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Analyzing the carbon dynamics in north western Portugal: calibration and application of Forest-BGC

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Abstract

Net primary production (NPP) is an important variable that allows monitoring forestry ecosystems fixation of atmospheric Carbon. The importance of monitoring the sequestred carbon is related to the binding commitments established by the Kyoto Protocol. There are ecophysiologic models, as Forest-BGC that allow for estimating NPP. In a first stage, this study aims to analyze the climate evolution at the Vila Real administrative district during the last decades. The historical information will be observed in order to detect the past tendencies of evolution. Past will help us to predict future. In a next stage these tendencies will be used to infer the impact of these change scenarios on the net primary production of the forest ecosystems from this study area. For a parameterization and validation of the FOREST-BGC, this study was carried on based on 500 m^2 sampling plots from the National Forest Inventory 2006 and are located in several County Halls of the district of Vila Real (Montalegre, Chaves, Valpaços, Boticas, Vila Pouca de Aguiar, Murça, Mondim de Basto, Alijó, Sabrosa and Vila Real). In order to quantify Biomass dinamics, we have selected 45 sampling plots: 19 from *Pinus pinaster* stands, 17 from *Quercus pyrenaica* and 10 from mixed of *Quercus pyrenaica* with *Pinus pinaster*. Adaptation strategies for climate change impacts can be proposed based on these research results.

1 Introduction

Global concern about increasing atmospheric concentrations of greenhouse gases, particularly carbon dioxide (CO_2) and the possible consequences of future climate change have generated interest in understanding and quantifying the role of terrestrial ecosystems in the global carbon cycle. Looking at previous periods, Lucas et al. (2000) have reported that the combustion of fossil fuels has led to a steady increase in the release of carbon dioxide and aerosol particles into the atmosphere since the beginning of the industrial revolution. They conclude that CO_2 levels in the atmosphere have risen by more than 20% during this period and should double pre-industrial levels over the next century. According to Puhe and Ulrich (2000), since the late nineteenth century a general warming of global surface temperatures has been observed, especially over continents at latitudes between 40° N and 70° N. They regard the speed of warming as remarkable, having reached an intensity of approximately 0.26 °C per decade since 1980s. In terms of precipitation, changes indicate a small global positive increase (1%) during the twentieth century. The picture in Europe is diverse: annual precipitation changes differ between northern Europe, slight increases, and southern Mediterranean Europe, general decreases in rainfall. In the case of Portugal, analysis carried out by the National Meteorological Service (NMS) for the period 1868–1998 indicates an increase in temperature averaging 0.0074 °C/year. The trend with respect to rainfall is less clear, although is indicative of an overall decrease, with the most distinct reduction occurring when the data for the month of March are examined over the period (−0.29 mm/month). The evolution of ecosystems is chiefly driven by the adaptation of species and by climate change (Puhe and Ulrich, 2000). At present and for the foreseeable future, climate change represents one of the most significant challenges facing scientists in developing their understanding of how ecosystems adapt to change. Whilst Phat et al. (2004) maintain that global climate change is becoming increasingly apparent, Nemani et al. (2003) have assumed that its impacts are already real (and dramatic). They claim that between 1980 and 2000 the Earth experienced two of the warmest decades in the instrumental record, underwent three intense and persistent El Niño events (1982 to 1983, 1987 to 1988, and 1997 to 1998), and saw noteworthy changes in tropical cloudiness and monsoon dynamics. Several predictions for the future have been reported, such as by Pastor and Post (1988) who suggest a 2–4 °C mean rise in global temperature with CO_2 doubling with greater warming in higher latitudes than near the equator on the basis of general circulation models. The new challenges reported by Phat et al. (2004) focus on the need to gain a deeper understanding of forest ecosystem processes, in particular photosynthesis and transpiration. Running (1994) argues that “global change” is now used as a summary term referring not only to physical and biological change, but also to socio-economic adjustment across the planet, which will influence the biosphere in ways that only can be projected. Although models are inevitably simplified, imperfect and limited versions of reality (Lucas and Curran, 1999; and Lucas et al., 2000), simulation modelling constitutes an essential tool for evaluating ecosystem activity at space and time scales beyond the limits of direct measurements (Running, 1994). Their benefits are particularly noted for understanding ecosystem function and thus predicting responses to global change (Ryan et al., 1996). Understanding the planet's processes and global ecological system is essential for managing the Earth's resources wisely and for ensuring that sufficient of these are available well into the future. It is important that we investigate how, why, and when these global changes could occur in order to avoid, or at least anticipate and plan for possible emergency situations in the future, thus address the perceived lack of knowledge reported by Lucas et al. (2000), Puhe and Ulrich (2000), and Nemani et al. (2003). The imbalance in the global budget for atmospheric CO_2 is one of the most important problems in the study of global change (Cao and Woodward, 1998). Forests are assumed to play an important role in climatic change at the global scale, because they potentially act as a major sink for CO_2. It has been suggested that trees should be planted expressly to sequester CO_2 and so mitigate the projected further increase in atmospheric CO_2 concentrations (Ford and Teskey, 1991). The 21st century has brought new challenges for forest management (Phat et al., 2004) and, in addition to ameliorative actions by people, forest ecosystems could constitute an extremely important tool to deal with climate change. Running et al. (1999) suggest that probably the single most fundamental measure of "global change" of practical interest to humankind is with respect to terrestrial biological productivity – the annual Net Primary Production (NPP), which expresses on a periodic basis carbon net fluxes between atmosphere and terrestrial vegetation through photosynthesis (Goetz and Prince, 1996). Field et al. (1995) report that although conceptually simple, estimation of NPP can be very difficult to measure accurately in situ. This becomes even more problematic when attempting to estimate NPP for large areas Investigators are now focusing attention on developing more practical methodologies for this task. NPP is complicated not only by difficulties of measurement and estimation, but also because it represents a holistic ecological perspective on ecosystems. Nevertheless, NPP is one of the key variables chosen to analyse the impact of climate change, or equally any other human or natural intervention in ecosystems. Furthermore, relatively few studies have compared NPP estimation from ecophysiological models with measured values from fieldwork.

