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Title: Application of Vegetation Index time series to value fire effect on Primary Production in a Southern European rare wetland

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Corresponding Author: Dr. Roberta Aretano,

Corresponding Author's Institution:

First Author: Teodoro Semeraro

Order of Authors: Teodoro Semeraro; Giorgio Vacchiano; Roberta Aretano; Davide Ascoli

Abstract: Fire disturbance is an intrinsic component of the Mediterranean biome playing an important role in ecosystem dynamics and processes. However, frequent and severe wildfires can be detrimental to natural ecosystems, particularly in small natural protected areas, where they may hamper the flow of ecosystem services (ES). While post-fire dynamics of individual ES are heavily context-dependent, the primary productivity of the ecosystem can be regarded as a generic driver of several provisioning and regulating ES, as it represents the amount of energy available to plants for storage, growth, and reproduction, which drives future ecosystem structure and functions. The aim of this study is to evaluate the effect of anthropogenic wildfire on the primary productivity of a rare wetland ecosystem in the Natura 2000 site "Torre Guaceto". Productivity was estimated by calculating a 15-year time series of vegetation indices (EVI and NDWI) from remotely sensed MODIS imagery. Our results in terms of PP trends may be relevant to assess the change in ecosystems services provided by wetlands. Interactions between wildfire, ecosystem productivity and climate were then analyzed. During the selected period, climate did not play a significant effect on primary productivity, which was mainly driven by post-fire vegetation recovery. Findings of the present study demonstrate that the wildfire affecting the Natural Protected Area of Torre Guaceto in summer 2007 had a major effect on primary productivity, inducing the regeneration of Phragmites and the replacement of old individuals by structurally and functionally better ones.

Cover letter

Jan Vymazal
Czech University of Life Sciences,
Prague, Czech Republic
Editors in Chief of
Ecological Engineering

Brindisi, 25 August 2018

Dear Editors,
please find enclosed the electronic revised version of the manuscript entitled "Application of Vegetation Index time series to value fire effect on Primary Production in a Southern European rare wetland" by Semeraro Teodoro, Vacchiano Giorgio, Aretano Roberta, Ascoli Davide, to be considered for publication in Ecological Engineering.
We have taken into account all comments and suggestions made by the two Reviewers. The comments were all addressed in the updated manuscript, and point-by-point in the response to reviewer.
We added a new author (Giorgio Vacchiano) expert of the subject to the previous authorship because it has made a significant contribution to the implementation and revision of the reported study.
I assure you that all co-authors agree with the content and with the submission and publication of this manuscript in Ecological Engineering.
No approvals are required for the research and the publication of results.

Best regards

Dr. Roberta Aretano
Apulian Regional Agency for the Environmental Prevention and Protection
Department of Foggia, Via G. Rosati 139, 71121 Foggia, Italy
E-mail: r.aretano@arpa.puglia.it

***Response to Reviewers**

Response to Reviewers

Dear Reviewers,

Thank you for the valuable feedback on our manuscript ECOLENG-D-17-01483 “Application of Vegetation Index time series to value fire effect in a Southern European rare wetland”.

We appreciate the chance to revise and improve our work.

Almost all the text has been revised and corrected by an English speaker to improve the use of English language. We have also introduced a new author expert of the subject (Giorgio Vacchiano) to implement the results and discussions. This author, not having participated in the first phase of the drafting of the work, has helped us to better focus and organize the objective and results of the manuscript and make the text clearer than the previous version.

We decided also to modify slightly the title of the manuscript to better focus it on the objective of the work, going from: "Application of Vegetation Index to a series of fire effects in Southern European rare wetland" to “Application of Vegetation Index time series to value fire effect on Primary Production in a Southern European rare wetland".

The introduction was almost simplified to make it clearer but the conceptual basis and structure remains the same of the first version. Materials and methods have been improved to better explain the choice of indices also according to the comments of the reviewer 1. Results and discussions were reorganized to make them more functional to the objective. The discussions have been implemented trying to better explain the link between the results and the provision of ecosystem services. In particular, we emphasized that the analysis of Primary Production (PP) variation is already a direct connection of ecosystem services because PP is a support ecosystem service and then we qualitatively explained the influence of the change in PP on other ecosystem services. The conclusions were reviewed by eliminating redundant parts with materials and methods and results and discussion. They have been focused on future perspectives and possible developments. The bibliography has also been increased with other new references suggested by the new author.

The comments were all addressed in the updated manuscript, and point-by-point below. We found the comments very helpful and believe the manuscript has been improved by taking them into account.

Please do not hesitate to contact us for further suggestions of improvement.

Thank you again

Authors

ECOLENG-D-17-01483 review

Reviewer #1:

- **The manuscript aims at analyzing the effect the a fire that has interested a wetland area in 2007 on primary production as a surrogate of ecosystem services provision, by using vegetation indices and remote sensing technique.I did not find this paper novel and deserving of publication for several reasons: (1) The Authors report that "The aim of this study is to understand the changes in PP of the vegetation in a small natural protected area**

in Southern Europe after a large fire in summer 2007 covering nearly the 15% of the Nature reserve by combining remote sensing technologies with carbon cycle processing with reference to vegetation indices. We have considered PP as a supporting service able to guarantee ecosystem services flow. In dealing with this issue, this paper aims to use EVI integrated with NDWI derivate by MODIS satellite, like suitable surrogates for the assessment of shifts in temporal dynamics of PP, useful to explore possible feedbacks between wildfire and ecosystem services. In particular, since the fire affected the wetland of a natural protected area, our aim is to analyse the ecological function of this ecosystem after the fire and therefore the ability of the wetland to provide ecosystem services. "Although I have found the aim very long and mixed with aspects more technical than of scientific importance, I think that the last sentence was the real aim. But they did not give any evidence of the ability of the wetlands to provide ecosystem function and services after fire, but only few considerations that are of general interest and not novel. It is obvious that the PP increases after a fire event, given the recovery of the vegetation cover as well as it is likely that an event fire happens where the vegetation is dry and, consequently, PP is low.

The work tries to develop an approach that can analyze directly and easily the effect of some disturbances or perturbations such as fire on ecosystem services, using PP as a support ecosystem service. The PP can be The primary productivity (PP) of an ecosystem is able to drive its structure, functioning, and generation of provisioning, regulation and cultural services. Therefore analyzing the changes in PP, it is possible to at least understand how the system is changing and the provision of ecosystem services. Therefore the work is proposed as a functional monitoring of ecosystems according to the different drivers that can modify it.

To better focus the aim of the work we have changed the text from: “*this paper aims to use EVI integrated with NDWI derivate by MODIS satellite, like suitable surrogates for the assessment of shifts in temporal dynamics of PP, useful to explore possible feedbacks between wildfire and ecosystem services. In particular, since the fire affected the wetland of a natural protected area, our aim is to analyse the ecological function of this ecosystem after the fire and therefore the ability of the wetland to provide ecosystem services*.”

to

“*This study aims to analyze the seasonality, trend and abrupt changes in PP of a Nature 2000 Southern European wetland of high conservation value before and after an anthropogenic fire event, estimated by selected Vegetation Indices, and to explore possible feedbacks between productivity, wildfire and climate in the post-fire recovery phase*”.

To give more evidence on the link between wetland and ecosystem services and how these can be altered due to fire, the following part has been added in the results and discussion: “*The regeneration of Phragmites after the fire may have led to a synchronised increase in both photosynthetic activity and leaf water content; this may have helped to increase PP in the wetland and therefore support its ecosystem services (Costanza et al., 2007; de Groot et al., 2010; Petrosillo et al., 2013). For example, an increase in PP should result in a higher gas exchange between the canopy and the atmosphere, which increases the ability of the wetland to absorb atmospheric CO_2, and in more nutrients absorbed by the roots, which improves the water purification capacity of the ecosystem. Other ecosystem services that may benefit from a higher biomass production in wetlands include flood mitigation, habitat, landscape connectivity, aesthetic quality, and water supply (Mitsch and Gosselink, 2007; Petrosillo et al., 2013; Semeraro et al., 2015)*” (line 179).

- **(2) The approach is not new for the Authors. They carried out similar analyses on PP but with different indices in the same area trying to explore possible feedbacks related to conservation management choices.**

This analysis has a different methodological approach compared to the methodology used in the past. In the previous work, vegetation indices were used to describe the spatial pattern of vegetation and how this was influenced by human activity. The analysis of the fire represented a secondary aspect of the research.

Furthermore, in the previous work only three time windows were used without considering seasonality, trends and residues. In this work, continuous time series have been constructed and they allow better to describe the functional behavior and the dynamics of the system in relation to the fire and climatic conditions. The choice of the indices was therefore focused on the new objective of the paper. Moreover, unlike the previous work, the current analysis, having continuous historical series, can also include the future evolution of the system. Therefore, while the previous work simply describes the consequence of an anthropic action on the environmental system without giving any indication of possible future dynamics, this work can also provide indications on system evolutions following a disturbance and therefore provide management indications.

- **(3) They justify the use of a new vegetation index (EVI) instead of NDVI supported by only one single reference. If they want to defend the use of EVI instead of NDVI the should know the main literature behind the use of NDVI and EVI and not just one reference. A recent paper on "Potentials and limitations of remote fire monitoring in protected areas" reports that the Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1973) and the Normalized Burn Ratio (NBR) (Key and Benson, 1999; Chuvieco et al., 2002) are the commonly used index in the detection of burned areas (Escuin et al., 2008).**

We agree with the reviewer 1 and we have deepened the motivations that have led the choice of vegetation indices also integrating the literature of this subject. In particular, as indicated by Xiao et al 2004, the EVI index was developed to specifically study burned areas in Brazil and is more performing than NDVI. However, conceptually, both indices refer to the same physiological property of vegetation because they use the same bands. The EVI, unlike the NDVI, is integrated with the BLU band to improve some NDVI limitations. As for Normalized Burn Ratio (NBR), this corresponds to the NDWI index we used in our analysis. It is the same index called differently. Probably in various applications it has undergone a different name. Since we refer to ecological functions, we preferred to leave the name NDWI. Probably the name NBR is indicated when this index is used to map the burned areas.

$$(NDWI \ or \ NBR) = \frac{NIR - SWIR}{NIR + SWIR}$$

Our analysis uses indices that estimate the same physiological parameters of the suggested work.

However we have modified part of materials and methods from (lines 91-119) "*In this study we applied linear techniques to time series data in order to analyse the persistence or alteration of the PP of the wetland as a result of fire disturbance. PP depends on the concentration of chloroplasts active in photosynthesis, the concentration of water in the leaf tissues and the weather. Consequently, high PP levels depend on high chloroplasts and water concentration. We therefore made reference to the Enhanced Vegetation Index (EVI) in combination with the Normalized Difference Water Index (NDWI). These indices are spectral transformations of two or more bands of satellite images designed to enhance vegetation properties and allow reliable spatial and temporal comparison of terrestrial photosynthetic activity and canopy structural variations (Huete et al., 2002). EVI was used to determine the status of green vegetation, linked mainly to the presence of chloroplasts in the canopy (Xiao et al., 2004), while NDWI was used to determine the presence of water in the canopy (Jackson et al., 2004; Gu et al., 2008). Therefore, two time series were created using the Enhanced Vegetation Index (EVI) and the Normalized Difference Water Index (NDWI), extracted from MODIS imagery from 2001 to 2015, which consisted of 345 MODIS images (USGS, 2017). Specifically, we constructed the average EVI and NDWI profiles considering the pixels of burned vegetation in the wetland in 2007.*

EVI is calculated as follows:

$$EVI = G * \frac{(NIR - RED)}{(NIR + C1 * RED - C2 * BLUE + L)} \qquad (1)$$

where NIR is the reflectance or radiance in the near infrared channel, RED is the reflectance or radiance in the visible channel, and BLUE is the blue band for atmospheric correction. The coefficients adopted in the

MODIS-EVI algorithm are; L = 1, C1 = 6, C2 = 7.5, and G (gain factor) = 2.5. The inclusion of the blue band for atmospheric correction is important when studying areas where burning of pasture and forest takes place throughout the dry season, either for agricultural purposes or as a result of natural fire events (Xiao et al., 2004).

NDWI is a remote sensing-based indicator sensitive to changes in the water content of leaves (Gao, 1996) and is calculated as follows:

$$NDWI = \frac{NIR - SWIR}{NIR + SWIR} \quad (2)$$

where SWIR is the reflectance or radiance in the short wave infrared channel

to

"*Numerous studies used either the Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1973) to estimate changes in PP (e.g., Barbosa et al., 2015; dos Santos et al., 2018), especially following disturbance by fire (Escuin et al., 2008). NDVI is mostly sensitive to photosynthetic activity, i.e., the amount of chloroplasts in the canopy (Xiao et al., 2004a). In this study, the Enhanced Vegetation Index (EVI) (Heute et al., 2002) was preferred to NDVI because it is much less sensitive to aerosol and soil background effects, and less subject to signal saturation (Huete et al., 2002; Xiao et al., 2003; Xiao et al., 2004a; Xiao et al., 2004b; Li et al., 2007; Viña,et al., 2011; Bajgain et al., 2015; Madugundu et al., 2017).*

EVI is calculated as follows:

$$EVI = G\frac{NIR-RED}{NIR+C1\ RED-C2\ BLUE+L}$$

where NIR is the reflectance or radiance in the near infrared channel, RED is the reflectance or radiance in the visible channl, BLUE is the blue band for atmospheric correction, and G, C1, C2, and L are fixed coefficients, which we set at values adopted by the MODIS-EVI algorithm (L = 1, C1 = 6, C2 = 7.5, G = 2.5). The inclusion of the blue band is important for a more effective atmospheric correction when studying areas where pastoral or forest fires take place during the dry season (Xiao et al., 2004a; Xiao et al., 2004b). Both NDVI and EVI have limited capability to retrieve information on vegetation water content, since vegetation greenness (chlorophyll content) is not directly and uniformly related to the quantity of water in the vegetation (Ceccato et al., 2001; Jackson et al., 2004; Gu et al., 2008). However, water content is very important for PP because it is a crucial factor for the regulation of both the rate of photosynthesis and the production and development of new leaves (Ceccato et al., 2002; Hopkins and Hunter, 2004). For this reason, we integrated the analysis of EVI by calculating the Normalized Difference Water Index (NDWI, also called Normalized Burn Ratio) (Key and Benson, 1999; Chuvieco et al., 2002), which is sensitive to changes in canopy water content (Gao, 1996). NDWI is calculated as follows (Hardisky et al., 1983; Gao, 1996):

$$NDWI = \frac{NIR - SWIR}{NIR + SWIR}$$

where SWIR is the reflectance in the shortwave infrared channel that is sensitive to the water content in the vegtation. After a fire, SWIR reflectance increases as a consequence of the reduction in leaf water content (Escuin et al., 2008). Time series of EVI and NDWI were calculated from biweekly MODIS images for the period 2001-2015, for a total of 345 MODIS images (USGS, 2017), averaging the values of all pixels included within the perimeter of the 2007 fire. " (lines 103 - 138)

- **(4) The use of English language: the language is poor with very long and circular sentences.**

The text has been revised and corrected by an English speaker to improve the use of English language.

Reviewer #2

- **The manuscript by Aretano et al is an interesting use of remote sensing data to investigate the effect of fire on wetland functioning. While the topic is interesting, there are problems with the manuscript as it is currently structured. The English is understandable, however there are many mistakes which make reading the manuscript less than enjoyable. I recommend that the authors have the revised text read and corrected by a native English speaker, preferably one who is familiar with the subject, before resubmitting it.**

The text has been revised and corrected by an English speaker to improve the use of English language.

- **2. The names of the indices must first be written in full the first time that they are mentioned in the text (line 66) as well as providing their acronyms. This is actually done later (lines 95-96). The acronyms then are just needed when there is any further mention of the indices. However, in line 103, again the full names and acronyms are given a second time.**

Yes, thanks. We have revised and corrected it. In line 104 the index Normalized Difference Vegetation Index and its acronym, in line 108 the Index Enhanced Vegetation Index and its acronym (EVI), while in line 127 the index Normalized Difference Water Index and its acronym NDWI are mentioned for the first time.

- **3. More importantly, the text is not always presented in a logical manner. For example, the information given in lines 134-146 (end of the Methods section) should be given earlier in the Methods.**

We have modified the structure of the text to make the presentation of the work more logical than in the previous one. The part of the materials and methods has been revised in many parts to meet the requirements of the reviewer 1.

Compared to the suggestion given to us, we left the indicated part (line 134-146) in the corresponding position but we have better specified the phases of the work: the first concerning the creation of the time series and the second step concerning the analysis of the time series through the decomposition in seasonality, trend and Residual.

