). Closed symbol represent the values from November 2002 – May 2003. The equation of the linear regression is $y = -2E-0.5x - 2E-0.5$. The r^2 value is shown on the figure

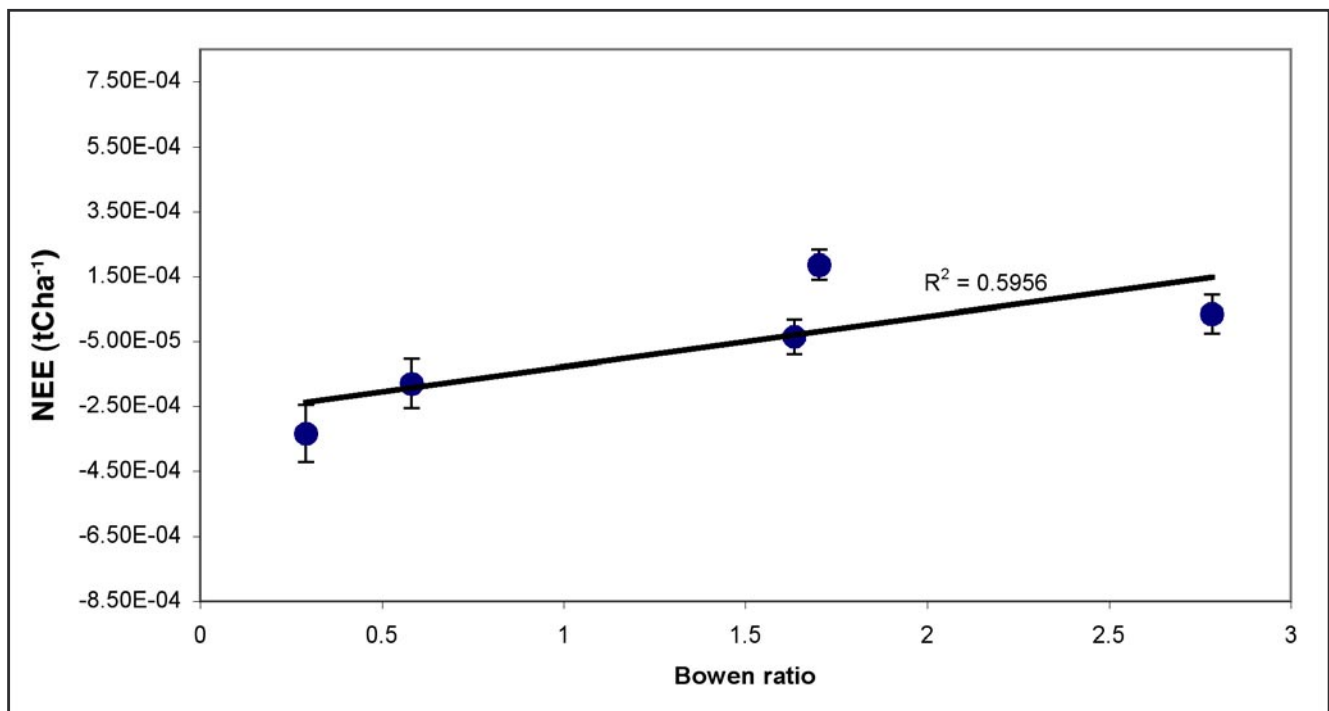


Figure 5 – Average of NEE (Net Ecosystem C Exchange) on monthly basis expressed as tCha⁻¹ vs Bowen ratio. Closed symbol represent the values of the period June - October 2002. The equation of the linear regression is $y = 0.0002x - 0.0003$. The r^2 value is shown on the figure

perature, also through vernalization effects (Sung & Aminosino, 2004). In the evergreen species of the macchia, where phenology is likely to have a minor effect on photosynthesis (Kyparissis *et al.*, 1997), temperature may also exert some control on photosynthesis but the total amount of C uptake can also be limited by the total amount of incoming radiation during the winter months. Accordingly, the significant observed correlation between NEE and soil temperature should be

interpreted more as the result of a combination of processes involving ontogenetic and biochemical responses to temperature and light rather than a simple direct temperature effect.

