PROTOCOL

on the estimated reduction in fire-related GHG emissions, under future climate change scenarios, in fire-smart and mosaic-like resilient Mediterranean landscapes

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Authors
Tim van der Schriek, Anna Karali, Konstantinos V. Varotsos, Christos Giannakopoulos

Lead partner
National Observatory of Athens

Layout
Erika Stellini (Istituto Oikos ETS)

Work package (WP II):
Development and application of a robust science-based methodology for estimating the reduction in fire-related GHG emissions under future climate change scenarios in fire-smart, mosaic-like resilient landscapes.

Activity AII.4: Protocol

This project is part of the European Climate Initiative (EUKI). EUKI is a project financing instrument by the German Federal Ministry for Economic Affairs and Climate Action (BMWK). The EUKI competition for project ideas is implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. It is the overarching goal of the EUKI to foster climate cooperation within the European Union (EU) in order to mitigate greenhouse gas emissions.

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List of abbreviations

Abbreviations	Definitions
BA	Burnt Area
BAU	Business-as-usual
CC	Climate change
EFFIS	European Forest Fire Information System
FSL	Fire Smart Landscape
FWI	Fire Weather Index
GHG	Green House Gas
GWIS	Global Wildfire Information System
RCP	Representative Concentration Pathway
SPEI	Standardised Precipitation Evaporation Index

1. Introduction

The MediterRE3 project aims to reduce future fire-related GHG emissions in three target landscapes (Greece, Montenegro and France; Fig. 1) through applying Forest Landscape Restoration principles.The project provides projections of Burnt Area (BA) and associated Green House Gas (GHG) emissions, under different scenarios of (i) future climate change and, (ii) fire-smart landscape interventions.

The National Observatory of Athens (NOA) is responsible for **Work package II** ("Development and application of a robust science-based methodology for estimating the reduction in fire-related GHG emissions under future climate change scenarios in fire-smart, mosaic-like resilient landscapes"). The results of WPII are summarised in three technical factsheets (activities AII.1 to AII.3), and in the **current protocol** (WPII, activity AII.4).

This protocol instructs on **how** to estimate the reduction in fire-related GHG emissions, under future climate change scenarios, through applying Forest Landscape Restoration principles in Mediterranean landscapes. The detailed explanation of the study approach, including examples, will help up-scaling of the study results. Interested parties are thus enabled to conduct a similar study, formulate regional mitigation plans and access new funding instruments.

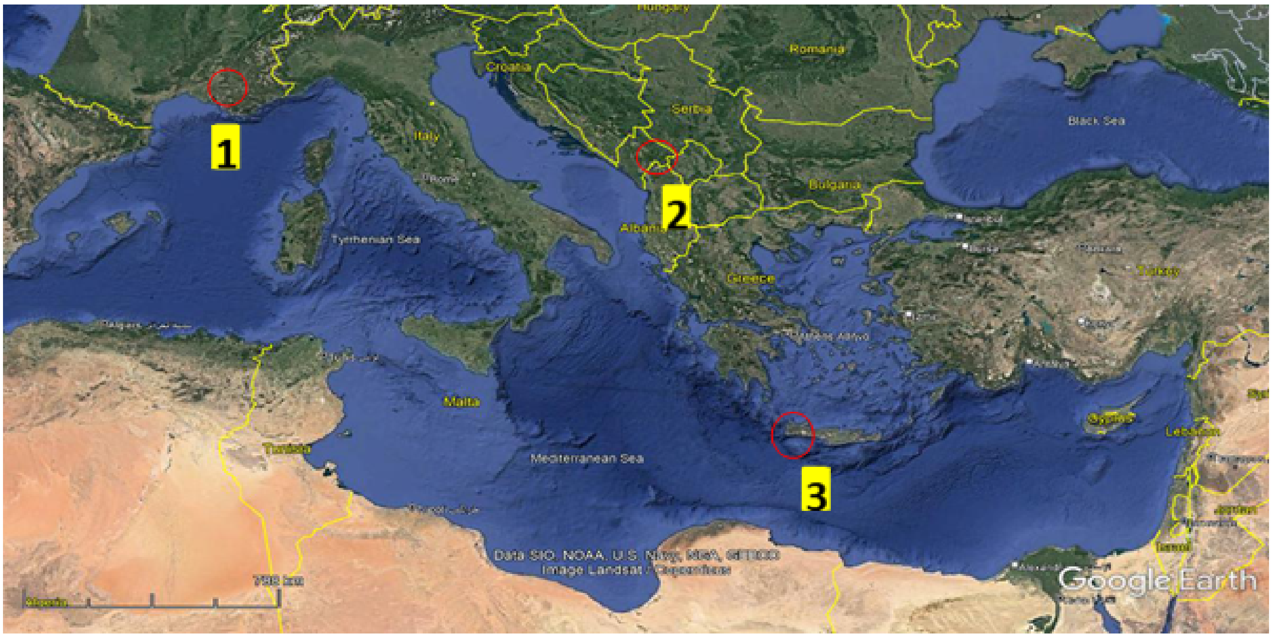

Figure 1. Location of the target areas (1. Luberon National Park, SE France; 2. Prokletije/Komovi National Park, SE Montenegro; 3. Chania Prefecture, W Crete, Greece).