The part that goes from line 120 to line 130 of the original manuscript has been modified and simplified in the new version from line 139 to line 142, so it has been modified from "*Other two time series were constructed using maximum daily temperature and daily precipitation data from the weather station located in a military base in Brindisi, 15 km from Torre Guaceto at the same quote. In this case, the temperature and precipitation data were aggregated to obtain the same frequency step (16 days) as the EVI and NDWI time series. In particular, for precipitation we calculated the accumulated precipitation with a 16-day step.*

Temperature analysis is fundamental because each plant species has its own relationship between chlorophyll and water content and an increase in chlorophyll content does not necessarily imply an increase in water content (Jackson et al., 2004). PP requires a good balance between the concentrations of chloroplasts and water in the leaf considering the maximum temperature during the day. Indeed, rising temperatures correspond to increased PP up to a threshold value, beyond which the PP decreases drastically (Hopkins and Hunter 2004)."

to

"*Climate series were constructed using maximum daily temperature (Tmax, years 2001-2015) and daily precipitation data (Prec, years 2008-2015) from a weather station in Brindisi, 15 km from Torre Guaceto at* *the same elevation. Biweekly series were built by averaging temperature data and cumulating precipitation over 16-day steps.”*

The part that goes from line 131 to line 133 has been eliminated because it is redundant: “*Correlation analysis was used to test if EVI and NDWI were correlated with the maximum temperature and cumulative precipitation data in order to verify the influence of weather conditions on the results*.”

The final part of the materials and methods that goes from line 145 to line 149 has been modified in the following way: from “*This was necessary to describe the time dynamics of PP before and after the fire isolating the effect of the fire on the PP. The second step was to apply cross correlation between the Remainder of EVI, NDWI, Tmax and cumulative precipitation to analyse the relationships between EVI and NDWI before and after the fire and the effect of weather conditions on the two vegetation index*.”

to

“*Finally, correlation analysis was used to assess the relationship between the residual EVI and NDWI time series, and between residual and measured climate variables before and after the fire.*”

- **4. The Discussion is very thin. In fact, most of the information given currently in the Conclusions should actually be in the Discussion. I also feel that, even after doing this, the authors could still do more with the data, in terms of what the data show and how they relate to other similar studies.**

The "results and discussion" section has been improved and reorganized in the presentation of the results. The first part of the results from line 152 to line 161 has been moved in the new version of the revised manusript between lines 189 and 196. While the part reported between lines 188 and 190 and the relative figure have been anticipated in the new manuscript and can be found between lines 170 and 174. This is to make the presentation of results more linear.

The discussion was implemented also referring to the link between the fire in the wetland and the ecosystem services that may be affected. For example from line 178 to line 186 this text was added:*The regeneration of Phragmites after the fire may have led to a synchronised increase in both photosynthetic activity and leaf water content; this may have helped to increase PP in the wetland and therefore support its ecosystem services (Costanza et al., 2007; de Groot et al., 2010; Petrosillo et al., 2013). For example, an increase in PP should results in a higher gas exchange between the canopy and the atmosphere, which increases the ability of the wetland to absorb atmospheric* CO_2*, and in more nutrients absorbed by the roots, which improves the water purification capacity of the ecosystem. Other ecosystem services that may benefit from a higher biomass production in wetlands include flood mitigation, habitat, landscape connectivity, aesthetic quality, and water supply (Mitsch and Gosselink, 2007; Petrosillo et al., 2013; Semeraro et al., 2015)*.

The final part of the discussion has been improved from line 208 to line 214: “ *If we compare this against the change in EVI and NDWI immediately following the fire disturbance in year 2007 , this appears to be the main driver for the variation in PP in the wetland ecosystem. EVI and NDWI declined with the ageing of vegetation, dropped abruptly due to the fire, but then recovered, showing a simultaneous increase in both photosynthetic activity and canopy water content. We therefore suggest that fire can pay a beneficial role for the productivity and flow of ecosystem services of Phragmites wetlands, especially if aged up, as it induced the replacement of old, dry plants by more productive saplings.* “

The conclusion has been modifed and some parts deleted because redundant.

The first part of the original manuscript was deleted because redundant and present in other parts of the revised manuscript: “*Differently from numerous studies using NDVI time series to estimate PP changes (Barbosa et al 2015), we have decided to apply a methodology that uses two time series compiled by EVI and NDWI vegetation indices. In particular, EVI was preferred to the NDVI because it is more effective in estimating PP in burnt areas. Indeed, this index was developed for areas burnt in Brazil (Xiao et al., 2004). In any case, both NDVI and EVI have limited capability for retrieving vegetation water content information,* *since provide information on vegetation greenness (chlorophyll), which is not directly and uniformly related to the quantity of water in the vegetation (Ceccato et al., 2001). However, the water content is very important for the PP because it depends on the opening of the leaves stem that regulates gaseous exchanges. For this reason, we integrated the analysis of EVI time series with NDWI time series that is a remote sensing based indicator sensitive to the change in the water content of leaves (Gao, 1996)."*

This part (from line 217 to line 225) has been added: "*The challenge for nature conservation managers is to guarantee the long-term sustainability of a protected area by preserving its ecological and cultural values against natural and human pressures so as to ensure the fruition of the ecosystem services (Daily, 2000; Palomo et al., 2013; Petrosillo et al., 2013a; Aretano et al., 2015). In this paper, we used vegetation indices derived from remote sensing as a fast and low-cost tool to achieve indirect continuous monitoring of primary productivity of a wetland ecosystem before and after a fire event. Time series analysis, which was made possible by the use of continuous monitoring by remote sensing imagery, proved useful to describe temporal trends, explore their correlations with potential driving factors (e.g., climate), and can be used to predict the future trend of the phenomenon.*"

The remaining part of the conclusion has been rewritten while still retaining the basic concepts and to make them more functional to the analysis done and to improve the English language.

- **5. The Results was not bad, but the Y-axes on several of the figures were hard to read. Please make the lettering and numbers larger (Figures 2, 4 and 5). If the authors make these changes, then the revised manuscript may be suitable for publication, following further review.**

Yes, thanks. The quality of figures has been improved to make them more easy to read.

Application of Vegetation Index time series to value fire effect on Primary Production in a Southern European rare wetland.

Abstract

Fire disturbance is an intrinsic component of the Mediterranean biome playing an important role in ecosystem dynamics and processes. However, frequent and severe wildfires can be detrimental to natural ecosystems, particularly in small natural protected areas, where they may hamper the flow of ecosystem services (ES). While post-fire dynamics of individual ES are heavily context-dependent, the primary productivity of the ecosystem can be regarded as a generic driver of several provisioning and regulating ES, as it represents the amount of energy available to plants for storage, growth, and reproduction, which drives future ecosystem structure and functions. The aim of this study is to evaluate the effect of anthropogenic wildfire on the primary productivity of a rare wetland ecosystem in the Natura 2000 site "Torre Guaceto". Productivity was estimated by calculating a 15-year time series of vegetation indices (EVI and NDWI) from remotely sensed MODIS imagery. Our results in terms of PP trends may be relevant to assess the change in ecosystems services provided by wetlands. Interactions between wildfire, ecosystem productivity and climate were then analyzed. During the selected period, climate did not play a significant effect on primary productivity, which was mainly driven by post-fire vegetation recovery. Findings of the present study demonstrate that the wildfire affecting the Natural Protected Area of Torre Guaceto in summer 2007 had a major effect on primary productivity, inducing the regeneration of *Phragmites* and the replacement of old individuals by structurally and functionally better ones.

1. Introduction

Fire disturbance is a key component of Mediterranean ecosystems, where it drives ecosystem functioning and promotes the regeneration of several species, whose resilience depends on fire-adaptive protective mechanisms as well as life-history and recovery traits (e.g. Keeley et al., 2012; Rundel et al., 2018). On the other hand, wildfires pose a significant threat to ecosystem services (ES) in the Mediterranean region (Moreira et al., 2011; Aretano et al., 2015; Corona et al., 2015; Semeraro et al., 2016). In particular, uncharacteristically frequent and severe wildfires might damage habitats of high conservation value, such as those that are partially or fully included in the European Natura 2000 network (San-Miguel-Ayanz et al. 2012, Foresta et al. 2016). Despite the efforts invested in wildfire prevention and suppression in the last decades, the negative impacts of fires on ES have considerably increased in recent decades (Moreira et al., 2011; Pausas and Fernandez Munoz, 2012; San-Miguel-Ayanz et al. 2017).

After such events, the recovery of vegetation and the need for active restoration of the ES it provides are determined by a combination of physical and climatological conditions, the spatial variability of fire severity, the pre-fire vegetation composition, and the presence or absence of exogenous disturbance factors during the recovery phase (e.g., Whelan, 1995; Lloret and Vilà, 2003). Continuous monitoring of pre- and post-fire conditions of both the vegetation and the environment is therefore necessary to assess the capacity of post-fire vegetation to sustain the flow of desired ecosystem services and the need and typology of post-fire restoration programs (Xie et al., 2008; Moreira et al., 2011; Ascoli et al. 2013; Aretano et al., 2015; Semeraro et al., 2016).

It is difficult to measure all environmental variables that control post-fire restoration and predict how locally variable ecosystem services will change after the fire event (Kremen and Ostfeld, 2005). However, it may be easier to monitor a more generic driver of ecosystem structure, functions and processes such as primary productivity (Holling, 2001; Gunderson and Holling, 2002; Aber and Melillo, 1991). The primary productivity (PP) of an ecosystem is a direct consequence of the solar energy captured by the system, representing the amount of energy available for plant storage, growth, and reproduction, and thus available to drive its structure, functioning, and generation of "provisioning" (food; fiber; raw meterials; genetic resources; water; energy), "regulation" (carbon sequestration; soil protection; water quality regulation; soil formation) and "cultural services" (recreation; tourism) (Odum, 1971; Costanza et al., 1998; Gaston, 2000; MEA, 2005; Costanza et al., 2007; Richmond et al., 2007; Wallace, 2007; de Groot et al., 2010, Petrosillo et al., 2013a).

PP is sensitive both to climatic drivers, such as temperature, precipitation and drought, which affect the gaseous exchange of the leaves, leaf water content and chloroplast functionality (e.g., Hopkins and Hunter, 2004), and to exogenous disturbances, such as fire, windstorm damage, or insect outbreaks (e.g., Zhang and Liang, 2014; Frolking et al., 2009; Gloor et al., 2009). Therefore, it is possible to study disturbance effects on ecosystem services by analyzing the change of PP before, during and after the disturbance, and highlighting the direction and degree of abrupt and slow changes. The relationship between PP and temperature is species-specific and nonlinear, as rising temperatures correspond to increased PP up to a threshold value, beyond which the productivity drastically decreases (Hopkins and Hunter, 2004). Likewise, the relationship between chloroplast activity and leaf water content is also species-specific and often nonlinear (Jackson et al., 2004).

Satellite remote sensing provides the means to detect disturbances events and PP response at local, regional and global scales (Goetz et al., 2005; Röder et al. 2008; Petrosillo et al., 2013a). Vegetation Indices are transformations of two or more spectral bands of satellite images designed to enhance vegetation properties and allow robust spatial and temporal comparison of terrestrial photosynthetic activity and canopy structural variations (Huete et al., 2002) and shifts in temporal dynamics of PP (Huete et al., 2002; Xiao et al., 2003; Xiao et al., 2004a; Xiao et al., 2004b; Jackson et al., 2004; Li, et al., 2007; Viña et al., 2011; Petrosillo et al., 2013a; Bajgain et al., 2015; Madugundu et al., 2017), especially following disturbances such as fire, drought, flood, frost, or other human-driven events (Pettorelli et al., 2005; Caccamo et al., 2014; Zurlini et al., 2014).

This study aims to analyze the seasonality, trend and abrupt changes in PP of a Nature 2000 Southern European wetland of high conservation value before and after an anthropogenic fire event, estimated by selected Vegetation Indices, and to explore possible feedbacks between productivity, wildfire and climate in the post-fire recovery phase.

2. Material and methods

2.1 Study Area

Torre Guaceto (40°43’N, 17°48’E) is a 1,100 hectares-wide natural reserve located in the Apulian Region, Southern Italy (Figure 1). The site was established in year 2000 under the Italian Law 394/1991. The main land cover types are wetlands and Mediterranean scrub. The wetland ecosystem with its 240 hectares is one of the largest in Southern Italy. As many wetlands had been reclaimed and converted into agricultural areas between the 40’s and 50’s, this site represents a relict of natural vegetation immersed in an agricultural matrix, and as such was declared Site of Community Importance (European code: IT9140005) under the EU Habitat Directive, and Important Bird Area (European code: IT9140008) under the EU Bird Directive. Most of the wetland is characterised by extensive stands of common reed (*Phragmites australis*) that cover about 60% of the entire area (Di Pietro et al., 2009). Precipitation is about 630 mm per year, with strong seasonality typical of Mediterranean-type climates, with meteorologically stable summers and unstable winters.

Despite its limited size, the site has its own management authority to take planning and management decisions (Petrosillo et al., 2010). The authority also maintains a wildfire prevention and mitigation plan; however, in August 2007 an anthropogenic fire originating in the surrounding agricultural area and driven by wind severely burned 170 ha of the wetland, putting the conservation of the wetland habitat at risk.

Please here Figure 1

2.2 Experiment design and analysis

The first step of the work was to build the time series of vegetation indices and climate data.

Numerous studies used either the Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1973) to estimate changes in PP (e.g., Barbosa et al., 2015; dos Santos et al., 2018), especially following disturbance by fire (Escuin et al., 2008). NDVI is mostly sensitive to photosynthetic activity, i.e., the amount of chloroplasts in the canopy (Xiao et al., 2004a). In this study, the Enhanced Vegetation Index (EVI) (Heute et al., 2002) was preferred to NDVI because it is much less sensitive to aerosol and soil background effects, and less subject to signal saturation (Huete et al., 2002; Xiao et al., 2003; Xiao et al., 2004a; Xiao et al., 2004b; Li et al., 2007; Viña,et al., 2011; Bajgain et al., 2015; Madugundu et al., 2017).

EVI is calculated as follows:

$$EVI = G\frac{NIR - RED}{NIR + C1\ RED - C2\ BLUE + L}$$

where NIR is the reflectance or radiance in the near infrared channel, RED is the reflectance or radiance in the visible channel, BLUE is the blue band for atmospheric correction, and G, C1, C2, and L are fixed coefficients, which we set at values adopted by the MODIS-EVI algorithm (L = 1, C1 = 6, C2 = 7.5, G = 2.5). The inclusion of the blue band is important for a more effective atmospheric correction when studying areas where pastoral or forest fires take place during the dry season (Xiao et al., 2004a; Xiao et al., 2004b). Both NDVI and EVI have limited capability to retrieve information on vegetation water content, since vegetation greenness (chlorophyll content) is not directly and uniformly related to the quantity of water in the vegetation (Ceccato et al., 2001; Jackson et al., 2004; Gu et al., 2008). However, water content is very important for PP because it is a crucial factor for the regulation of both the rate of photosynthesis and the production and development of new leaves (Ceccato et al., 2002; Hopkins and Hunter, 2004). For this reason, we integrated the analysis of EVI by calculating the Normalized Difference Water Index (NDWI, also called Normalized Burn Ratio) (Key and Benson, 1999; Chuvieco et al., 2002), which is sensitive to changes in canopy water content (Gao, 1996). NDWI is calculated as follows (Hardisky et al., 1983; Gao, 1996):

$$NDWI = \frac{NIR - SWIR}{NIR + SWIR}$$

where SWIR is the reflectance in the shortwave infrared channel that is sensitive to the water content in the vegetation. After a fire, SWIR reflectance increases as a consequence of the reduction in leaf water content (Escuin et al., 2008). Time series of EVI and NDWI were calculated from biweekly MODIS images for the period 2001-2015, for a total of 345 MODIS images (USGS, 2017), averaging the values of all pixels included within the perimeter of the 2007 fire.

Climate series were constructed using maximum daily temperature (Tmax, years 2001-2015) and daily precipitation data (Prec, years 2008-2015) from a weather station in Brindisi, 15 km from Torre Guaceto at the same elevation. Biweekly series were built by averaging temperature data and cumulating precipitation over 16-day steps.

The second step was to apply linear time series decomposition analysis to the EVI, NDWI and maximum temperature data, using the "ast" package of the R statistical framework to decompose the original time series data into three separate components (Masarotto, 2000; Jacquin et al., 2010):

- Trend, corresponding to the direction of change during the study period, i.e., the tendency to grow, decrease or remain constant;
- Seasonal, indicating the phenological cycle of the local vegetation for the study period;
- Residual, representing the random component of the system unexplained by trend and seasonal components.

The analysis was carried out by splitting EVI and NDWI time series into two parts, before (January 2001 to December 2006), and after the fire (January 2008 to December 2015). Finally, correlation analysis was used to assess the relationship between the residual EVI and NDWI time series, and between residual and measured climate variables before and after the fire.

3. Results and Discussion

The EVI and NDWI time series showed a consistent behaviour, and were successfully decomposed into a trend, seasonal and residual components (Figure 2; Figure 3).