2 The model FOREST-BGC

The model FOREST-BGC was developed at the University of Montana (Running and Coughlan, 1988) where it had been originally applied to coniferous forest stands. It works simulating water, carbon and nitrogen fluxes within homogeneous forests.

FOREST-BGC is a process level ecosystem model developed by Running and Nemani (1988), which calculates canopy interception and evaporation, transpiration, photosynthesis, growth and maintenance respiration, carbon allocation above and below-ground, litter fall, decomposition and nitrogen mineralization. This model seeks to establish a compromise between mechanistic detail and simplifying generality that will allow for its implementation in regional scale ecological research. Some assumptions were made in order to simplify the model. Firstly, the model treats fluxes only in the vertical dimension, so that horizontal homogeneity is assumed for any defined area. Secondly, the model treats the forest canopy as a homogeneous three-dimensional leaf of depth proportional to the total leaf area index not projected. Ryan et al. (1996) consider FOREST-BGC as the big leaf model due to these assumptions. The model combines daily and yearly resolution. Running and Coughlan (1988) explain the reasons for this approach. According to them, hydrologic balances, plant water availability and canopy gas exchange processes are most conveniently treated on a daily basics because meteorological data are routinely summarised as daily averages or totals, and these processes react diurnally to environment conditions. However, daily calculation of carbon allocation, litter fall and decomposition processes are not reliable because the minimum routinely measurable increment of these processes typically occurs on a monthly basics. LAI is a key variable for controlling NPP and the most important variable in the FOREST-BGC algorithm. However, LAI was not regarded as an input variable in this system. The model estimates LAI indirectly, according to the Eq. (1).

$$\text{leaf area index} = \frac{\text{specific leaf area} \cdot \text{leaf carbon}}{\text{ground surface area}} \tag{1}$$

3 Study area and data

The Trás-os-Montes area is divided into three slightly different climatic zones: The Hot Zone, the Transition Zone and the Cold Zone. From a thermic point of view the delimitation seems to be between an annual average of 12.0 °C and 13.0 °C for the Cold Zone and 14.0 °C and 15 °C for the Hot Zone, the Transition Zone showing annual average temperatures ranging from 13.0 °C to 14.0 °C. The diversity of the repartition of temperatures in a relatively small area is due to a complicated orography and to the fact that it is located in the transition zone between the influence of the Atlantic Ocean and the Continental climate characteristic of the Iberian Peninsula.