2. Set-up and rationale

Mean annual **Burnt Area** (BA) and **Green House Gas** (GHG) emissions by wildfires in the Mediterranean are projected to increase significantly by 2070 under future climate change (assuming non-significant changes in external factors such as land-use, vegetation change, fire suppression and human activities).

There are large regional differences in future projections across the Mediterranean. No single method is used to estimate future BA and GHG emissions, which makes comparisons between studies and regions difficult. Here we present an approach to estimate future BA and GHG emissions from wildfires, which may be applied throughout the Mediterranean, thus allowing comparisons between regions.

The main aim of this protocol is to provide a ready and tested methodology for estimating future BA and associated GHG emissions, under different scenarios of climate change and fire-smart landscape (FSL) interventions, to be used in policy documents and grant applications. Linking adaptation strategies, such as FSL interventions, to mitigating impacts (i.e., the reduction of GHG emissions from wildfires) aims to:

- Support the Mediterranean countries in meeting the GHG emission cut 2030-target;
- Support target landscapes and countries in shifting fire management practices from suppression to integrated landscape fire management systems;
- Enable target countries to access existing financial mechanisms.

2.1 Outline of the Approach

Our approach for providing estimations of future BA and associated GHG emissions, under different scenarios of climate change and FSL interventions, consists of 5 steps:

1. Calculation of the **percentage-reduction in the total BA** under different FSL management scenarios, compared to the business-as-usual scenario.
2. Creation of **statistical models**, calibrated for each area, linking observed BA/GHG to climate variables, fire-danger & drought indices;
3. **Simulation of future climate** data utilizing state-of-the-art climate models (horizontal resolution of 12km, developed within the EURO-CORDEX initiative);
4. **Calculation of future BA and associated GHG emissions** under a business-as-usual management scenario. BA and GHG emissions were calculated under 3 future climate change scenarios (RCP 2.6, RCP4.5 and RCP8.5), up to 2070, using the calibrated statistical models (of step 3);
5. Application of **numerical correction factors** to the future BA simulations, under different climate scenarios, to derive the potential reduction in fire GHG emissions under fire-smart landscape management.

It should be noted that the **temporal and spatial scales are different** from those that are usual in fire landscape management. As wildfires are linked to climate, we need access to long term average weather characteristics (spanning >15 years), as well as BA and GHG emission data-series of the same temporal length. Furthermore, fire-related BA (and associated GHG emissions) can only be linked to climate variables when looking at large surface areas (upwards of 50x50km).

Our approach relies on publicly available data and is thus applicable throughout the Mediterranean region. **Regarding expertise**, it is essential to have access to specialist(s) with climatic and statistical know-how. In the following sections we will outline each of the steps, the data required, and provide relevant examples.

This protocol will **only look at the influence of climate change** on BA and GHG emissions. It assumes that all other variables are stable: no change is assumed in land-use (cover), vegetation, fire-suppression methods and fire-ignition causes, as well as climate-fire & fire-vegetation feedbacks. This is a common approach for modelling studies, to keep the range of alternative future scenarios within limits.

3. Step One: calculation of percentage-reduction in BA under FSL management

There are several ways to derive numerical estimates on the the effectiveness of FSL interventions in reducing annual BA for a given landscape. Estimates may be based on published studies, though conducting new studies (by experts, using established methodologies), or through a simple GIS-based methodology. The MediterRE3 project used the latter approach (explained in **Annex A**), which may be applied over large areas, using the same methodology, thus allowing direct comparison between study sites. This makes it highly suitable for regional analyses, for example, across the Mediterranean Basin. Local to regional studies using fire-vegetation models (see section below) are likely more accurate in estimating the impact of FSL management, but difficult to apply across large regions due to the detailed data-series required as input (not everywhere available), and limited access to models and experts.

3.1. Background

Fire-smart landscape management is defined as "an integrated approach primarily based on fuel treatments through which the socio-economic impacts of fire are minimized while its ecological benefits are maximized" **[1]**. For FSL management to be effective in reducing BA and GHG emission from forest wildfires, it needs to be applied over large areas (i.e., at a regional level).

Long-term observational studies (>15 years) that detail the effects of fire-smart landscape management are not available in the Mediterranean or elsewhere in the world, as these management methods have not been implemented for long time-periods. Therefore, models (and typically **fire-vegetation models**) are usually employed to estimate the influence of fire-smart landscape management on BA and fire conditions **[e.g., 2, 3 *and references therein*]**.

The fire-vegetation feedbacks and their complex interactions with fire-suppression policies and land-use changes make fire dynamics difficult to predict, which challenges decision-making due to the large uncertainty of alternative FSL management scenarios. Therefore, when **modelling FSL management impacts on fire characteristics**, other variables (such as fire-suppression policies, land-use change and climate change) are kept stable. This keeps the number of alternative scenarios limited and thus easier to compare. Percentage differences between FSL scenarios are commonly calculated against a Business-As-Usual (BAU) management scenario.

Few studies look at the effect of fire-smart landscape management in the Mediterranean. Most existing studies are in the Iberian Peninsula **[4 *and references therein*]**. There are many different effectiveness scenarios, depending on local conditions (including, for example, topography, vegetation & land-use). However, indicative studies suggest that fire-smart management of around 3% of the total region may lead to a 10-20% reduction in annual averaged BA **[2,3]**.