Please here Figure 2 and Figure 3

Both indices showed a decreasing trend from 2004 to 2007, indicating a reduction in photosynthetic activity and hence a declining PP before the fire (Figure 4; Figure 5). Immediately after the fire there was an inversion of the trend of both EVI and NDWI, with an increase until 2011. This is a sign of post-fire recovery, with the substitution of older plants consumed by fire by younger tissues that produce more chlorophyll and hold more water. A fast recovery was possible because local spread of common reed occurs predominantly through vegetative growth and regeneration (Gucker and Corey, 2008; Van der Toorn and Mook, 1982; Van Rooyen et al., 2004; Thompson and Shay, 1985). Fire is in fact typically only a top-killing disturbance in common reed stands, and new sprouts may appear in as few as 5 days after fire (Ward, 1968). In particular, the average value of EVI and NDWI after the fire was higher than before the fire, which could suggest a higher chlorophyll and water content by plants during the recovery stage, possibly due to their younger age and higher resistance to high temperature stress. After year 2011 there was again a decrease of both EVI and NDWI.

Please here Figure 4 and Figure 5

The correlation between residual EVI and NDWI chronologies was positive but low before the fire of summer 2007 (Pearson's $R = 0.268$, $p > 0.05$), while it was stronger ($R = 0.417$, $p < 0.05$) after the fire. The regeneration of *Phragmites* after the fire may have led to a synchronised increase in both photosynthetic activity and leaf water content; this may have helped to increase PP in the wetland and therefore support its ecosystem services (Costanza et al., 2007; de Groot et al., 2010; Petrosillo et al., 2013a). For example, an increase in PP should result in a higher gas exchange between the canopy and the atmosphere, which increases the ability of the wetland to absorb atmospheric CO_2, and in more nutrients absorbed by the roots, which improves the water purification capacity of the ecosystem. Other ecosystem services that may benefit from a higher biomass production in wetlands include flood mitigation, habitat, landscape connectivity, aesthetic quality, and water supply (Mitsch and Gosselink, 2007; Petrosillo et al., 2013a; Semeraro et al., 2015).

Climate analysis showed that the maximum daily temperature never exceeded 35°C during the entire period of analysis (Figure 6). This is important considering that photosynthesis increases from -10°C to about 40°C and declines rapidly thereafter, reaching zero at 50°C (Hopkins and Hunter, 2004). Respiration has a much higher optimum (55°C, falling to zero at about 60°C), meaning that heat stress may determine a net reduction of primary productivity – an eventuality that has never occurred in the study area during the monitoring period. The precipitation record (Figure 7) showed evidence of periods of summer drought and rainy winters with mild temperatures, as it is typical of the Mediterranean climate.

Please here Figure 6 and Figure 7

Tmax showed a downward trend before the fire and an upward trend after the fire (Figure 8), while cumulated precipitation showed an increase from January 2008 to January 2011 and a decrease in subsequent years. Years 2011 and 2015 were the driest ones (Figure 9).

Please, here Figure 8 and Figure 9

However, the analysis of the cross correlation of the Residual of the time series shows no link between the time series of vegetation indices and time series related to climatic data (the correlation are not significant and close to zero). If we compare this against the change in EVI and NDWI immediately following the fire disturbance in year 2007, this appears to be the main driver for the variation in PP in the wetland ecosystem. EVI and NDWI declined with the ageing of vegetation, dropped abruptly due to the fire, but then recovered, showing a simultaneous increase in both photosynthetic activity and canopy water content. We therefore suggest that fire can pay a beneficial role for the productivity and flow of ecosystem services of *Phragmites* wetlands, especially if aged up, as it induced the replacement of old, dry plants by more productive saplings.

4. Conclusion

The challenge for nature conservation managers is to guarantee the long-term sustainability of a protected area by preserving its ecological and cultural values against natural and human pressures so as to ensure the fruition of the ecosystem services (Daily, 2000; Aretano et al., 2013; Palomo et al., 2013; Petrosillo et al., 2013b; Aretano et al., 2015). In this paper, we used vegetation indices derived from remote sensing as a fast and low-cost tool to achieve indirect continuous monitoring of primary productivity of a wetland ecosystem before and after a fire event. Time series analysis, which was made possible by the use of continuous monitoring by remote sensing imagery, proved useful to describe temporal trends, explore their correlations with potential driving factors (e.g., climate), and can be used to predict the future trend of the phenomenon.

Our results in terms of PP trends may be relevant to assess the change in ecosystem services provided by the wetland (Ayanu et al., 2012). Findings of the present study demonstrate that the wildfire affecting the Natural Protected Area of Torre Guaceto in summer 2007 had a major effect on primary productivity, inducing the regeneration of *Phragmites* and the replacement of old individuals by structurally and functionally better ones (see the figure in the Appendix A). The capacity of the wetland to support PP was indeed higher after the disturbance than before, especially due to an improved canopy water content (NDWI).

Indeed, fire disturbance represents an intrinsic component of several terrestrial ecosystems throughout the world, and plays an important ecological role by maintaining ecosystem dynamics and processes, biodiversity, and productivity (FAO, 2007; Rundel et al., 2018), including several protected areas and habitats in Europe. Managing fire as a regenerative component of ecosystems can help to improve the capacity of the landscape to support human life by ensuring the flow of ecosystem services (Fernandes et al. 2013). Effective ecosystem management requires an understanding of when fire should be managed as a regeneration factor, and when it must be prevented or fought in order to avoid damages to important ecosystem services.

Our results suggest that prescribed burning, i.e., the planned use of fire to achieve land management goals, could be a suitable tool to regenerate *Phragmites* wetlands and also prevent larger, uncontrolled wildfires by reducing cured fuel loads. Burning treatments should be implemented within a time window starting soon after the summer period (early October) and ending before the arrival of nesting birds in late winter (mid February). This conclusion can support the decisions of protected area managers regarding the opportunity of using prescribed burning in vegetation management, starting from Torre Guaceto (which has been so far denied by the Regional administration the authority to apply prescribed burning as a wetland management practice). In this context, the use of higher temporal- and spatial-resolution images, e.g., by using multispectral sensor mounted on Unmanned Aerial Vehicles (UAV), can help localize the points where prescribed burning should be implemented, highlighting areas dominated by dry wetland vegetation.

Finally, this study may find application also in supporting the management of constructed wetlands for water purification. Here, continuous monitoring of primary productivity, photosynthetic activity and canopy water content may inform about the best timing to apply regenerative measures (such as by prescribed burning), in order to maintain a high efficiency of these plants over time. In this case, fixed sensors and automatic calculation software could also be used to obtain fast and continuous monitoring data.

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List of Figures

Figure 1

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Figure 2

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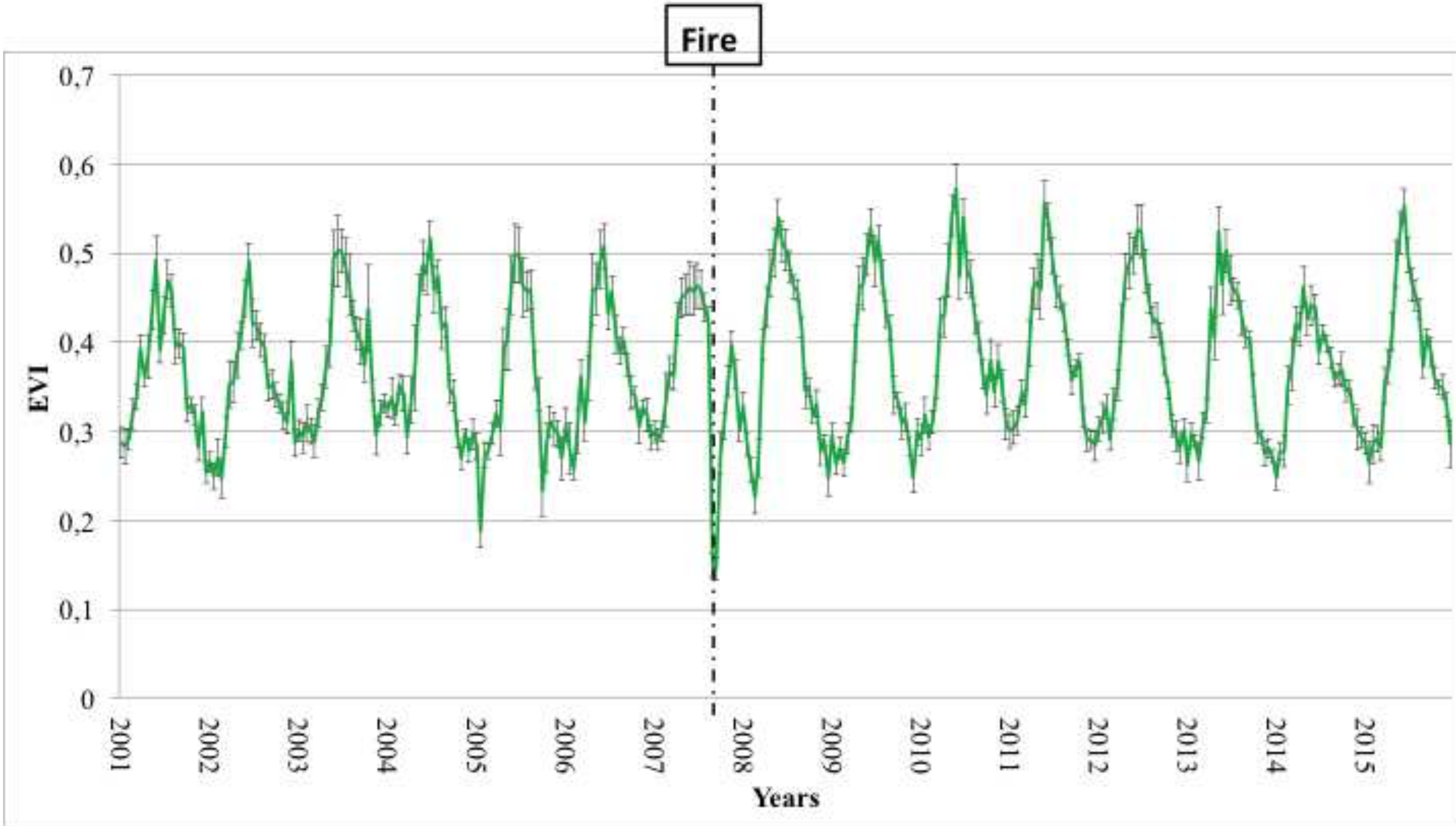

Figure 3
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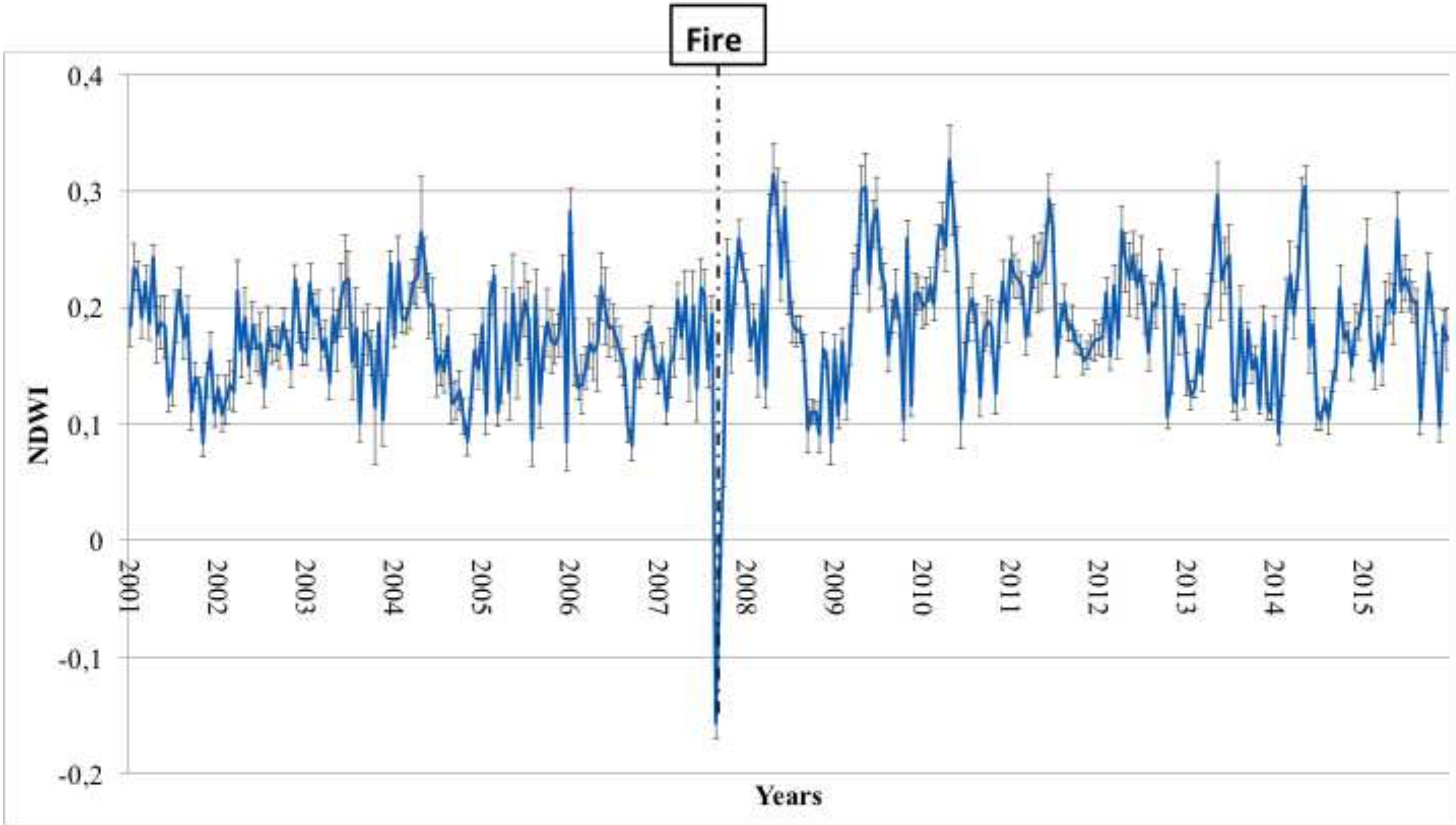

Figure 4

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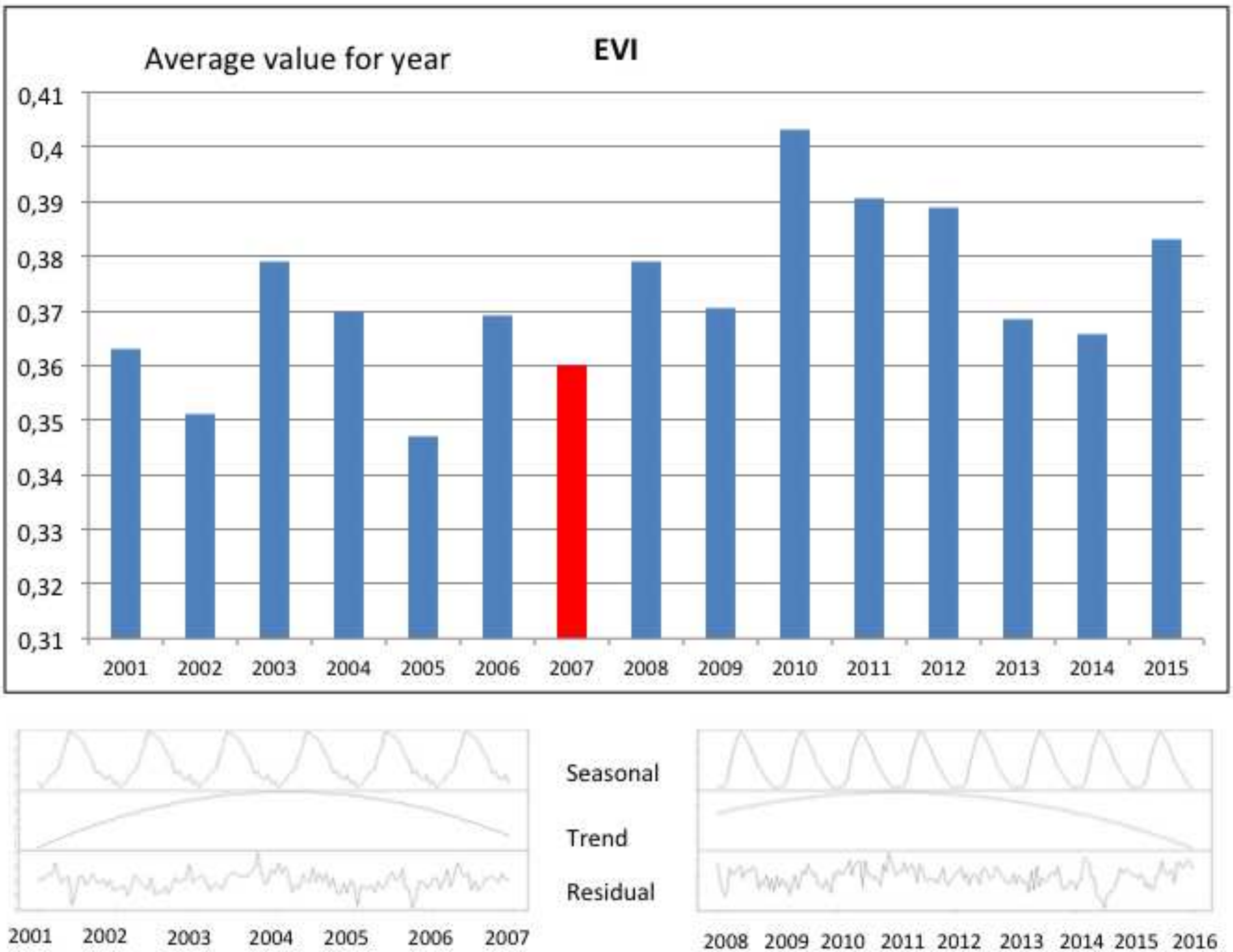