The selected portions for our study, are all located in the Trás-os-Montes area, each one covers an area of 500 m^2. Those portions are part of the national Woodland Inventory of 2006, located in different circumscriptions of the Vila Real district and they are as follows: Montalegre, Chaves, Valpaços, Boticas, Vila Pouca de Aguiar, Murça, Mondim de Basto, Alijó, Sabrosa e Vila Real. For the biomass analysis we use 45 sampling portions (19 of *Pinus pinaster*, 17 of *Quercus pyrenaica*, and 10 mixed with *Pinus pinaster* and *Quercus pyrenaica*). The populations include trees of different ages, and level of occupation, so as to consider a wide range of tree's dimensions.

3.1 Meteorological data

The state of the atmosphere can be described thanks to a package of measures of the most important climatic elements for its characterization. According to Peixoto and Oort (1992), the most important climatic elements characterizing a climate in a particular area are the precipitations and the temperature.

Leite (1991), states that the repartition of the precipitation in space and time, its changeability and the frequency of its intensity is essential to understand how precipitation works in a particular area. As we have said previously, for our present study we have selected three weather stations: Bragança, Vila Real and Mirandela as they characterize the climate of three sub-areas: Cold Zone, Transition Zone and Hot Zone.

3.1.1 Data quality

A cautious and scrupulous study of data, was particularly telling. With a first observation, we noticed that there were figures missing, and that can be caused by machines that have broken down, the impossibility to carry on with the observation whether for lack of an observer or difficult climatic conditions or others. During the preliminary preparation for the series of climatic observations we needed to solve that problem, as the trial methods for statistic analysis require a series of figures equally divided. The available precipitation data in the National system of information on hydrological resources (http://snirh.pt/) regarding the weather station under study, have a high percentage of missing figures and as the missing figures happen to be at the start or at the end of the series, or that they represent a fairly long period regarding the missing figures of the observation in the first or the last years of the record, it seemed to us that it was appropriate to shorten the original series. As mentioned before, thanks to the analysis of our series under study, we realized that, in a lot of days when there had been no records, the observations in nearby weather stations showed the apparent non existence of figures for temperatures and precipitations. The omission of annual totals and some monthly precipitation results, totalizing 25 per cent of the available weather stations represent a series of lack of records for our study, particularly in mountainous zones where the precipitations change a lot from a station to another. This is a recurrent problem in any study on the climate of an area.

As the series of precipitations of the selected stations for our study show a huge number of missing figures, our investigation in methods for filling in the blanks, was restricted to simple procedures, so not to add more discrepancies in the series. In fact, our main goal, as well as filling in the blanks, was not to alter significantly the accurately recorded climatic information in the weather stations. We used the correlation ratio determination method between the weather stations where we noticed the blanks and station as reference. The station we used as a reference was the weather station of Bragança, as it has a minimum lack of records and it is certified by the European Climate Assessment.

3.1.2 Data analysis

According to Rodrigues (2009) in Bragança, the annual average temperature has a tendency to increase by 0.16 °C/10 years, which is due to an increase of 0.3 °C/10 years in the maximum temperature and to an increase by 0.1 °C of the minimum temperature. We notice a tendency to increase by 44.9 mm/decade in the annual precipitations accumulated in Bragança, probably caused by oscillations of great amplitude. In Mirandela, keeping in mind that the series is 50 years shorter, the average temperature decreases by 0.3 °C/10 years, and that contributes greatly to the decrease of the minimum temperature by 0.4 °C/10 years. The maximum temperature increases by less than 0.1 °C/10 years, which is by far, insufficient to counterbalance, in terms of annual averages, the tendency to increase of the maximum temperature. An important characteristic of the climate in Mirandela is that thick radiating fogs are quite frequent in all that orographic depression where this city is located and the Tua Valley. They are caused by the brutal daily thermic variations that can happen sometimes for nine consecutive days. Mirandela shows fairly inferior accumulated annual precipitation figures, but with an interesting particularity that is a more balanced repartition of the precipitations throughout the year. In Vila Real, The tendency to decrease of the annual average temperature is quite insignificant, four centesimal of degrees in 10 years, that is caused by a decrease by almost 0.2 °C/10 years in the maximum temperature. The tendency to increase of the minimum temperature is inferior to a decimal of degrees as such it is not enough to contradict the tendency to decrease of the maximum temperature. As far as the series of precipitation is concerned the record of accumulated annual precipitations presents a slight tendency to decrease by 24.6 mm/decade.