3.2 MediterRE3 case-study: reduction of BA/GHG emissions under FSL management

The project looked at the influence of future CC on BA due to wildfires under a business-as-usual land management scenario, and under a scenario that implements FSL management at the target areas. Regarding the latter, the potential reduction in BA was calculated under 2% and 5% FSL-management scenarios (i.e., 2% and 5%, respectively, of the study area experiences interventions along access roads only). The methodology uses GIS-based calculations, and is detailed in Annex A.

Numerical estimates on the the effectiveness of fire-smart interventions in reducing annual BA for each of the target landscapes is detailed in Table 1. Please note that all of these intervention scenarios are at the low end of published studies (claiming often 10-20% reduction) [*2,3*], but all use the same approach and are thus directly comparable.

Study Area	Reduction in annual BA, under:	
	2% FSL interventions	5% FSL interventions
Samaria NP (Crete, Greece)	3.2%	7.9%
Luberon NP (France)	4.7%	11.8%
Prokletije NP (Montenegro)	5.6%	13.9%

Table 1:numerical estimates of the effectiveness of fire-smart interventions in reducing annual BA for each of the target landscapes. ***Annex A*** *details the data and methodology behind these estimates.*

4. Step Two: creation of statistical models

Here we present a method for estimating BA and associated GHG emissions, which is applicable throughout southern Europe, using a novel statistical model that is driven by climatic variables and fire-danger & drought indices. Published studies indicate that temperature and precipitation variables, as well as the Fire Weather Index (FWI) and the Standardised Precipitation Evapotranspiration Index (SPEI), are strongly correlated to wildfire-related BA in the Mediterranean area **[6-9]**.

Our statistical model needs to select optimum variables and indices (explained in section 4.3), and to be calibrated, at each target site and is therefore area specific. For meaningful statistical correlations of BA to climatic and fire-danger indices, study areas need to be sufficiently large. When focussing on small study areas, there are often no fires at all during days characterised by high fire danger. There is only over extensive areas a correspondence between high fire danger and fires/BA.

This method needs the following site-specific datasets (all of which needed to cover >15 years): BA records, fire-emission data and meteorological data (described in sections below).

4.1. Data sources

When **regional high-resolution BA records** are available, study areas need to have a minimum surface area of about 50 x 50 km. Larger study areas are required (minimum size of about 100 x 100 km) when obtaining **European BA data** from EFFIS (European Forest Fire Information System, **https://effis.jrc.ec.europa.eu/**), as only large fires were registered up to 2017.

The Rapid Damage Assessment module of EFFIS provided the daily update of the perimeters of burnt areas in Europe for fires of about 30 ha or larger, from 2003 until 2017, twice daily. Since 2018, the use of Sentinel-2 imagery allows the detection of fires below the 30 ha threshold and it is estimated that the areas mapped in EFFIS represent about 95% of the total area that burns in the EU every year (**https://effis.jrc.ec.europa.eu/about-effis/technical-background/rapid-damage-assessment**).

Recent climatic data were obtained from the **ERA5-Land reanalysis** dataset (Resolution: 9km, spanning: 1950-present) [5]. Fire-danger (based on the Fire Weather Index, **FWI**) and drought indices (i.e., the Standardised Precipitation Evapotranspiration Index, **SPEI**) were calculated from these data. **GHG emission** data from past wildfires (processed using the FAOSTAT methodology [**10**]) were downloaded from **GWIS** (**https://gwis.jrc.ec.europa.eu/**).

4.2. Selected fire and drought indices

FWI is a daily **meteorologically based index** used worldwide to estimate **fire danger** in a generalised fuel type (mature pine stands). It consists of different components that account for the effects of fuel moisture and wind speed on fire behaviour & spread. The **meteorological inputs** to the FWI system are daily noon values of temperature, air relative humidity, 10m wind speed and precipitation during the previous 24hrs (Fig. 1). Since 2007, the FWI has been adopted at the EU level by the European Forest Fire Information System (EFFIS) of the Copernicus Emergency Management Service (CEMS) to assess fire danger level in a harmonized way.