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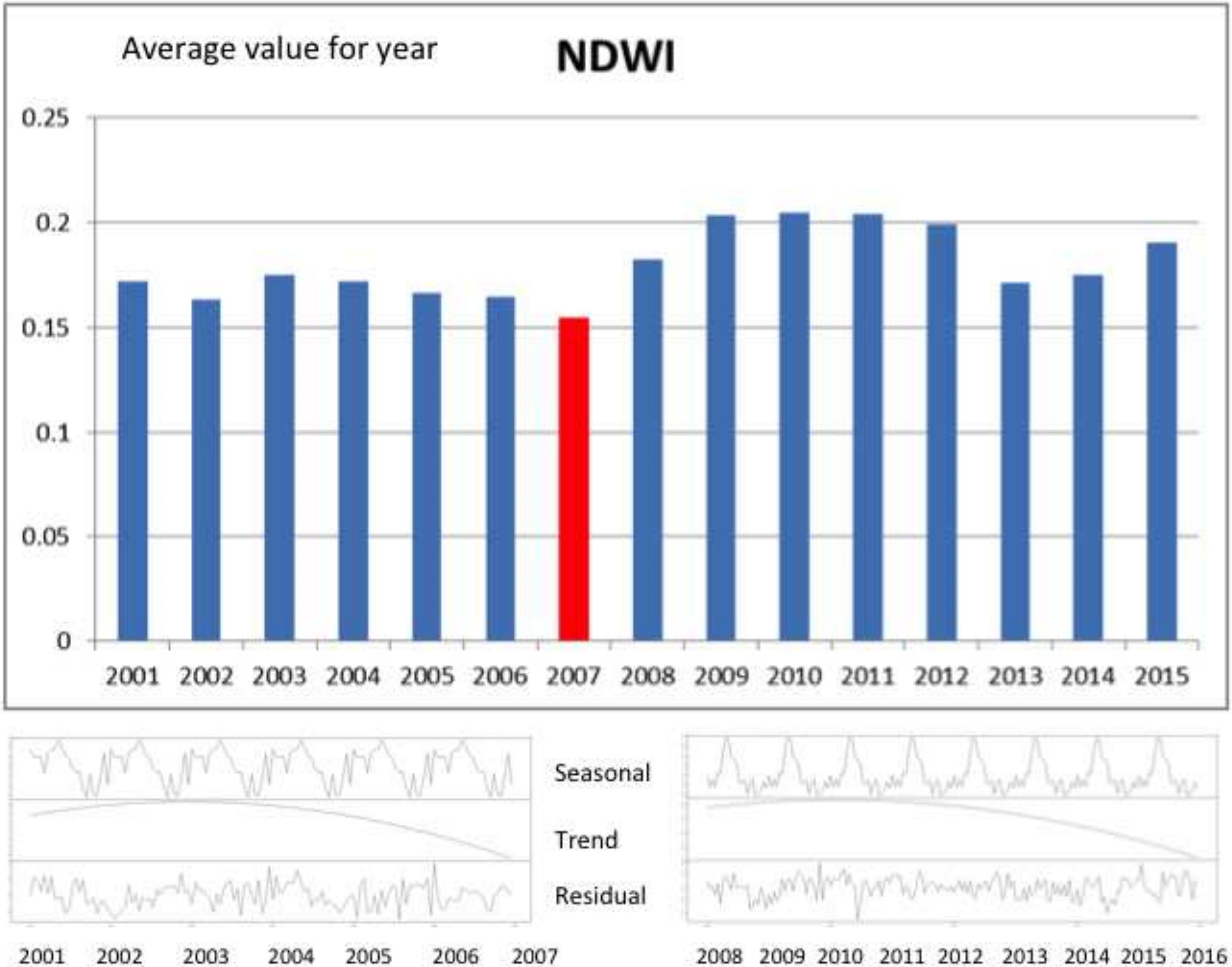

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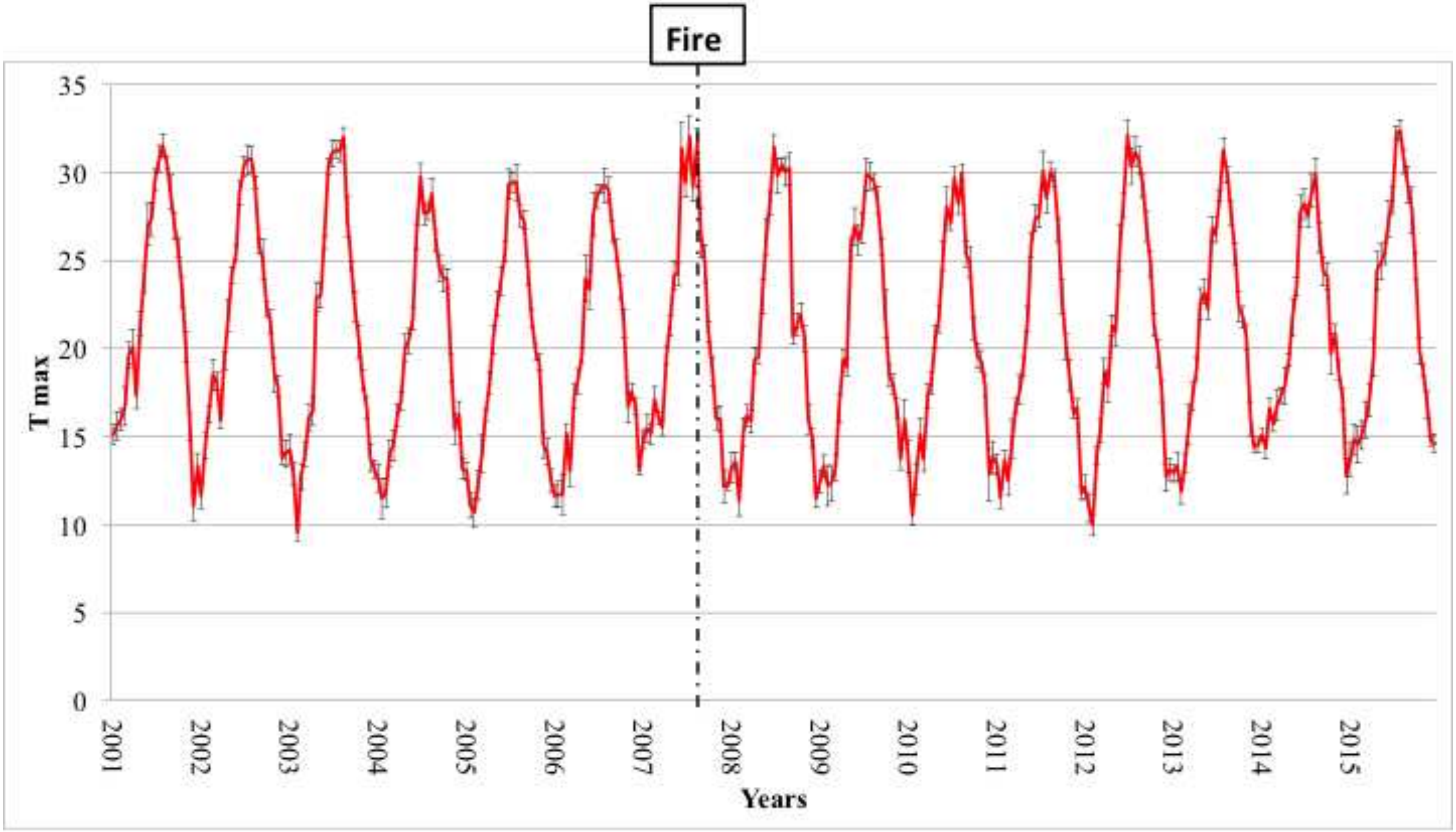

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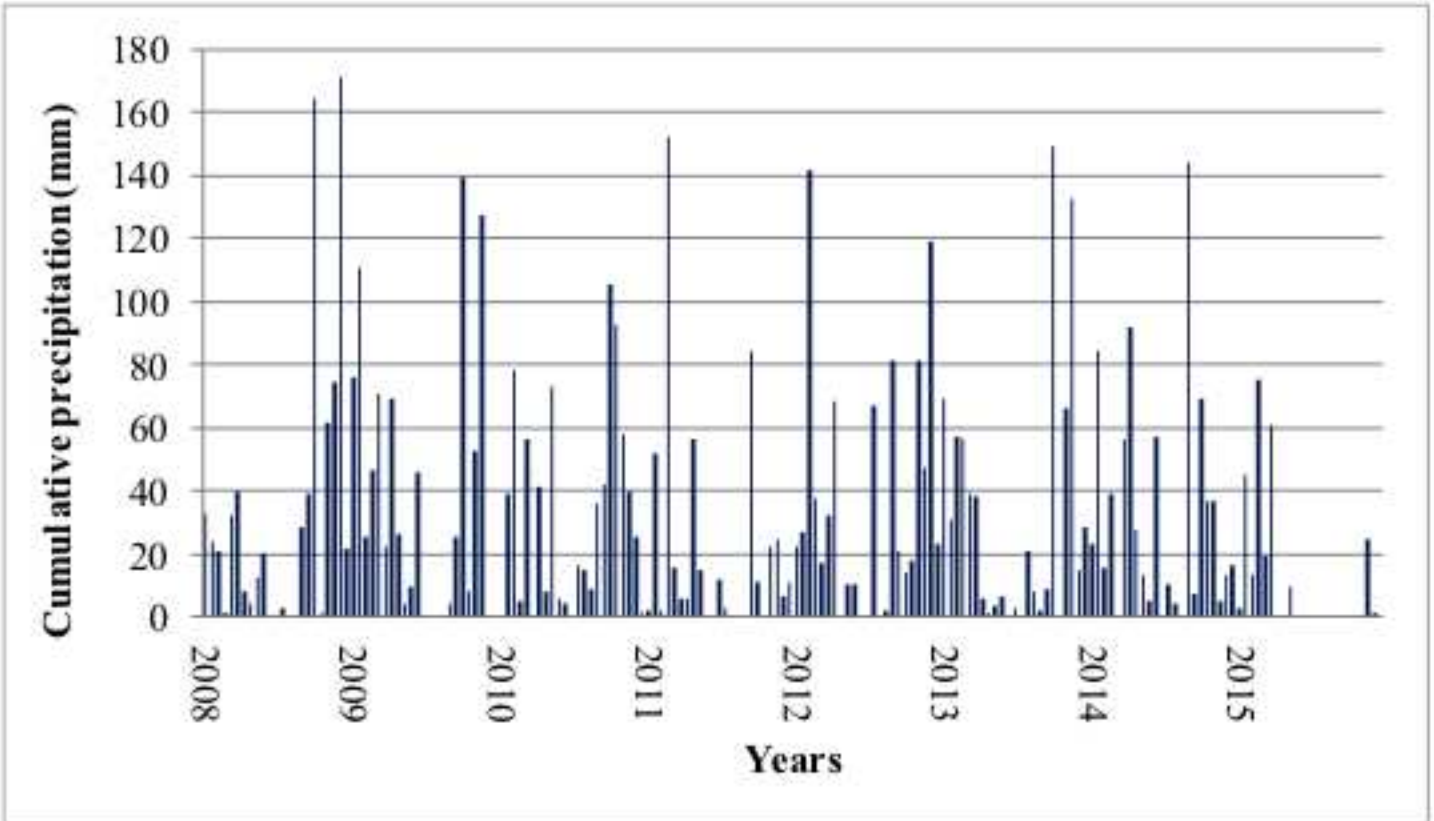

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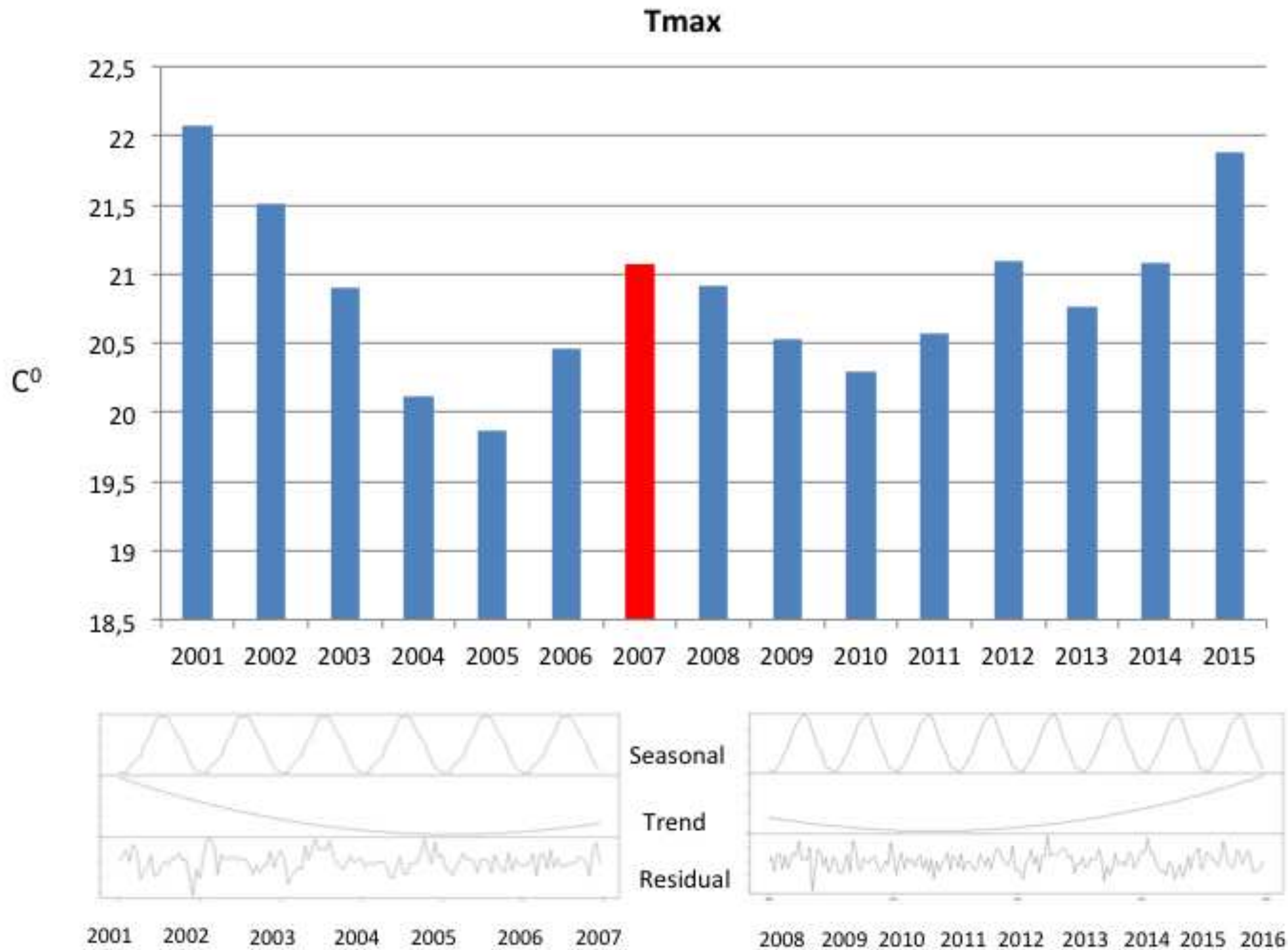