3.2 Ground data: measurements of LAI

The in index of the foliar area (LAI) was obtained thanks to field data and was already known for the *Pinus pinaster* thanks to Lopes (2005). As regards the *Quercus pyrenaica* this figure was determined, through the random gathering of 30 leaves in different parts of all the trees of the same species, in a sampling portion chosen at random. Afterwards, each leaf was numbered one by one (from 1 to 30) and each leaf was traced in an acetate sheet. We used the ArcMap software, to determine an area projected by the leaves. After that, the leaves were dehydrated in greenhouses and its anhydride weight was determined afterwards. It was so possible to determine the specific area index (SLA) that links which biomass is the one referring to the area of each leaf. Thanks to the estimated figures of the foliar area for phase 1 and 2, we determined that SLA for the *Quercus pyreneica* whose value is 33.14 m^2/kg. According to Lopes (2005) the value is of 5.25 m^2/kg for the specie *Pinus pinaster*. After we knew the SLA for each species in analysis we underwent the determination of the foliar biomass for each sampling portion.

4 Data processing

4.1 Calibration of FOREST-BGC

FOREST-BGC was designed to be particularly sensitive to leaf area index (LAI), which is used as the main independent variable for calculating the major physiological processes in the model. Two input files needed to execute the simulations: one containing the climate input data and another the site parameters and constants. The first file, “filename.CLM”, contains daily information from the year in question (optional if simulation includes more than one year), the Julian day (JD), the maximum temperature ($T_{\max}$, in °C), the minimum temperature ($T_{\min}$, in °C), the dew point (Dewp, in °C), and the total daily amount of rainfall (Prec., in cm). The second file, “filename.DAT”, contains the input-output processor controls. There are three possible output files: a filename.Day file, providing daily figures for soil water, outflow, evaporation, transpiration, water potential, photosynthesis, and maintenance respiration; a second output file, filename.GRW, which provides annual figures for transpiration, photosynthesis, maintenance respiration, and leaf, stem and root carbon. The Forest-BGC was run, using the averages figures for all the input parameters for each study area with only leaf carbon content changing. The complexity of the model, the number of changing variables and the variability of the study areas had suggested some simplification of the methodology for prediction how Quercus and Pinus ecosystems react.

5 Results

In the initial situation, considering the general average of the three portions, the most productive populations were located in the transition zone and the least productive in the Cold Zone. In the area of the transition land and the cold land, PPL is higher in the pure Pb, except for those of the Hot Land where, because of the climatic characteristics, the Pinus specie has adapted so well. In every situation the mixed ones are the least productive, more over the sole simplistic vision of the analysis of production, without considering other aspects like biodiversity need to be carefully pondered. A variation in the maximum temperature affects indistinctively the three types of population, in the three climatic zones in analysis. In the transition zone the mixed populations are the most affected. In the Cold Zone the pure from Quercus are the most affected. In the Hot Zone it is those which are pure of Pinus, followed by those pure of Quercus.

When we change the minimum temperature, the behaviour is identical to the one in the maximum temperature. It is not strange that the Forest-BGC determines the average temperature with the arithmetic average of the maximum and minimum temperatures. In the analysis of the transition zone, the effects of the variation of the precipitations are identical to what happened with the temperatures, but with a minor impact. In the Cold Zone, the variation of precipitations had a greater impact than the change of temperatures. That impact is also greater in the Hot Zone. As a conclusion we can say that the most extreme climatic situation, the variations in precipitations influence more the productivity than the temperature.

From the analysis of the variation of temperatures with precipitations, we noticed that it is the temperature that is more subject to productivity, in the case of the Transition Zone. The tendencies to evolution come from an increase of productivity in this climatic zone. In the Cold zone there is a different characteristic, precipitations are those that produce a change and the effect is greater when we change both meteorological patterns. In the Hot Zone they don't have a linear behaviour with differentiated behaviours according to the type of population. As a conclusion we can say that is a complex situation with a more erratic behaviour.