Drought limitations to photosynthesis are very common in Mediterranean ecosystems and have been already extensively documented (Damesin & Rambal, 1995; Methy *et al.* 1996, Reichstein *et al.*, 2002; Hoff & Rambal, 2003; Reichstein *et al.*, 2003). Those limitations can be effective on annual and

perennial vegetation. In Pianosa, the herbaceous layer that occupies most of the abandoned land rapidly senesces in response to drought by the contrary the macchia vegetation stays green over the whole summer period. So, while in the first case photosynthesis and C uptake are mainly limited by plant ontogenesis, limitations in C uptake of the macchia vegetation are mainly caused by stomatal limitations driven by severe water deficiency in the soil. It has already been observed (Rambal, 1993; Vilagrosa *et al.*, 2003; Llorens *et al.*, 2003; Gratani & Varone, 2004) that the drought response of Mediterranean shrubs that limit transpiration in order to maintain sufficient turgor and prevent leaf senescence, is very effective to cope with episodic rain events that may eventually occur during the driest part of the season. In those cases, in fact, water becomes suddenly available in the soil, and plants are ready to acquire new C resources as they do not require the formation of new leaves for photosynthesis.

The annual NEE of the Island of Pianosa was surprisingly large in comparison to other more productive ecosystem types of the Mediterranean region. Annual NEE of Pianosa was only 37% less than the mean annual NEE of a typical Mediterranean evergreen pine forest of San Rossore, near Pisa (G. Matteucci data not published) or the oak forest of Castelporziano (R. Valentini, Castelporziano, Euroflux dataset, 2003) which is located on an alluvial plain along the Tyrrhenian coast at 41° 45' N of latitude and that have access to ample groundwater resources throughout the year. On the other hand, the net C uptake in Pianosa was approximately 10% greater than the mean annual NEE of the macchia vegetation of Northern Sardinia (Reichstein *et al.*, 2002; Reichstein *et al.*, 2003) that has a similar species composition.

We hypothesize that this high NEE may be due to the special development stage of most of the vegetation in the island, where the abandoned land is being invaded by macchia at its early succession (i.e. highly productive) phases.

Conclusions

Data shown in this paper indicate that the Island of Pianosa was, at least during this study period, a substantial sink for atmospheric C. Considerations on the specific land use history of the island, together with a comparison of C concentration of the soils of the macchia and the abandoned agriculture ecosystem type of the island (Santi *et al.*, this issue), suggest that soils of Pianosa ecosystems lost a significant fraction

of their organic C during the period in which the island was subjected to highly intensive cultivation. Subsequent land abandonment has likely turned the island from a C source into a sink. Assuming that in absence of major disturbances, the island will be recolonised by the macchia vegetation, the total amount of organic C (above plus below ground) that could be potentially contained by the terrestrial ecosystems of in the Island of Pianosa will be equal to or larger than the unit C content of areas that are currently covered by the Mediterranean macchia multiplied by the entire surface of the island. This value equals 133 Kt of C (Colom *et al.*, this issue and Santi *et al.*, this issue) and compares with the 59 Kt of organic C that are estimated to be contained in the island, at present (Colom *et al.*, this issue; Santi *et al.*, this issue). The difference between those two numbers is obviously only a very crude estimate of the potential C sink of Pianosa, which based on the simplified assumptions that the recolonisation of the shrubland will really occur. Despite those numerous and largely untested assumptions, our observations suggest that if the annual NEE that was observed during our study period will be sustained in the future, the island will continue to be a C sink for several years. Pianosa is a very good analogue of a large portion of the Mediterranean Region, where intensive agriculture activity has been abandoned and it is currently unmanaged. Since 1990, 10 to 20% of the agricultural land in Mediterranean countries was abandoned (Grove & Rackham, 1996.) and this suggests, by simple analogy, that the current carbon sink that can be provided by such land in the Mediterranean could be much larger than previously expected. And this could be particularly true while considering that the total surface of abandoned agricultural land is estimated to exceeds a total of 17.4 millions of hectares in the Mediterranean region; a surface which is 3.5 times larger than what is currently occupied by forests (Faostat, 2004).

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