Figure 9
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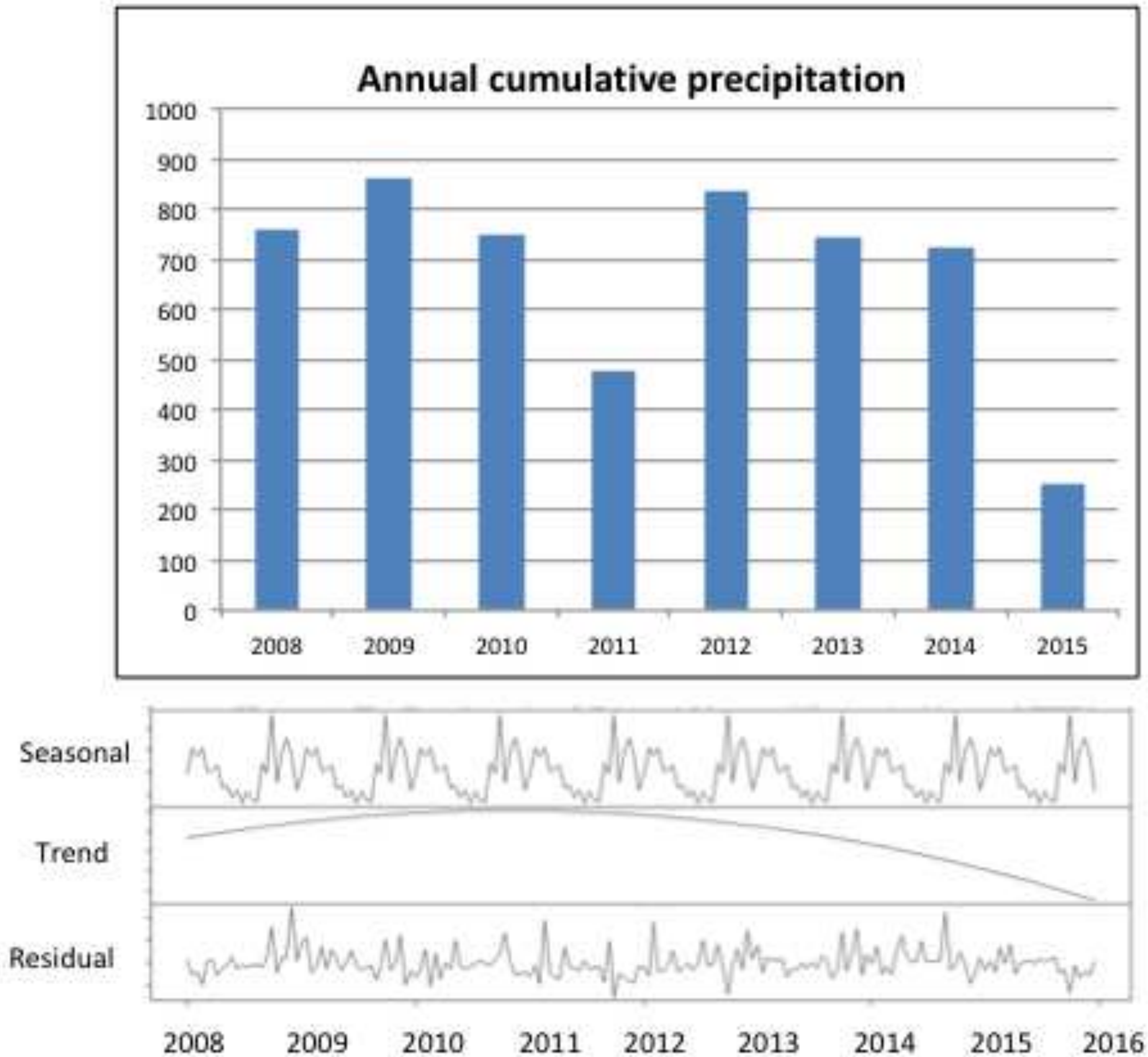

Research Highlights

- Primary production was estimated by using indices (EVI and NDWI) derived by MODIS
- We perform an ex-ante and ex-post analysis of a fire disturbance in a wetland
- EVI and NDWI time series show a similar trend before and after the fire
- After the fire EVI and NDWI are positive correlated
- There is no correlation between indices and climatic data (temperature and precipitation)

Supplementary Material
Click here to download Supplementary Material: Appendix A.docx

Abstract

Natural fire regimes are an intrinsic component of the Mediterranean ~~ecosystems~~biome, as they play an important ~~ecological~~ role in ~~maintaining~~ ecosystem dynamics and processes. However, anthropogenic uncontrolled wildfires can be detrimental to natural ecosystems, particularly in small natural protected areas ~~of the Mediterranean Basin~~, ~~and~~ where they ~~can~~ may ~~change~~ hamper the flow ~~their capacity to provide a flow~~ of ecosystem services (ES). While post-fire dynamics of individual ES are heavily context-dependent, the ~~There is still a lack of knowledge about the ecology behind the provision of ES, however, it is widely recognized that ES are underpinned by physical structures and processes called "supporting services". Since Net Primary Production~~primary productivity of ~~(NPP)~~the ecosystem can be regarded as a generic driver of several provisioning and regulating ES ~~is~~, as it represents the amount of energy available to plants for ~~for plants'~~ storage, growth, and reproduction, which drives future ecosystem structure~~,~~ . ~~it is recognized as a fundamental supporting service.~~ The aim of this study is to evaluate the effect of anthropogenic wildfire on the primary productivity ~~persistence of structures and functions that support NPP after an anthropogenic wildfire in~~of a rare wetland ecosystem in the Natura 2000 site ~~a rare wetland ecosystem of Southern Europe, in a small NATURE 2000 protected area (the Nature Reserve~~ "~~of~~ Torre Guaceto"~~)~~. Productivity was estimated by calculating a 15-year time series of vegetation indices ~~Primary production was estimated by combining remote sensing technologies with carbon cycle processing by using indices~~ (EVI and NDWI) from remotely sensed MODIS imagery Our results in terms of PP trends may be relevant to assess the change in ecosystems services provided by wetlands.. ~~derivate by MODIS satellite, like suitable surrogates for the assessment of shifts in temporal dynamics of NPP. This data allow building time series along a period covering 15 years useful to explore possible~~ Interactions~~feedbacks~~ between wildfire~~,~~ , ecosystem productivity ~~and ecosystem services~~ and climate ~~conditions~~were then analyzed. ~~In particular results show that c~~During the selected period, climate ~~limatic conditions do not seem~~

Comment [r11]: Controllare titolo articolo: occorre citare la primary productivity (e al limite i vegetation indices), ma NON gli ecosystem services, che non sono stati analizzati todid not haveplay a predominantsignificant effect on PP variation.primary productivity, which was mainly driven by post-fire vegetation recovery. Findings of the present study demonstrate that the wildfire affecting the Natural Protected Area of Torre Guaceto in summer 2007 had a major effect on primary productivity, inducing the regeneration of *Phragmites* and the replacement of old individuals by structurally and functionally better ones.

the fire instead acts by regenerating dry vegetation and increasing the level of PP over time.In particular, Tthis analysis allows us to perform an ex-ante and ex-post analysis related to fire disturbance event on the wetland ecosystem highlighting a major effect of the fire of 2007 on NPP in the wetland.

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1. Introduction

The challenge for nature conservation managers is to ensure guarantee the long-term sustainability of a protected area by preserving its ecological and cultural values against predictable and unpredictable natural and human pressures and, at the same time,so as to ensuring ensure the fruition of the ecosystem services (Daily, 2000; Palomo et al., 2013; Petrosillo et al., 2013;a; Aretano et al., 2015).

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Natural fire is a key component of Mediterranean ecosystems, where it drives ecosystem functioning and promotes the regeneration of several species, whose resilience depends on fire-adaptive protective mechanisms as well as life-history and recovery traits (e.g. Keeley et al., 2012; Rundel et al., 2018). On the other hand, aAnthropogenic wildfires regimes pose a significant threat to ecosystem services in the Mediterranean region (Moreira et al., 2011; Aretano et al., 2015; Corona et al., 2015; Semeraro et al., 2016). In particular, uncharacteristically frequent and intense severe wildfires might damage habitats of high conservation value, including such as those that are partially or fully included in the European NATURA Natura 2000 network (Birds Directive

Comment [r15]: ATTENZIONE: Questa prospettiva di natural vs. anthropogenic fire non trova consequenzialità nell'articolo. Intanto non si dice chiaramente se l'incendio del 2007 era natural o antrhopogenic; inoltre, la conclusione è che il fuoco fa bene al Phragmites, indipendentemente dalla sua origine. Forse è più coerente introdurre il discorso dicendo che il fuoco ha una doppia natura, essendo parte integrante degli ecosistemi ma anche mettendo a rischio alcuni servizi ecosistemici (indipendentemente dalla sua origine e frequenza, che non vengono esaminate in questo studio)

79/409/EEC, Habitats Directive 92/43/EECcitazioni) or in other protected areas. Despite the efforts invested in wildfire prevention and suppression in the last decades, the the general trend in the extent of burnt areasnegative wildfire impacts of anthropogenic fires haves considerably increased in Mediterranean landscapes, principally due to land use/cover and climate changesrecent decades (European Commission, 2013; Moreira et al., 2011; Pausas and Fernandez Munoz, 2012; European Commission, 2017).

After such events, the recovery of vegetation and the need for active restoration of the ecosystem services it provides Natural fire regimes in Mediterranean habitats rangelands has promoted the adaptation of vegetation whose fire resilience depends on adaptive protective mechanisms as well as life-history and recovery traits (e.g. Noble and Slatyer 1980; Quinn 1994; Foster et al., 2017; Kelley Keeley et al., 2012; Rundel et al., 2018). The manifestation of post-fire secondary succession isare determined by a combination of local physical and climatological conditions, the spatial variability in of burn fire severity, the pre-fire vegetation cover composition, and the presence or absence of exogenous disturbance factors during the phase of recovery phase (e.g., Quinn 1994; Whelan, 1995; Lloret and Vilà, 2003; Eidenshink et al. 2007; Rollins 2009). Continuous monitoring of pre- and post-fire conditions of both the vegetation and the environment is therefore necessary IHowever, it is critical to obtain current states of vegetation cover andn order to assess the capacity of thepost-fire vegetation to sustain the flow of desired ecosystem services in orderand the need to initiateand typology of vegetation protection andpost-fire restoration programs in consequences of fire disturbance it is critical to obtain current states of vegetation cover (Xie et al., 2008; Moreira et al., 2011; Aretano et al., 2015; Semerarto et al., 2016). Iit is difficult to assess measure -all single environmental variables that control post--fire restoration, and predict how locally variable ecosystem services will change after the fire event (Kremen and Ostfeld, 2005). However, but it ismay be easier to monitor a possible act on somemore generic driver of ecosystem structure, functions and processes such as primary productivity key control function or processes that are representative of evolution of system. The complexity state of the

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https://core.ac.uk/download/pdf/38627732.pdf

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Comment [r19]: Ho tolto il riferimento ai "supporting services" perché nelle più recenti classificazioni di ES sono stati rimossi nature emerges from a smaller number of key-controlling processes (Holling, 2001; Gunderson and Holling, 2002). and much of the fundamental information of the system can often be captured and described by single key variables (Holling 2001). The pFor example, it is difficult to evaluate all single ecosystem services that an ecosystem produces and how they change after the fire event (Kremen and Ostfeld, 2005). But, rimary productivity (PP) of an ecosystem is a direct consequence of thePP is supporting service that measure of the solar energy captured by the system, representing the amount of energy available for plant storage, growth, and reproduction, and thus available to drive its structure, functioning, and generation of ing and others ecosystem services: "provisioning" services" (fFood; fiber; ecological stocks;raw meterials; genetic resources; biological chemicals; fesh water-; energysupply),; "rRegulation services" (cCarbon sequestration; soil erosion protection; water quality regulation; soil formation) and "cultural services" (rRecreation; tourism and ecoturism) .Therefore, PP is a key-control function of overall ecosystem functioning, corresponding to the amount of energy available for plant storage, growth, and reproduction (MEA, 2005), and providing the energy flow that maintains the secondary production. In an ecological system, we can consider PP like a supporting service able to guarantee ecosystem services flow. (Odum, 1971; Costanza et al., 1998; Gaston, 2000; MEA, 2005; Costanza et al., 2007; Richmond et al., 2007; Odum, 1971; Gaston, 2000; Costanza et al., 1998, 2007; Wallace, 2007; Richmond et al., 2007; de Groot et al., 2010, Petrosillo et al., 2013).

In the context of ecosystem services, Primary Productivity (PP) can be used as a surrogate to describe parts of the whole complexity that characterizes ecosystem services (Petrosillo et al., 2013; MEA, 2005).in addition to being linked to functional aspects of vegetation, the PP is also linked to structural aspects of vegetation because it depends on the canopy of the plants. The higher is the canopy of the vegetation, higher is the level of PP and therefore the energy available for the system. Canopy structural parameter of vegetation fundamental importance for quality and quantitative studies of physiological processes related to global carbon cycle and nutrient: transpiration, photosynthesis, autotrophic respiration (Chen et al., 2002; Dusseux et al., 2014; Cowling & Fild,

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Aber, J.D., and Melillo, J.M. 1991. Terrestrial ecosystems. Saunders College Publishers, Philadelphia.

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2003; Viña et al., 2011). The canopy is an important parameter used to monitoring: vegetation growth, vegetation disease, vegetation yield estimation and forecasting, vegetation stress, and also in deciding on suitable management practices (Liu et al., 2012; Xie et al., 2016).

the PP is sensitive both to climatic drivers, such asalso correlated at the environmental variables like temperature, and precipitation and drought, which affect . strong dry seasons can produce negative effect on the gaseous exchange of the leaves, leaf water content and and chlorophyllchloroplast functionality. These reduce the capacity of the system to act photosynthesis process fundamental for PP (e.g., Hopkins and Hunter, 2004), and to exogenous disturbances, such as fire, windstorm damage, or insect outbreaks (e.g., citazioni). Therefore, it is possible

PP is a measure of the solar energy captured by the system and thus available to drive its functioning. It is therefore a key indicator of overall ecosystem functioning, corresponding to the amount of energy available for plant storage, growth, and reproduction (MEA, 2005), and providing the energy flow that maintains the secondary production (; Odum, 1971; Gaston, 2000; Costanza et al., 1998, 2007; Richmond et al., 2007; de Groot et al., 2010, Petrosillo et al., 2013).

Therefore, Primary Productivity (PP) can be used as a surrogate to describe parts of the whole complexity that characterizes ecosystem services and the evolution of the system (Costanza et al., 2007; De Groot et al., 2010; Petrosillo et al., 2013; MEA, 2005).

In this context, it is useful to study of the perturbation or disturbance fire effects on ecosystem services by analyzing the change of using retrospective analyses of PP before, during and after the disturbance, and highlighting the that links the present day system status with its past dynamics. Retrospective analyses is and enablesuseful in the identification of possible evolutionary trajectories to reveal continuity, turnover, direction ands, or degree of abrupt and slow changes. The relationship between PP and temperature is species-specific and nonlinear, as rising temperatures correspond to increased PP up to a threshold value, beyond which the productivity drastically decreases (Hopkins and Hunter, 2004). Likewise, the relationship between chloroplast activity and leaf water content is also species-specific and often nonlinear (Jackson et al., 2004).

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Frolking, S., Palace, M. W., Clark, D. B., Chambers, J. Q., Shugart, H. H., & Hurtt, G. C. (2009). Forest disturbance and recovery: A general review in the context of spaceborne remote sensing of impacts on aboveground biomass and canopy structure. Journal of Geophysical Research: Biogeosciences, 114(G2).

Gloor E., Phillips O.L., Lloyd J., Lewis S.L., Malhi Y., Baker T.R., Lopez-Gonzalez G., Peacock J., Almeida S., Alves de Oliveira A.C., Alvarez E., Amaral I., Arroyo L., Aymard G., Banki O., Blanc L., Bonal D., Brando P., Chao K.J., Chave J., Davila N., Erwin T., Silva J., Di Fiore A., Feldpausch T.R., Freitas A., Herrera R., Higuchi N., Honorio E., Jimenez E., Killeen T.J., Laurance W.F., Mendoza C., Monteagudo A., Andrade A., Neill D., Nepstad D., Nuñez Vargas P., Peñuela M.C., Peña Cruz A., Prieto A., Pitman N.C.A., Quesada C.A., Salomão R., Silveira M., Schwarz M., Stropp J., Ramirez F., Ramirez H., Rudas A., Ter Steege H., Silva N., Torres A., Terborgh J., Vasquez R., Van Der Heijden G.. 2009. Does the disturbance hypothesis explain the biomass increase in basin-wide Amazon forest plot data? Global Change Biology, 15 (10) : p. 2418-2430.

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Satellite remote sensing provides the means to detect ~~the past land use dynamic and~~ disturbances events and PP response at local, regional and global scales (Verstate, 1996; Goetz et al., 2005; Röder et al. 2008; Petrosillo et al., 2013; Petrosillo et al., 2013). Vegetation Indices~~ex,~~ are transformations of two or more spectral bands of satellite images designed to enhance vegetation properties and allow robust spatial and temporal comparison of terrestrial photosynthetic activity and canopy structural variations (Huete et al., 2002) and shifts in temporal dynamics of PP (Huete et al., 2002; Xiao et al., 2003; Xiao et al., 2004a; Xiao et al., 2004b; Jackson et al., 2004; Li, et al., 2007; Viña et al., 2011; Petrosillo et al., 2013; Bajgain et al., 2015; Madugundu et al., 2017), especially following ~~derivate by satellites, is recognized as a spatially explicit robust indicator to gauge impact of~~ disturbances such as fire, drought, flood, frost, or other human-driven ~~disturbances~~ events (Pettorelli et al., 2005; Caccamo et al., 2014; Zurlini et al., 2014~~; Pettorelli et al., 2005~~).