6 Conclusions

The principal focus of this study has been on the important role of the NPP in relation climate change, biodiversity and forest management. This work has also examined the applicability and accuracy of the FOREST-BGC as a production simulation model. Results showed that the FOREST-BGC is able to capture the overall pattern of NPP for both ecosystems. In addition to describing the general pattern of NPP in the ecosystems, this ecophysiological model provided some logical explanation about the ecosystems behavior in terms of production. FOREST-BGC was used to simulated the impact of different climate change scenarios on these forest ecosystems' NPP. The major limitation of this ecophysiological model was its inability to incorporate atmospheric CO_2 as input. Results could change significantly if this factor was taken into account. Regardless this increase or decrease of NPP the most significant fact is that climate change will have a very strong impact on the production of ecosystems and in carbon sequestration, and consequently in the balance of those ecosystems. This investigation can be said to have contributed towards an advancement in the understanding of the essential role played by forest ecosystems, mainly due to their constituting extremely important reservoirs of carbon in the globe.

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Table 1. NPP estimation (kg ha^{-1} year^{-1}) by the simulation of Forest-BGC for diferent climate scenarios with variation of temperature (ΔT) and variation of rainfall (ΔR).

Region	Sampling Portions	Initial	ΔT_{max}	ΔT_{min}	$\Delta T_{\text{max+min}}$	ΔR	$\Delta R + \Delta T_{\text{max}}$	$\Delta R + \Delta T_{\text{min}}$	$\Delta R + \Delta T_{\text{max+min}}$
Transition	*Pinus pinaster*	2590	2607	2586	2598	2595	2601	2593	2597
	Quercus pyrenaica	2095	2107	2088	2097	2096	2102	2091	2097
	Mixed	1599	1655	1656	1655	1639	1638	1638	1639
Cold	*Pinus pinaster*	2584	2523	2560	2495	2452	2398	2430	2372
	Quercus pyreneica	2079	1418	1464	1493	3433	3367	3411	3344
	Mixed	1607	1596	1583	1524	1655	2204	2233	2182
Hold	*Pinus pinaster*	2118	2600	2784	2753	1846	1844	1858	1855
	Quercus pyreneica	2631	2103	2206	2191	2030	2016	2121	2105
	Mixed	1596	1582	1685	1669	1511	1496	1601	1586

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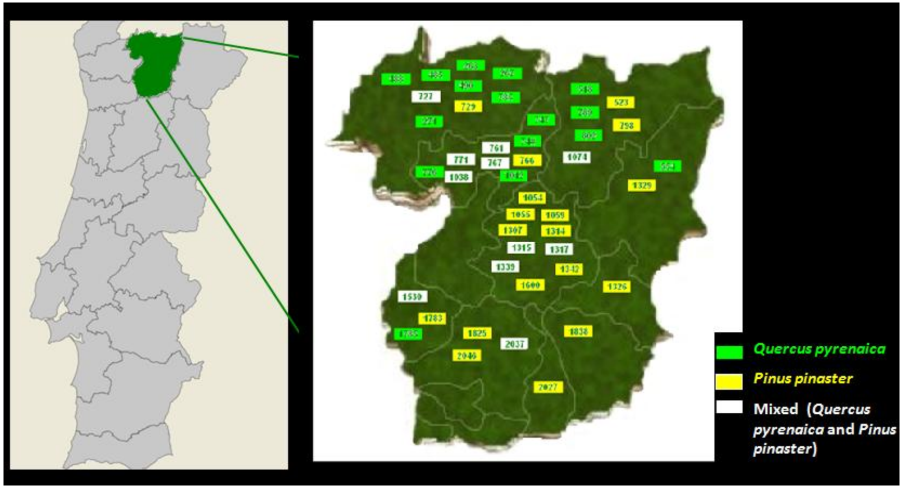

Fig. 1. Location of the study area and inclusion of the sampling portions (Rodrigues, 2009).

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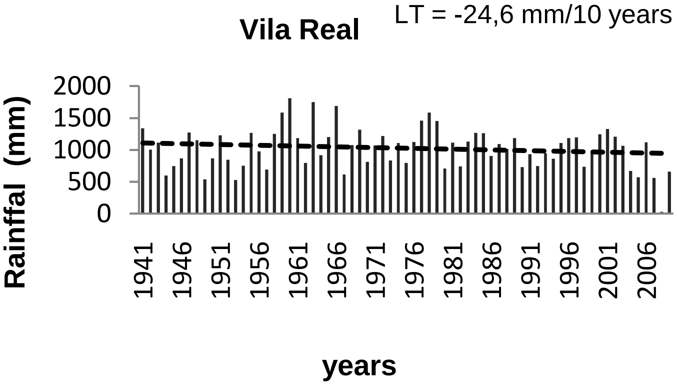

Fig. 2. Representation of the annual rainfall Vila Real station series.