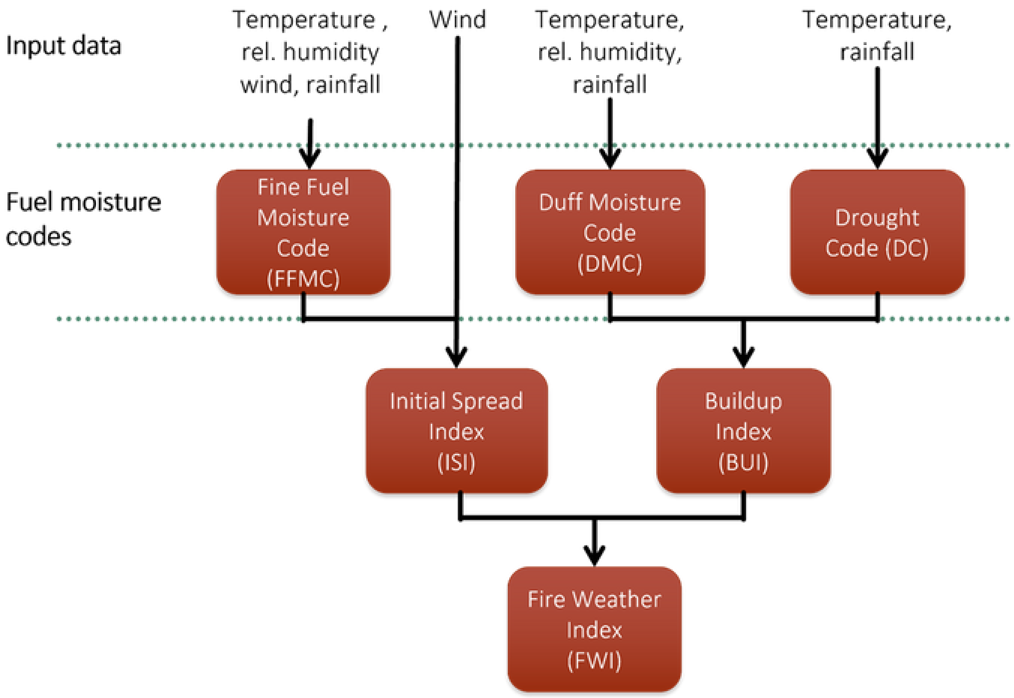

*Figure 2: Fire Weather Index (FWI) structure & climate variables used as input. For a full explanation of the FWI see [**11**].*

SPEI is a drought index that needs monthly temperature and precipitation data for its calculation (Fig. 2). The index is standardized against the long-term climatic data of an area; the required variables should span at least a 15-year period. This drought index may be calculated over one or multiple preceding months. The number of months incorporated in the index is reflected in the number behind "SPEI". For example, SPEI-6 is the drought index calculated over the previous 6 months at a given area and compared to the long-term average (over the same 6-month period) at this area.

The **SPEI** is a **multi-scalar drought index based on climatic data**. It can be used for determining the onset, duration and magnitude of drought conditions with respect to normal conditions in a variety of natural and managed systems such as crops, ecosystems, rivers, water resources, etc.

SPEI has an intensity scale in which both positive and negative values are calculated, identifying wet and dry events. It can be calculated for time steps of as little as **1 month up to 48 months or more**.

It **needs monthly temperature and precipitation data for its calculation**. The inclusion of temperature along with precipitation data allows SPEI to account for the impact of temperature on a drought situation.

The **output** is **applicable for all climate regimes**, with the results being comparable because they are standardized. With the use of temperature data, SPEI is an ideal index when looking at the impact of climate change in model output under various future scenarios.

Figure 3: Explanation of the Standardized Precipitation Evapotranspiration Index (SPEI).

4.3. Selection of statistical model variables

We calculated correlation coefficients between total monthly Burned Area (BA) and multiple variables for the fire season, ranging from June to September (JJAS), over the years 2000-2021, to establish the best matches (Table 2).

FWI, TX (maximum temperature) and SPEI6H (H for Hargreaves) were the selected variables, the first two from the matrix (Table 2) and the third from trial-and-error while modeling BA. Optimum variables were the same for all target areas from the MediterRE3 case-study. However, other Mediterranean areas may have different optimum variables. Therefore, the selection of statistical model variables is an essential step for each new study area.

Climate indices of the months **outside the JJAS fire season** (JFMAM and OND) cannot be reliably related to BA as **no significant correlation coefficients** were found in our analysis. To calculate the total annual BA, it was assumed that the relative percentages (%) of BA over the fire season vs the other months (JFMAM and OND) **are stable** for each of the target areas.

The percentage BA over the fire season is above 90% for all target areas. Specifically, the relative amount of BA over the fire season (JJAS) and outside the season (JFMAM and OND) are: 96% vs 4% for Chania Province, 93% vs 7% for Montenegro, and 91% vs 9% for the Luberon NP.