~~These indices are spectral transformations of two or more bands of satellite images designed to enhance vegetation properties and allow reliable spatial and temporal comparison of terrestrial photosynthetic activity and canopy structural variations (Huete et al., 2002).~~

~~Some Vegetation indices are suitable surrogates for the assessment of shifts in temporal dynamics of PP (Huete et al., 2002; Xiao et al., 2003; Xiao et al., 2004a; Xiao et al., 2004b; Jackson et al., 2004; Li, et al., 2007; Bajgain et al., 2015; Madugundu et al., 2017; Viña,et al., 2011; A.V. Petrosillo et al., 2013;).~~

~~The aim of this study is to understand the changes in PP of the vegetation in a small natural protected area in Southern Europe after a large fire in summer 2007 covering nearly the 15% of the Nature reserve by combining remote sensing technologies with carbon cycle processing with reference to vegetation indices.~~

~~The aim of t~~This study ~~is the ability~~aims to ~~provide~~analyze the seasonality, trend and abrupt changes in PP– of a Southern European wetland before and after an anthropogenic fire event, estimated by selected Vegetation Indices, and to explore ~~trends analysis of Vegetation Indices linked with PP function allowing detection of both abrupt and slow changes over time exploring~~

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possible feedbacks ofbetween productivity, wildfire and climate conditionsin the on fire post-fire restorationrecovery phase. of ecosystem services flow (Figure 1). In particular, this study does not focus on timely variations in time, but on the analysis of both the seasonality and the trend of vegetation indices like surrogate of PP, to detect abrupt changes due to accidental or unforeseeable events and slower variations due to natural changes such as effects due to climate changes.

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Please here Figure 1

We have considered PP as a supporting service able to guarantee ecosystem services flow. In dealing with this issue, this paper aims to use EVI integrated with NDWI derivate by MODIS satellite, like suitable surrogates for the assessment of shifts in temporal dynamics of PP, useful to explore possible feedbacks between wildfire and ecosystem services. In particular, since the fire affected the wetland of a natural protected area, our aim is to analyse the ecological function of this ecosystem after the fire and therefore the ability of the wetland to provide ecosystem services.

2. Material and methods

2.1 Study Area

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The Natural Protected Area (NPA) of “Torre Guaceto” (40°43’N, 17°48’E) (Apulian Region, southern Southern Italy) (Figure 1) is a 1,100 hectares-wide small naturale reserve of 1,100 ha located in the Apulian Region, Southern Italy (Figure 12)Southern Italy. The site that was established in year 2000 under the Italian Law 394/1991. The main land cover types are Inside the NPA there are Wwetlands and mMediterranean maquis scrub. The wetland ecosystem with its that represent the main land-cover types. Actually, the wetland ecosystem of Torre Guaceto, with 240 hectaresa of extension is one of the most representativeslargest in Southern Italy. As many wetlands ; indeed, the Southern wetlands havehad been reclaimed and converted into agricultural areas between the 40's and 50's~~. Therefore~~, ~~it~~ this site represents a relict of ~~historical~~ natural vegetation immersed in an agricultural matrix, and as such was ~~. It was~~ declared Site of Community Importance (European code: IT9140005) under the EU Habitat Directive, and ~~an~~ Important Bird Area (European code: IT9140008) under the EU Bird Directive. Most of the wetland is characterised by extensive stands of common reed (*Phragmites australis*) that cover about 60% of the entire area (citazione). Precipitation is about 630 mm per year, with strong seasonality typical of Mediterranean-type climates, with meteorologically stable summers and unstable winters.

Despite its limited size, the site has its own ~~the nature reserve stretches for only 1,100 ha, Torre Guaceto represents an administrative unit where the~~ management authority ~~constantly~~ to takes planning and management decisions (Petrosillo et al., 2010). The ~~management~~ authority ~~systematically~~ also maintains a ~~develops a plan to prevent~~ wildfire prevention and mitigation plan; however,~~s and mitigate their negative effects on ecosystem services. However,~~ in August 2007 ~~the wetland was completely burned by~~ a fire ~~originated~~ originating~~by an arson~~ in the surrounding agricultural area and driven by wind~~. This fire was pushed expanded in the wetland driven by the wind and~~ severely ~~destroyed burned~~burned ~~about~~ 170 ha of the wetland, putting the conservation of the wetland habitat at risk.

Please here Figure ~~2~~1

2.2 Experiment design and analysis

~~In this study we applied linear techniques to time series data in order to analyse the persistence or alteration of the PP of the wetland as a result of fire disturbance. PP depends on the concentration of chloroplasts active in photosynthesis, the concentration of water in the leaf tissues and the weather. Consequently, high PP levels depend on high chloroplasts and water concentration. t~~~~The first step was to build time series of vegetation indices representative of the dynamics of the PP.~~

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Numerous studies usingused either the Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1973) time series to estimate PP changes in PP (e.g., Barbosa et al., 2015) or Some papers (; dos Santos et al., 2018), especially following disturbance by fire (Escuin et al., 2008). NDVI is mostly sensitive to photosynthetic activity, i.e., the amount of chloroplasts in the canopy (Xiao et al., 2004a). reports that the Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1973) and the Normalized Burn Ratio (NBR) (Key and Benson, 1999; Chuvieco et al., 2002) are the commonly used index in the detection of burned areas (Escuin et al., 2008).

In this specific study, we have decided to apply a methodology that uses two time series compiled by EVI and NDWI, or in an papers calledcommonly named Normalized Burn Ratio (NBR) vegetation indicesex (dos Santos et al., 2018REF). In particular, , the Enhanced Vegetation Index (EVI) (Heute et al., 2002) EVI was preferred to the NDVI because it is more effective in estimating PP in burnt areas. Indeed, this index was developed for areas burnt in Brazil and it is much less sensitive to aerosol and soil background effects, and less subject to signal saturation phenomena than NDVI with large amounts of chlorophyll. in addition, EVI is less affected by the background effect of the soil (Huete et al., 2002; Xiao et al., 2003; Xiao et al., 2004a; Xiao et al., 2004b; Li, et al., 2007; Viña,et al., 2011; Bajgain et al., 2015; Madugundu et al., 2017; Viña,et al., 2011; A.V.).).

We therefore made reference to the Enhanced Vegetation Index (EVI) in combination with the Normalized Difference Water Index (NDWI). These indices are spectral transformations of two or more bands of satellite images designed to enhance vegetation properties and allow reliable spatial and temporal comparison of terrestrial photosynthetic activity and canopy structural variations (Huete et al., 2002).

EVI was used to determine the status of green vegetation, linked mainly to the presence of chloroplasts in the canopy (Xiao et al., 2004), while NDWI was used to determine the presence of water in the canopy (Jackson et al., 2004; Gu et al., 2008). Therefore, two time series were created using the Enhanced Vegetation Index (EVI) and the Normalized Difference Water Index (NDWI), extracted from MODIS imagery from 2001 to 2015, which consisted of 345 MODIS images

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(USGS, 2017). Specifically, we constructed the average EVI and NDWI profiles considering the pixels of burned vegetation in the wetland in 2007.

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EVI is calculated as follows:

$$EVI = G \frac{NIR - RED}{NIR + C1\,RED - C2\,BLUE + L}$$

$$EVI = G * \frac{(NIR - RED)}{(NIR + C1 * RED - C2 * BLUE + L)}$$

(1)

where NIR is the reflectance or radiance in the near infrared channel, RED is the reflectance or radiance in the visible channel, and BLUE is the blue band for atmospheric correction, and G, C1, C2, and L are fixed coefficients, which we set at values . The coefficients adopted in by the MODIS-EVI algorithm are;(L = 1, C1 = 6, C2 = 7.5, and G (gain factor)G = 2.5). The inclusion of the blue band for atmospheric correction is important for a more effective atmospheric correction when studying areas where pastoral or forest fires burning of pasture and forest takes place throughout during the dry season, either for agricultural purposes or as a result of natural fire events (Xiao et al., 2004a; Xiao et al., 2004bXiao et al., 2004).

In any case, bBoth NDVI and EVI have limited capability forto retrieve information oning vegetation water content information, since provide information on vegetation greenness (chlorophyll content), which is not directly and uniformly related to the quantity of water in the vegetation (Ceccato et al., 2001; Jackson et al., 2004; Gu et al., 2008). However, the water content is very important for PPthe PP because it depends on the opening of the leaves stem that regulates gaseous exchanges. Therefore, it is a crucial factor for the regulation of both the rate of photosynthesis and the speed of production and development of new leaves (Ceccato et al., 2002; Hopkinns and Hunter, 2004). For this reason, we integrated the analysis of EVI by calculating the Normalized Difference Water Index (NDWI, also called Normalized Burn Ratio) (Key and Benson, 1999; Chuvieco et al., 2002), which is time series with NDWI time series that is a remote sensing based indicator sensitive to the changechanges in thecanopy water content of leaves (Gao, 1996).

NDWI is a remote sensing-based indicator sensitive to changes in the water content of leaves (Gao, 1996) and is calculated as follows (Hardisky et al., 1983; Gao, 1996):

$$NDWI = \frac{NIR - SWIR}{NIR + SWIR}$$

$$NDWI = \frac{NIR - SWIR}{NIR + SWIR} \qquad (2)$$

where SWIR is the reflectance or radiance in the short-wave infrared channel that is sensitive to the water content in the vegetation. After a fire, (http://edo.jrc.ec.europa.eu/documents/factsheets/factsheet_ndwi.pdf).

NDWI index is also called Normalized Burn Ratio (NBR) and is commonly used for mapping burned areas (Escuin et al., 2008; dos Santos et al., 2018) because with the passage of fire the SWIR spectrum reflectance increases likeas a consequence of the reduction in leaf water content reduction (Escuin et al., 2008).

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To summarize , EVI was used to determine the status of green vegetation, linked mainly to the presence of chloroplasts in the canopy (Xiao et al., 2004), while NDWI was used to determine the presence of water in the canopy (Jackson et al., 2004; Gu et al., 2008). Therefore, tTimewo time series of were created using the Enhanced Vegetation Index (EVI) and the Normalized Difference Water Index (EVI and NDWI were calculated from biweekly NDWI), extracted from MODIS imagesry fromfor the period 2001- to 2015, whichfor a total consisted of 345 MODIS images (USGS, 2017), averaging the values of all pixels included within the perimeter of the 2007 fire. . Specifically, we constructed the average EVI and NDWI profiles considering the pixels of burned vegetation in the wetland in 2007.

Climate series ~~Other two time series~~ were constructed using maximum daily temperature (Tmax, years 2001-2015) and daily precipitation data (Prec, years 2008-2015) from ~~the~~ a weather station ~~located in a military base~~ in Brindisi, 15 km from Torre Guaceto at the same ~~quote~~elevation. Biweekly series were built by averaging temperature data and cumulating precipitation over 16-day steps.

~~In this case, the temperature and precipitation data were aggregated to obtain the same frequency step (16 days) as the EVI and NDWI time series. In particular, for precipitation we calculated the accumulated precipitation with a 16-day step.~~

~~Temperature analysis is fundamental because each plant species has its own relationship between chlorophyll and water content ad an increase in chlorophyll content does not necessarily imply an increase in water content (Jackson et al., 2004). PP requires a good balance between the concentrations of chloroplasts and water in the leaf considering the maximum temperature during the day. Indeed, rising temperatures correspond to increased PP up to a threshold value, beyond which the PP decreases drastically (Hopkins and Hunter 2004).~~

~~Correlation analysis was used to test if EVI and NDWI were correlated with the maximum temperature and cumulative precipitation data in order to verify the influence of weather conditions on the results.~~

Comment [T22]: Spostato sotto

The ~~first~~ second step was to apply linear time series decomposition analysis to the EVI, NDWI and maximum temperature data ~~(from January 2001 to December 2015)~~, using the ~~R software~~ “ast” package of the R statistical framework to decompose the original time series data into three separate components (Masarotto, 2000; Jacquin et al., 2010):

- Trend, corresponding to the direction of change during the study period, i.e., ~~;~~ the tendency to grow, decrease or remain constant;
- Seasonal, indicating the phenologicaly cycle of the local vegetation for the study period;
- ~~Remainder~~Residual, representing the error un~~eerratic nature of the phenomenon. It represents what is not e~~xplained by trend and seasonal components.

The analysis was carried out by splitting EVI and NDWI the time series into two parts,: before the wetland fire(, from January 2001 to December 2006), and after the wetland fire (, from January 2008 to December 2015). This was necessary to describe the time dynamics of PP before and after the fire isolating the effect of the fire on the PP.

In the third stepFinally, Ccorrelation analysis was used to assess the relationship between the residual test if EVI and and NDWI time series, were correlated withand between the trend+seasonal components and measured climate variables the maximum temperature and cumulative precipitation data in order to verify the influence of weather conditions on the results. The second third step was to apply cross correlation between the Remainder of EVI, NDWI, Tmax and cumulative precipitation to analyse the relationships between EVI and NDWI before and after the fire and the effect of weather conditions on the two vegetation index. Effect size of Tmax and Prec on ECI and NDWI was assessed by the slope of a linear ordinary least squares regression.

3. Results and Discussion

In the study area, the maximum daily temperature (Tmax) never exceeds exceeded 35°C (Figure 2) during the period of analysis (YYYY-YYYY). This is important considering that Gross Primary Production (GPP) increases from -10°C to about 40°C and declines rapidly thereafter to zero at 50°C (Hopkins and Hunter 2004). Net Primary Production (NPP) and Respiration (R) show a similar pattern but the optimum for NPP is about 35-36°C, falling to zero at 50°C, while for R the optimum is about 55°C, falling to zero at about 60°C. Therefore, the wetland vegetation in our study area does not appear to suffer from poor conditions in terms of temperature. Figure 3 shows the cumulative precipitation with a frequency of 16 days. Unfortunately, according to the availability of precipitation data, it has been possible to build the time series only from 2008 to

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Comment [r123]: Secondo me la correlazione con il clima va fatta con queste componenti, e non con il residuo, perché credo che il clima sia il principale driver del trend e della stagionalità di PP (come si spiegherebbe altrimenti?).

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Comment [r124]: E' possibili effettuar[e] questa analisi per confrontare l'effect size con la variazione di EVI e NDWI causata dall'incendio (che mi aspetto essere dominante)?

Comment [R25]: Penso che temperature e precipitazioni non debban[o] essere inserite fra i risultati ma in appendice in quanto non son dei risultati ma dei dati che vengono usati per le analis[i] e per varie considerazioni

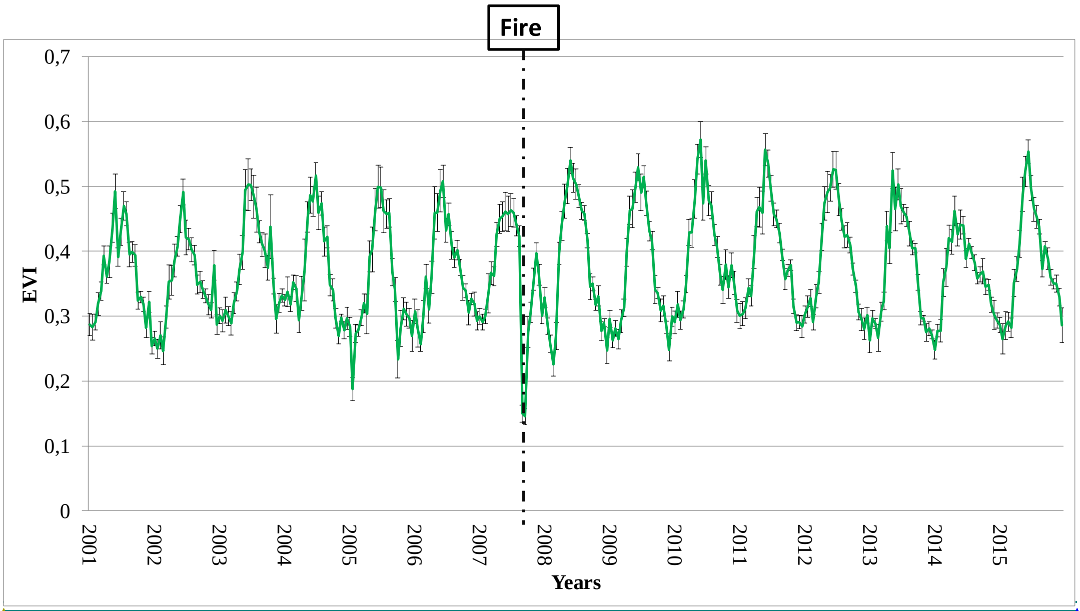
Comment [R26]: Indicare la serie temporale

Comment [T27]: La serie storica è stat[a] costruita da noi qundi secondo me è un risultato. Comunque spostato tutto sotto

2015. It can be noticed that climatic conditions are characterized by a long period of summer drought and rainy winters with mild temperatures, typical of the Mediterranean climate.

Please here Figure 2 and Figure 3

The EVI and NDWI time series showed a consistent behaviour, and were successfully decomposed into a trend seasonal components The EVI and NDWI time series of the wetland are characterised by both low frequency lined with daily conditions, and high frequency linked with seasonal conditionsperiodic and chaotic components, both before and after the fire (Figure 234; Figure 345).