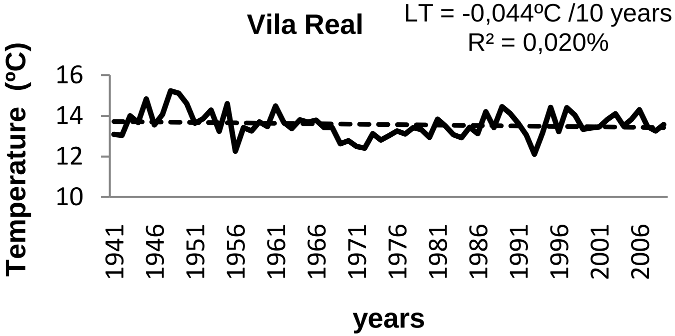

Fig. 3. Representation of the annual mean temperature Vila Real station series.

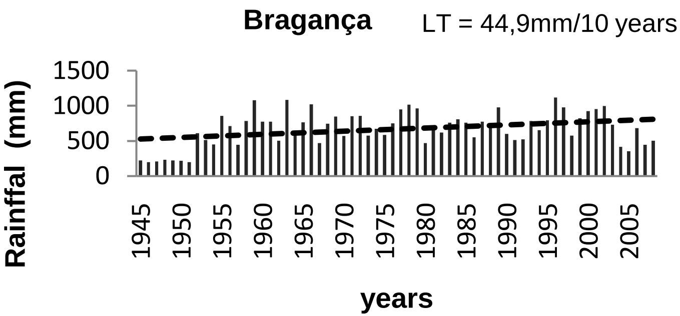

Fig. 4. Representation of the annual rainfall Bragança station series.

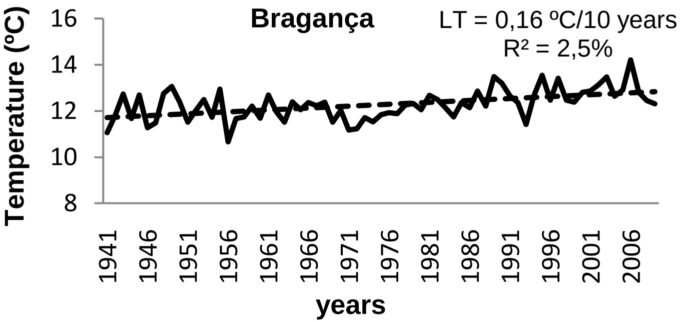

Fig. 5. Representation of the annual mean temperature Bragança station series.

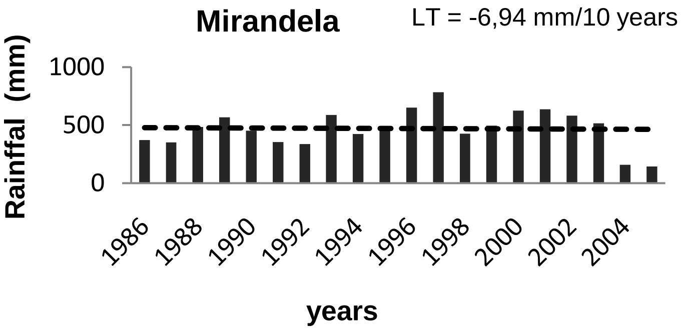

Fig. 6. Representation of the annual rainfall Mirandela station series.

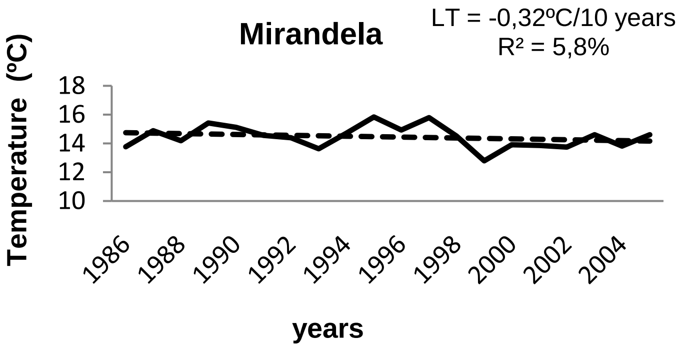

Fig. 7. Representation of the annual mean temperature Mirandela station series.