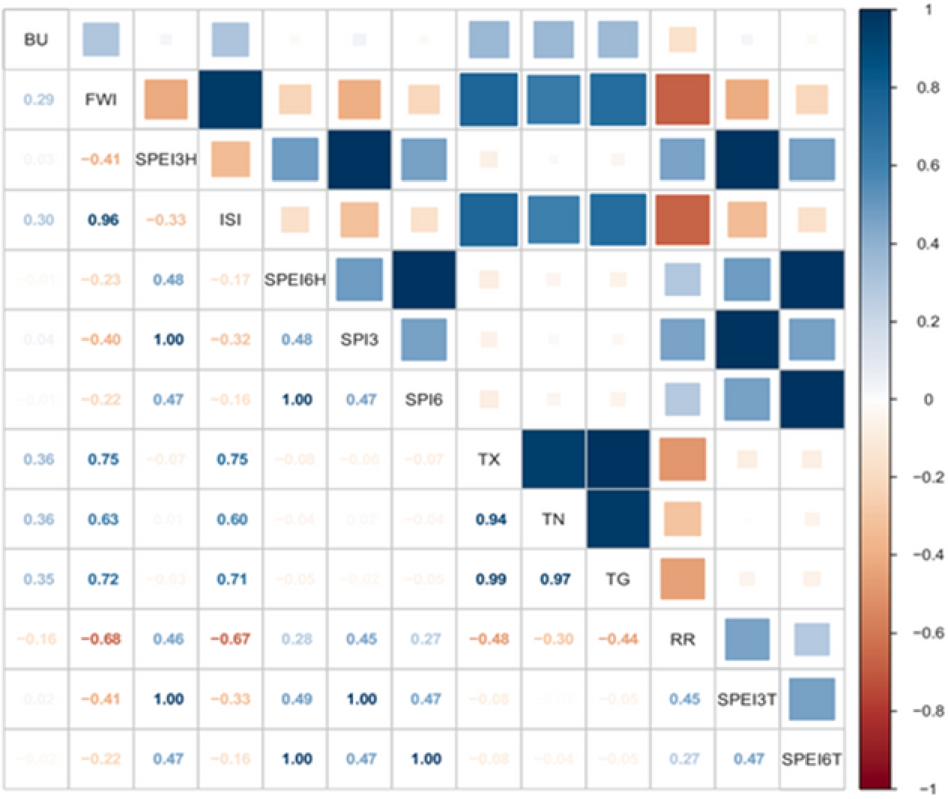

Table 2: Example of correlation matrix between Burnt Area and a number of variables (BU: Build Up Index, FWI: Fire Weather Index, SPEI3H/T: 3-month averaged Standardized Precipitation Evapotranspiration Index – Hargreaves / Thornwait, ISI: Initial Spread Index, SPEI6H/T: 6-month averaged Standardized Precipitation Evapotranspiration Index – Hargreaves / Thornwait, SPI3: 3-month averaged Standardized Precipitation Index, SPI6: 6-month averaged Standardized Precipitation Index, TX: averaged maximum temperature for the fire season, TN: averaged minimum temperature for the fire season, TG: averaged temperature for the fire season, RR: Rainfall Rate).

4.4. Response variable modelling & testing

GAMs (Generalized Additive Models) were used to model the response variable (total BA) by selected independent variables (FWI, TX, SPEI6H), which are in the form of some smooth functions [e.g., $\log_{10}(BA) = s(FWI) + s(SPEI6H) + s(TX)$]. The statistical model was optimized using leave-one-out cross validation.

The relationship between the BA & GHG emissions is assessed through Reduced Major Axis regression. This area-specific relationship was subsequently used to derive future estimations of GHG emissions related to wildfire BA. Thus, future emissions were based on long-term observed relationships between BA and GHG emissions from wildfires. Subsequently, all models were tested against the observed values (for an example, see Fig. 4).

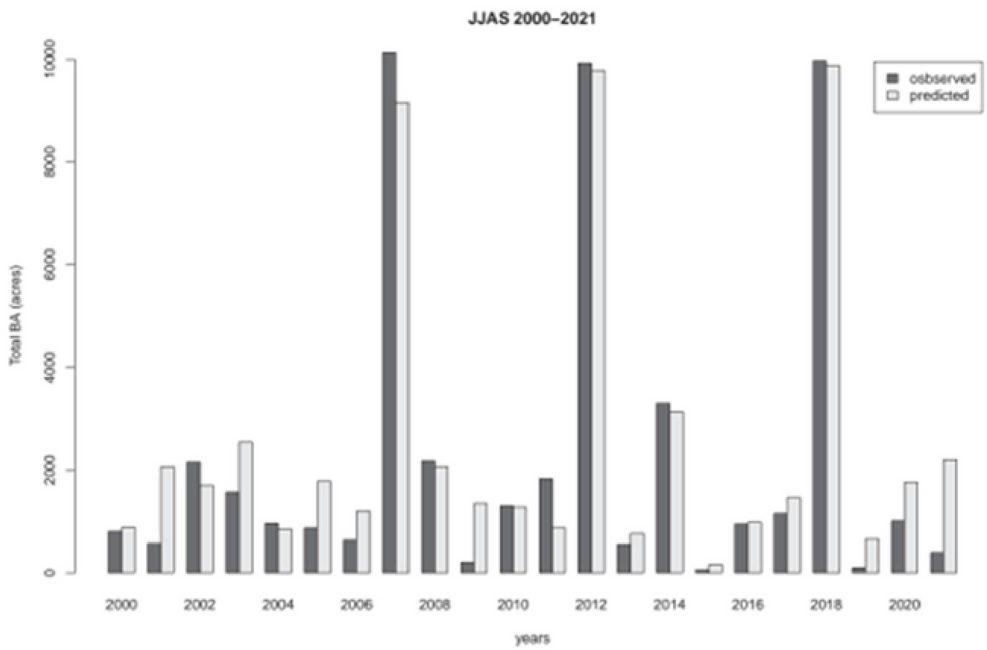

Figure 4: Example of testing of the response variable. The observed vs predicted total seasonal (JJAS) BA is shown for the years 2000-2021 (Chania Province, West Crete, Greece). The model predicts the total BA over this period quite well, with the mean bias being 65 acres. In addition, the model can capture the high values of 2007, 2012 and 2018.

5. Step Three: simulation of future climate

State-of-the-art regional climate models must feed the statistical models (section 4) that drive BA & GHG-emission estimates under a business-as-usual management scenario.

The MediterRE3 case-study used advanced climate models at a horizontal resolution of about 12km developed within the EURO-CORDEX initiative to simulate future climate data (Table 3). Future wildfire BA and associated GHG emissions were calculated under **three future climate change scenarios** (i.e., Representative Concentration Pathways (RCPs) 2.6, 4.5 and 8.5; Fig. 5) and with **business-as-usual landscape management scenario**, up to 2070.