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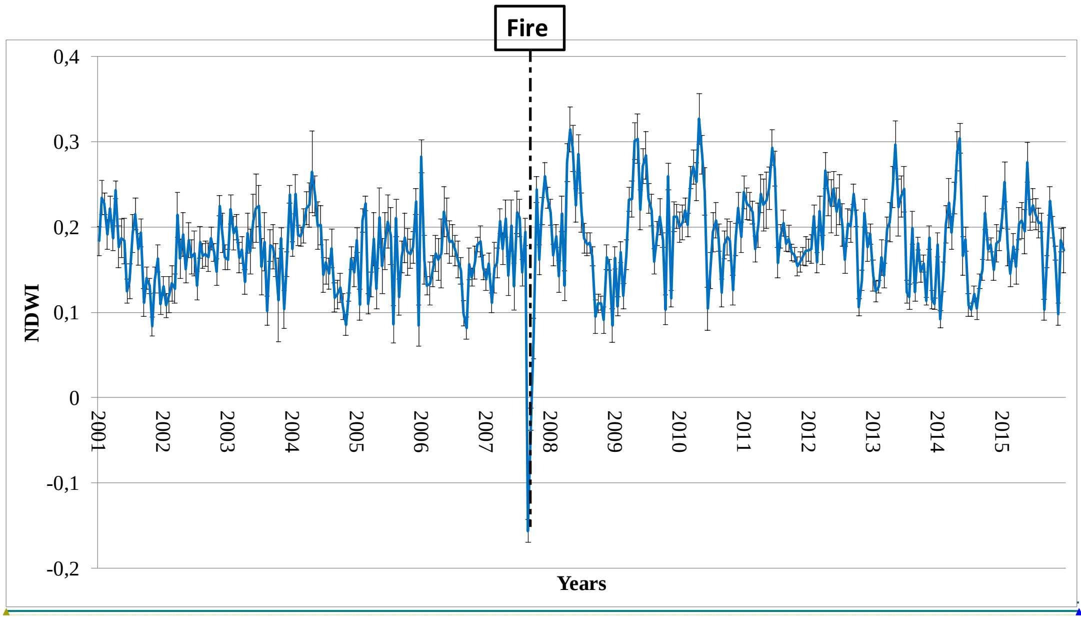

Please here Figure 234 and Figure 345

We split the time series into two parts, excluding the year of the fire (2007), . This was expected to assist into better understanding the different behaviour of EVI and NDWI before and after the fire. EVI and NDWI time series showed a similar trend before and after the fire. In particular, bBoth time seriesindices showed a decreasing trend from 2004 to 2007, indicating that before the fire there was a reduction in photosynthetic activity and hence a declining PP before the fire (Figure 456; Figure 567). Immediately after the fire there were was an inversion of the trend of both EVI and NDWI, with an increase until 2011. This could isbe a sign of post-fire recoveryn effect of the regeneration of the wetland plants after the fire, with the substitution of older or burned plant parts with by younger tissues that produce more chlorophyll and hold more water content. A fast recovery was possible because local spread of common reed occure predominantly through vegetative growth and regeneration (citazione). Fire is in fact typically only a top-killing disturbance in common reed stands, and new sprouts may appear in as few as 5 days after fire

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Comment [r128]: Gucker, Corey L. 2008. Phragmites australis. In: Fire Effects Information System, [Online]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). Available: https://www.fs.fed.us /database/feis/plants/graminoid/phraus/all.h tml [2018, August 4].

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(citazione). In particular, the average value of NDWI after the fire was higher than before the fire, which could suggest a higher water content by plants during the recovery stage, possibly due to their younger age and higher resistance to high temperature stress. ~~However, a~~After ~~the~~ year 2011 there was again a decrease of ~~the trend for~~ both EVI and NDWI.

~~In particular the average value of NDWI after the fire seems higher than the one before the fire and this could suggest higher water content in the plants. Presumably, the young plants have greater vigour after the fire and are more able to withstand high temperatures.~~

Please here Figure 4~~5~~ and Figure 5~~6~~

~~Analysing the cross correlation between the Remainder, it was found that t~~The correlation between residual EVI and NDWI chronologies was positive but low ~~here was no strong correlation between EVI and NDWI~~ before the fire of summer 2007 (~~correlation~~ Pearson's R = 0.268, p >0.05), while it was stronger (R = 0.417, p <0.05) ~~, this could suggest that there was not a good condition for PP and also for ecosystems services flow because there were low concentrations of chloroplasts active in photosynthesis. After the fire, there was a high significant positive correlation between EVI and NDWI (correlation = 0.417).~~ after the fire. The regeneration of ~~*the wetland*~~*Phragmites* ~~plants~~ after the fire may have led to ~~major~~ a synchronised increase in both~~ation of chlorophyll~~ photosynthetic activity and leaf water content; ~~. T~~this may have helped to increase PP in the wetland and ~~so~~ therefore support its ecosystem services (Costanza et al., 2007; ~~Petrosillo et al., 2013;~~ de Groot et al., 2010; Petrosillo et al., 2013~~MEA, 2005~~).

For example, ~~Indeed, A~~an increase in PP ~~certainly~~should ~~corresponds~~results in ~~to~~ a ~~greater~~higher ~~gaseous~~gas exchange between the ~~substrate~~canopy and the atmosphere, which ~~. This~~ increases the ~~produces an increase in the~~ ability of the wetland to absorb atmospheric CO_2, and in more ~~and t~~ nutrients absorbed by the roots, which ~~o bring nutrients to the root area,~~ improves~~ncreasing~~ the water purification ~~purifying~~ capacity of the ecosystem. Other ecosystem services that may benefit

Comment [r129]: Ward, P. 1968. Fire in relation to waterfowl habitat of the delta marshes. In: Proceedings, annual Tall Timbers fire ecology conference; 1968 March 14-15; Tallahassee, FL. No. 8. Tallahassee, FL: Tall Timbers Research Station: 255-267. [18932]

Comment [r130]: Invece EVI no?

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Comment [R31]: Direi che questa considerazione è una buona risposta al revisore #1 che critica la mancanza di un nesso con la ricostituzione dei servizi ecosistemici. Non son sicuro se sia meglio inserirla nelle discussioni o nelle conlusion

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Comment [R32]: Dire se questo è uno dei principali servizi ecosistemici dell'area…ci potrebbe essere già una anticipazione di questo nella introduzione from a higher biomass production in wetlands include f~~Furthermore, a higher level of PP corresponds major amount of energy or biomass produced by vegetation through photosynthesis over a unit of time (Pingintha et al., 2010; Vashum and Jayakumar, 2012). Therefore, can also directly and indirectly support human well-being by providing several valuable wetland ecosystem services (Mitsch and Gosselink, 2007) such as f~~lood ~~abatement~~mitigation, habitat, landscape connectivity, aesthetic quality, and ~~food, a clean~~ water supply ~~, habitats, aesthetic beauty, educational and recreational benefits~~ (Mitsch and Gosselink, 2007; Petrosillo et al., 2013; Semeraro et al., 2015).

Comment [R33]: Riportare altre citazioni

~~In particular the average values of NDWI after the fire seems higher than the one before the fire and this could suggest higher water content in the plants. Presumably, the young plants have greater vigour after the fire and are more able to withstand high temperatures.~~

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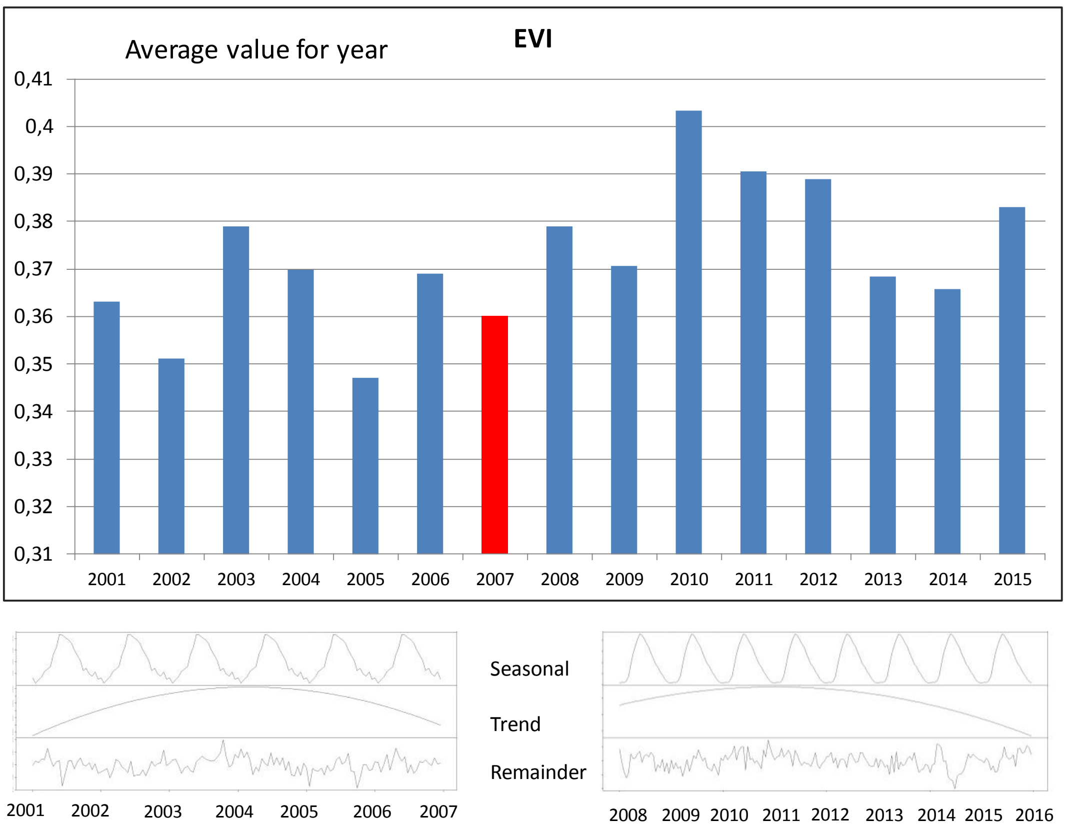

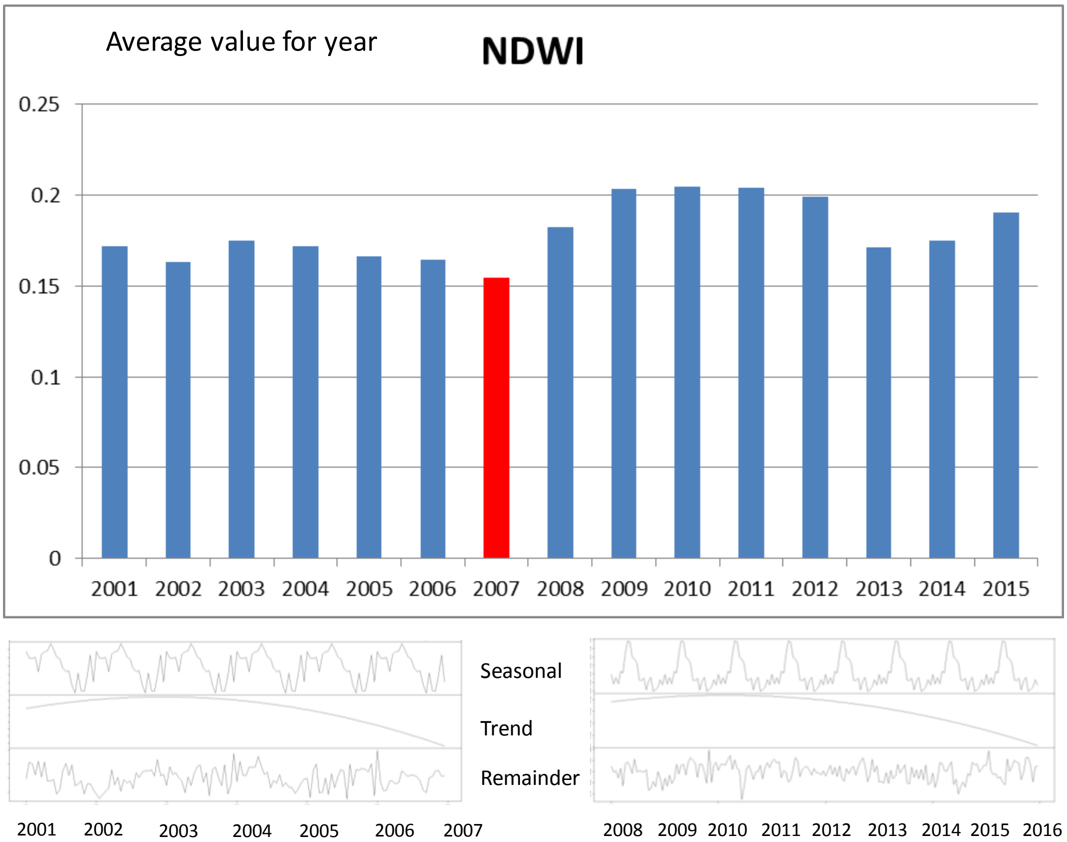

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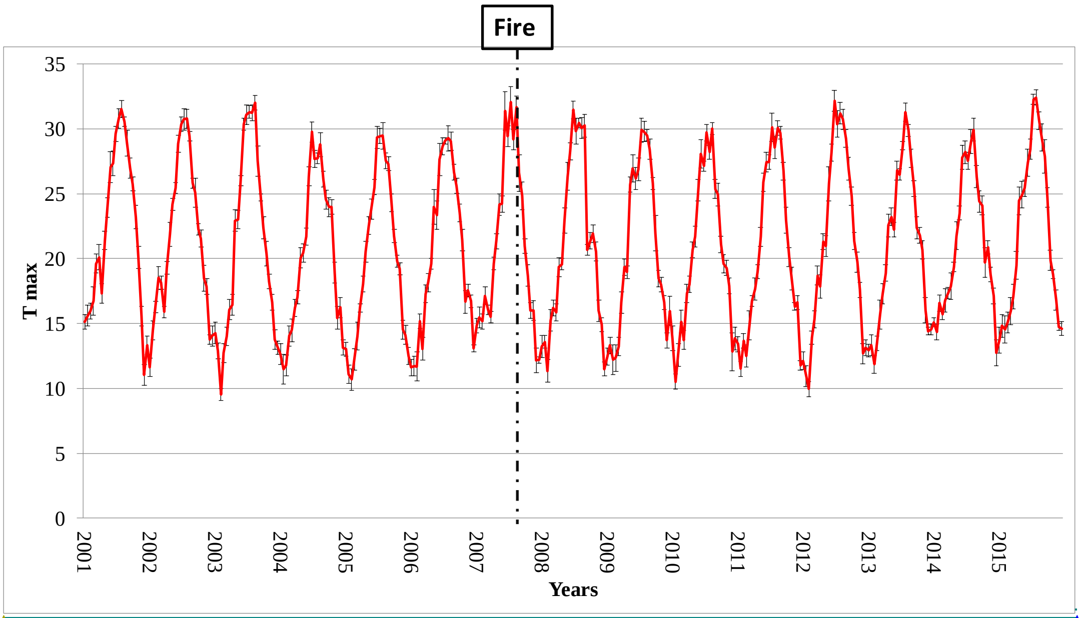
~~Please here Figure 56 and Figure 67~~

Climate analysis showed that ~~In order to verify the effect of climatic conditions, time series of maximum temperature and cumulative precipitation were analysed.~~

~~In the study area,~~ the maximum daily temperature ~~(Tmax)~~ never exceeded 35°C ~~(Figure 7~~ during the entire period of analysis (Figure 6~~7~~)~~(from year 2001 to year 2015~~. This is important considering that ~~Primary Production (PP)~~photosynthesis increases from -10°C to about 40°C and declines rapidly thereafter, reaching ~~to~~ zero at 50°C (Hopkins and Hunter, 2004). ~~For~~ R~~R~~espiration has a much higher optimum (~~the optimum is about~~ 55°C, falling to zero at about 60°C), meaning that heat stress may determine a net reduction of primary productivity – an eventuality which has never occurred in the study area during the monitoring period. The precipitation record (Figure 7~~8~~)

Comment [r134]: Non c'è in bibliogafia. Ma parlano del Phragmites, delle wetlands o in generale di tutti i biomi terrestri? Specificare nel testo showed evidence of . Therefore, the wetland vegetation in our study area does not appear to suffer from poor conditions in terms of temperature. Figure 8 shows the cumulative precipitation with a frequency of 16 days. Unfortunately, according to the availability of precipitation data, it has been possible to build the time series only from 2008 to 2015. It can be noticed that climatic conditions are characterized by a long periods of summer drought and rainy winters with mild temperatures, as it is typical of the Mediterranean climate.