EURO-CORDEX GCM/RCM pairs (hor. Resolution ~ 12km)		
Institute	**RCM**	**GCM**
Swedish Meteorological and Hydrological Institute (SMHI)	RCA4	ICHEC-EC-EARTH
Swedish Meteorological and Hydrological Institute (SMHI)	RCA4	MPI-M-MPI-ESM-LR
Swedish Meteorological and Hydrological Institute (SMHI)	RCA4	MOHC HadGEM2-ES

Table 3: Climate models used in this study. Reference period: 1971-2000, Future period: 2011-2070.

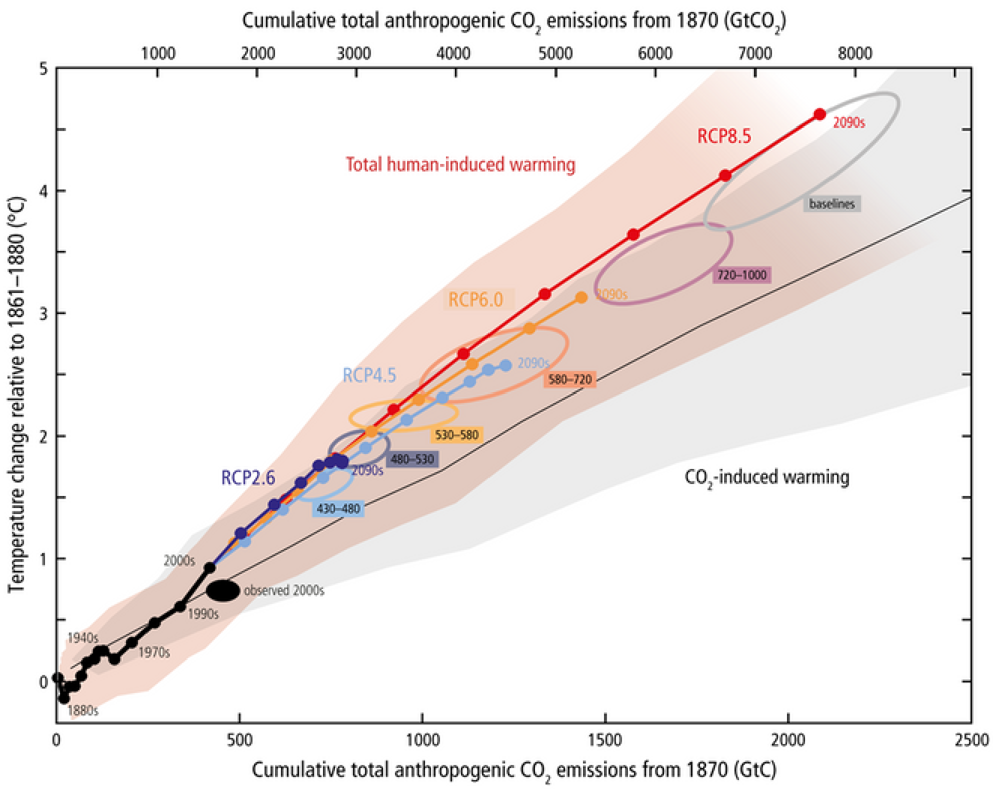

Figure 5: Representative Concentration Pathways (RCPs) used in this study are RCP2.6 (ambitious mitigation policies), RCP4.5 (moderately ambitious mitigation policies), and RCP8.5 (business as usual, no mitigation). Currently, pathways RCP4.5 is considered the most likely (up to 2,5oC warming by 2090s).

6. Step Four: calculation of future BA and GHG emissions

Simulated climate data (section 5) are used to calculate the FWI and SPEI. Selected variables subsequently feed the area-specific statistical model (section 4) to estimate the future BA and GHG emission[10] related to wildfires under a business-as-usual scenario.

Case-study: examples under business-as-usual management

The results for MediterRE3 were presented in box plots for each of the target study areas. Included below are the box plots for Chania Province (West Crete, Greece), for illustration. See factsheet 3 for a detailed discussion of the results for all target study areas.

In each figure, "**M**" = **mean**, and "**Δ**" = **difference compared to control** period. Mean BA in hectares and GHG-emissions (in Gigagrams; Gg) are rounded to the nearest whole number, as only these integers are statistically significant.

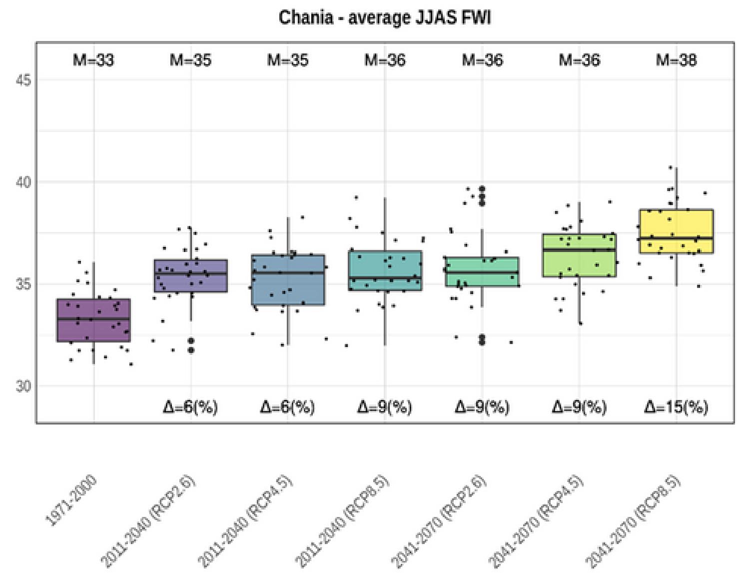

Figure 6: Future FWI

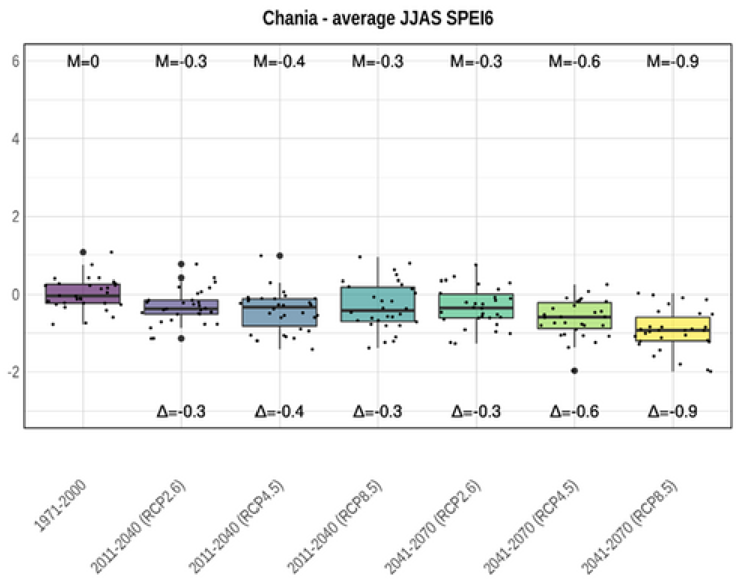

Figure 7: Future SPEI-6

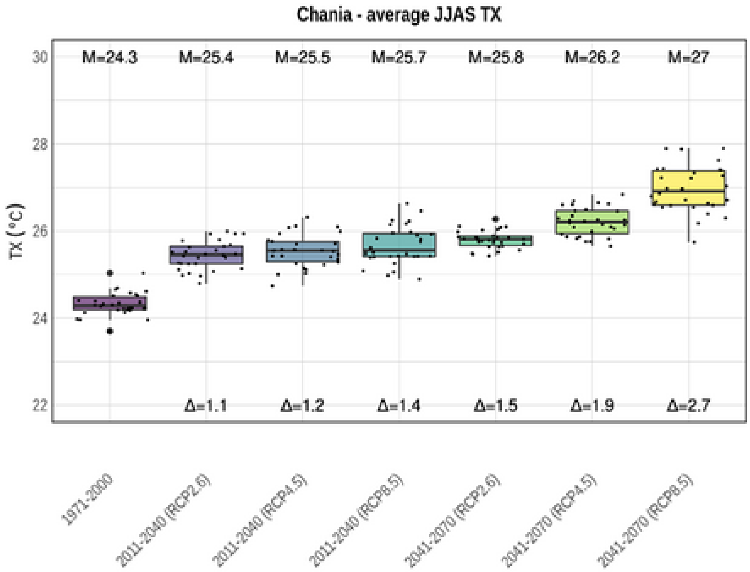

Figure 8: Future T max

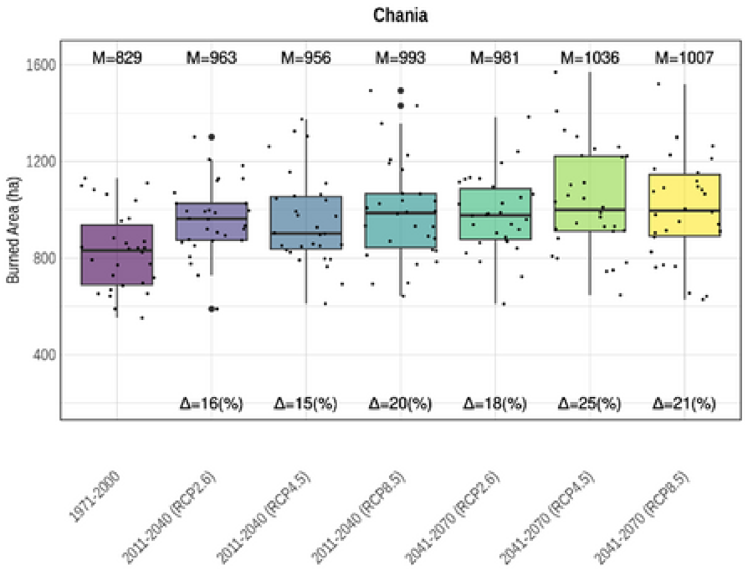

Figure 9: Future BA

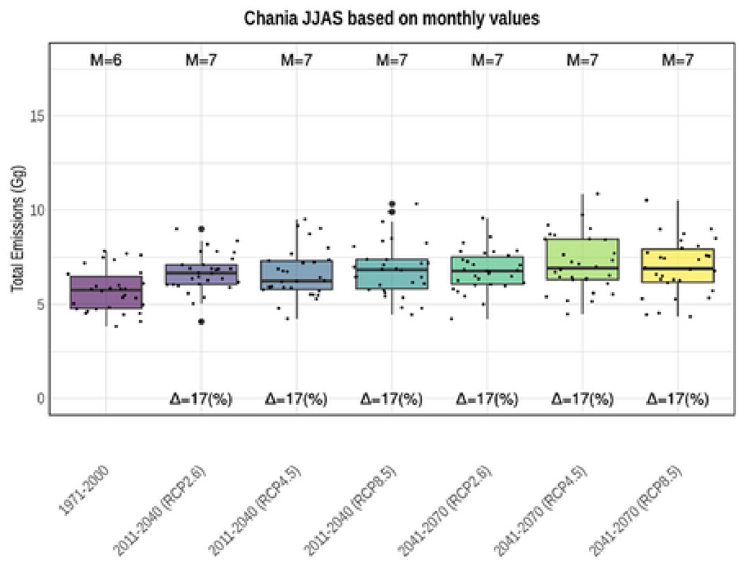

Figure 10: Future emissions

7. Step Five: calculation of future BA and GHG emissions under FSL management

Subsequently, numerical correction factors (explained in section 3) are applied to the future BA simulations, under different climate scenarios, to derive the **potential reduction** in fire GHG emissions for[10] landscapes under fire-smart landscape management.

Case-study: examples of potential GHG reduction under FSL management

For the target areas of the MediterRE3 project, the potential reduction in BA under Fire-Smart Landscape (FSL) management were calculated (see Table 4). These numerical correction factors were applied to future BA simulations.

Study Area	Reduction in annual BA, under:	
	2% FSL interventions	5% FSL interventions
Samaria NP (Crete, Greece)	-3.2%	-7.9%
Luberon NP (France)	-4.7%	-11.8%
Prokletije NP (Montenegro)	-5.6%	-13.9%

Table 4:numerical estimates of the effectiveness of fire-smart interventions in reducing annual BA for each of the target landscapes. ***Annex A*** *details the data and methodology behind these estimates. The effect of these interventions is relatively low, compared to published FSL-impact studies. The effects of our 5% FSL intervention scenarios are in line with published FSL-impact studies, albeit at the lower end.*

The 2% and 5% FSL management intervention scenarios can be interpreted as the lowest possible impact and the average impact, respectively, of any fire-smart landscape management interventions. Even the impact of the 5% FSL intervention scenario is low, compared to the effect indicated by published studies (see discussion in factsheet 1). Table 5 (below) compares the future changes under a business-as-usual landscape management scenario and the 2% & 5% FSL intervention scenarios, respectively, for the three target study areas.