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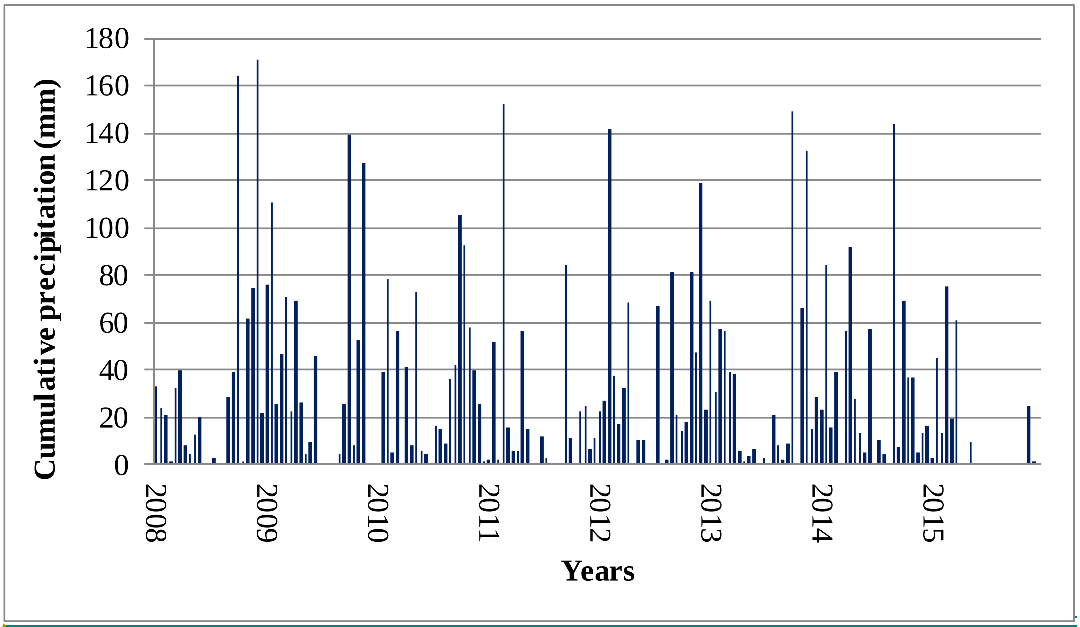

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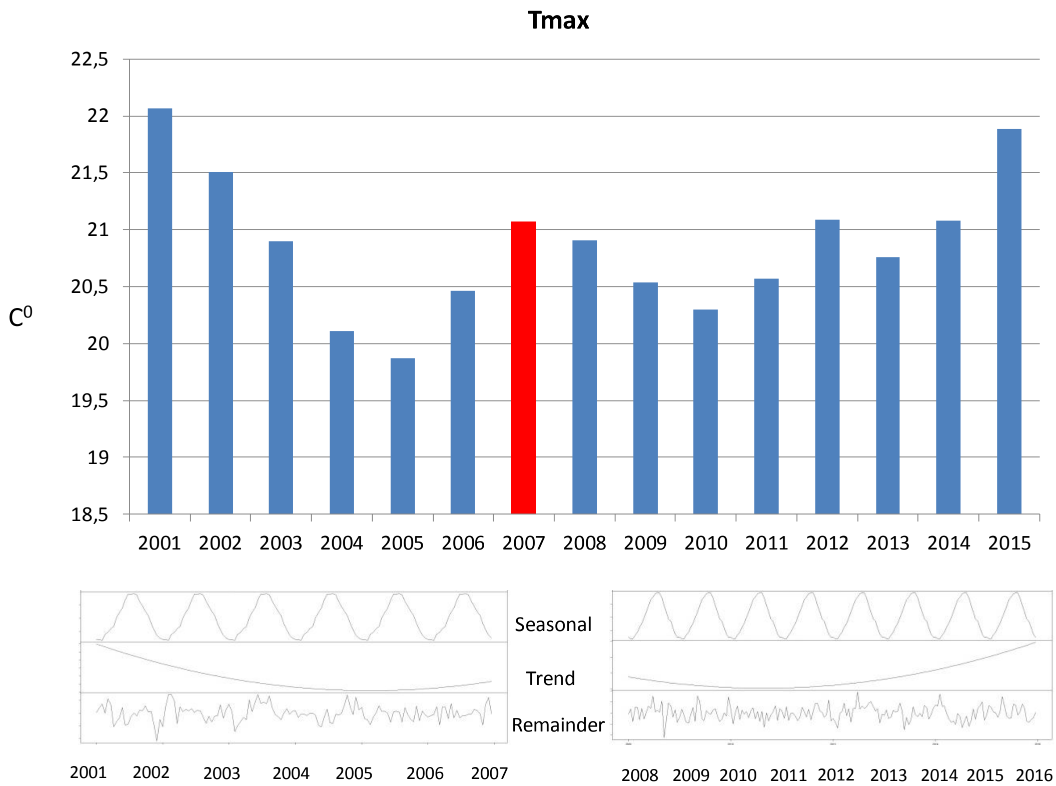
Please here Figure 67 and Figure 78

The Tmax time series showed a downward trend before the fire and an upward trend after the fire (Figure 898), while the cumulatedive precipitation showeds an increase from January 2008 to January 2011 and a decrease in the subsequent years. In particular, considering the cumulative annual precipitation, Years 2011 and 2015 are were the most drought dry yearsdriest ones (Figure 9109).

Comment [r135]: Questi trend sono significativi?

The trend of the maximum temperature shows an opposite trend to that of EVI and NDWI in both time intervals, while the cumulative precipitation forro 2008 to 20156 showed a similar trend of EVI and NDWI.



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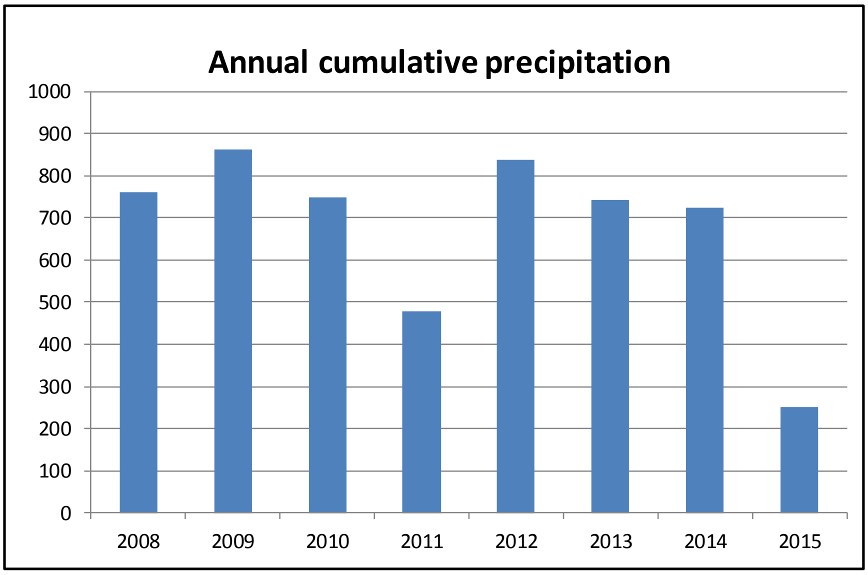

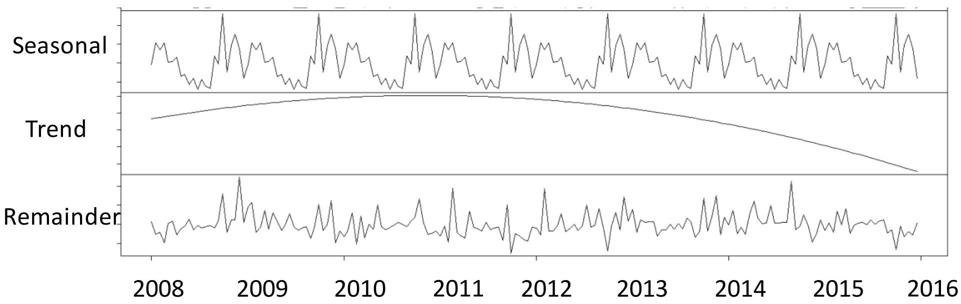

Please here Figure 89 and Figure 910

However, the analysis of the cross correlation of the Residual of the time series shows no link between the time series of vegetation indices and time series related to climatic data (the correlation are not significant and close to zero). If we compare this against the change in EVI and NDWI immediately following the fire disturbance in year 2007, this appears to be the main driver for the variation in PP in the wetland ecosystem. EVI and NDWI declined with the ageing of vegetation, dropped abruptly due to the fire, but then recovered, showing a simultaneous increase in both photosynthetic activity and canopy water content. We therefore suggest that fire can pay a

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beneficial role for the productivity and flow of ecosystem services of *Phragmites* wetlands, especially if aged up, as it induced the replacement of old, dry plants by more productive saplings.

Tmax and precipitation were significantly correlated to EVI and NDWI both before and after the fire, with a negative and positive correlation, respectively (R_{tmax} = … and …, p = … and …; R_{prec} = … and …, p = … and …). The effect size of climate variable on EVI and NDWI was -….. per each °C of Tmax, and +….. per each mm of precipitation. If we compare this against the change in EVI and NDWI immediately following the fire disturbance in year 2007 (…. and ….., respectively), this appears to be However, the analysis of the cross correlation of the remainder of the time series shows no link between the time series of vegetation indices and time series related to climatic data (the correlation are not significant and close to zero).

So probably the 2007 fire is the main driver form of perturbation that affects thefor the variation ofin the PP in the wetland ecosystemsince 2008. EVI and NDWI declined However, with the aageing of the vegetation, dropped abruptly due to the fire, but then recovered, showing a simultaneous increase in both photosynthetic activity and canopy water content. n there is a reduction of the PP.

Therefore, the wildfire generates abrupt changes in EVI and NDWI in the wetland that can condition thats is not affected by the weather conditions. or climate change Probably, the wetland before the fire is characterized by dry vegetation that have not good relations between Cloroplasts contents (EVI) and water contents (NDWI). this can act negatively on the PP of the wetland and for the linked ecosystem services.We therefore suggest that fire can pay a beneficial role for the productivity and flow of ecosystem services of *Phragmites* wetlands, especially if aged up, as it induced the replacement of old, d The fire, in this condition, act like vegetation regeneration that destroy dry plants gettingby more productive saplings better vegetation conditions for PP.

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Comment [r136]: A mio parere Tmax e precipitation devono essere correlati con la componente "trend + seasonal" perché sono i principali responsabili delle variazioni di produttività (quale ipotesi alternativa esiste altrimenti per i trend di PP?).

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fires currently managed as damaging events to be avoided within the wetlands could be introduced as a natural cycle of disturbance to regenerate vegetation and the ecological functions that endure ecosystem services.

Comment [R37]: Questa è una conclusione

4. Conclusion

The analysis of a continuous historical series can have different utility compared to the analysis of hotspot temporal points:

- briefly describe the trend over time of a phenomenon; the graph of a series, in particular, easily highlights both regularities and anomalous values;
- explains the phenomenon analyzed, identifying its generator mechanism and possible relations with other phenomena;
- predict the future trend of the phenomenon.

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Differently from numerous studies using NDVI time series to estimate PP changes (Barbosa et al 2015), we have decided to apply a methodology that uses two time series compiled by EVI and NDWI vegetation indices. In particular, EVI was preferred to the NDVI because it is more effective in estimating PP in burnt areas. Indeed, this index was developed for areas burnt in Brazil (Xiao et al., 2004). In any case, both NDVI and EVI have limited capability for retrieving vegetation water content information, since provide information on vegetation greenness (chlorophyll), which is not directly and uniformly related to the quantity of water in the vegetation (Ceccato et al., 2001). However, the water content is very important for the PP because it depends on the opening of the leaves stem that regulates gaseous exchanges. For this reason, we integrated the analysis of EVI time series with NDWI time series that is a remote sensing based indicator sensitive to the change in the water content of leaves (Gao, 1996In this paper, we used vegetation indices derived from remote sensing (Ayanu et al., 2012). as has been demonstrated being a fast and low-cost tools to achieve efficient indirect monitoring continuous historicalmonitoring of primary productivity of a wetland ecosystem before and after a fire event. Time series analysis, which was made possible by

Comment [T38]: Spostato nei materiali e metodi, diventava ripetitivo the use of continuous monitoring by remote sensing imagery, proved useful to describe temporal trends, explore their correlations with potential driving factors (e.g., climate), and can be used to predict the future trend of the phenomenon.

Our results in terms of PP trends may be relevant to assess the change in ecosystem services provided by the wetland (Ayanu et al., 2012). series assessment of ecosystem services because by monitoring vegetation indexes indicative of Primary Productivityit provides consistent time series of data and real-time data for monitoring ecosystem services (Ayanu et al., 2012). This is very useful to evaluate disturbance effect, like fire, because it allows obtaining measurements of environmental parameters in past time and so performing ante and posting disturbance evaluations. In particular, remote sensing allows us to perform an ex-ante and ex-post analysis related to a disturbance event and then to highlight the effect of this disturbance on the environment. In this case, it was very important to divide the time series into two parts, before the fire and after the fire.

Findings of the present study demonstrate that the wildfire that occurred inaffecting the Natural Protected Area of Torre Guaceeto in the summer of 2007 had a major effect on the wetlandprimary productivity, inducing the regeneration of *Phragmites* and the replacement of old individuals by structurally and functionally better ones . It produces produced structured regeneration (see the figure in the Appendix A). The : new plants after the fire; but also functions regeneration: it increased the capacity of the wetland to support PP was indeed higherafter the disturbance than before, especially due to an improved canopy water content (NDWI). . In this perspectiveIndeed, f Indeed, fire disturbance represents an intrinsic component of several terrestrial ecosystems throughout the world, playing and plays an important ecological role by maintaining ecosystem dynamics and processes, biodiversity, and productivity (FAO, 2007; Rundel et al., 2018), including that of several some protected European areas and habitats in Europe.

 Managing fire as a regenerative component of ecosystems can help to improve the capacity of the landscape to support human life by ensuring the flow of ecosystem services (Fernandes et al. 2013). Therefore, fire has plays potentially a dual role in the landscape: destructive and regenerative.

Correct lEffective andscape ecosystem management of the landscape requires an understanding of when fire should be managed as a regeneration factor, and when it must be avoided prevented or fought in order to prevent avoid the destruction ofdamages to important ecosystems or vegetation services (Fernandes et al., 2013).

This study can be taken as a reference to indicate to institutional bodies the importance of using the fire prescribed in forest management. In fact, the Regional institutional bodies denied at Torre Guaceto authority to apply the prescribed fire as a wetland management practice.

On the basis of these Our results suggest that, prescribed burning, i.e., the planned use of fire to achieve land management goals, could be a suitable tool to manage regenerate *Phragmites* wetlands area in Torre Guaceto and also prevent larger, uncontrolled wildfires by reducing cured fuel loads. This Managing fire as a regenerative component of ecosystems can help to improve the capacity of the landscape to directly or indirectly support the quality of human life by ensuring the flow of ecosystem services, supported by ecosystem functions (de Groot, 1992; Costanza et al., 1997; Fernandes et al. 2013).This studyconclusion can support the decisions of protected area managers regarding the opportunity of using prescribed fire in vegetation management, starting from Torre Guaceto (which has been so far denied by -can be taken as a reference to indicate to institutional bodies the importance of using the fire prescribed in forest management. In fact, the Regional institutional bodiesadministration the -denied at Torre Guaceto authority to apply the prescribed fire as a wetland management practice).

Comment [r139]: A patto di non eseguirlo nella stagione di nidificazione (è una Important Bird Area!)

In this context, the use of higher temporal- and spatial-resolution images, e.g., by using multispectral sensor mounted on Unmanned Aerial Vehicles (UAV), can be of help in localizesing the points where prescribed burning should be implemented, highlighting the areas dominated pattern byof dry wetland vegetation and so better locating the position where to apply prescribed burning.

Finally, this study may find application also in supporting the management of constructed wetlands for water purification. Here, continuous mThe use of drones in which optical sensors are mounted could facilitate to capture images in the multispectral bands with high resolution. This could have two consequences: in the short term, by reducing the risk of large fire risk reduction occurrence by biomass removal creating a safer landscape for fire-fighter and tourism, and in the medium term, by the enhancing enhancement the level of the wetland primary production and consequently the flow of ecosystem services. A practical appendage could be developed within the constructed wetlands systems that simulate real wetlands. This type of monitoring of primary productivity, photosynthetic activity and canopy water content may inform about the best timing to apply regenerative measures (such as by prescribed burning), in order with the purpose of providing PP regeneration interventions, such as the prescribed fire, could be important to guarantee maintain a higha high efficiency of these plants over time. I. in this case, fixed sensors and automatic calculation software could also be used to obtain fast and continuous monitoring data.

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However, this study cannot be generalized to all kinds of ecosystems, for example, in ecosystems that have a strong cultural value, such as "old olive groves", fire can not be treated used in terms ofto increase primary productivity, because in this case the functional aspect surely can recover over time, but not the cultural economical one. For this reason these studies should be contextualized to the type of ecosystem and to the referral site.

Comment [r140]: conclusione "negativa" e fuori tema, eliminare.

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BibliographyReferences

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