	BA change		**Emissions change**	
	near future (2011-2040)	**distant future (2041-2070)**	**near future (2011-2040)**	**distant future (2041-2070)**
Chania – no FSL change	**+15 to +20%**	**+18 to +25%**	**+17%**	**+17%**
Chania – 2% FSL intervention	**+12 to +16%**	**+15 to +21%**	**+17%** (only RCP8.5)	**+17%**
Chania – 5% FSL intervention	**+6 to +10%**	**+9 to +15%**	**0**	**+17%** (only RCP4.5)
Montenegro – no FSL change	**-33% to +47%**	**+36 to +127%**	**-33% to +47%**	**+36 to +127%**

	BA change		Emissions change	
	near future (2011-2040)	distant future (2041-2070)	near future (2011-2040)	distant future (2041-2070)
Chania – no FSL change	**+15 to +20%**	**+18 to +25%**	**+17%**	**+17%**
Chania – 2% FSL intervention	**+12 to +16%**	**+15 to +21%**	**+17%** (only RCP8.5)	**+17%**
Chania – 5% FSL intervention	**+6 to +10%**	**+9 to +15%**	**0**	**+17%** (only RCP4.5)
Montenegro – no FSL change	**-33% to +47%**	**+36 to +127%**	**-33% to +47%**	**+36 to +127%**
Montenegro – 2% FSL intervention	**-37% to +39%**	**+29 to +114%**	**-37% to +40%**	**+19 to +115%**
Montenegro – 5% FSL intervention	**-42% to +27%**	**+17 to +95%**	**-42% to +27%**	**+18 to +96%**
Luberon – no FSL change	**+38 to +40%**	**+32 to +111%**	**+100%**	**+100%**
Luberon – 2% FSL intervention	**+29 to +33%**	**+26 to +101%**	**+100%**	**+100%** (0% RCP2.6)
Luberon – 5% FSL intervention	**+22 to +26%**	**+19 to +90%**	**+100%** (0% RCP2.6)	**+100%** (0% RCP2.6)

Table 5: Projected future BA and emissions associated with wildfires in the target study areas.

8. Conclusions

This document presents an approach to estimate future BA and GHG emissions from wildfires, which may be applied throughout the Mediterranean, thus allowing comparisons between regions.
Our statistical model is quite accurate in projecting BA based on input of the fire-danger & drought indices (FWI & SPEI, respectively), and one climatic variable (averaged maximum temperature) over the fire season (JJAS). It provides the best results when using regional high-resolution BA data, but publicly available EFFIS data may be used if no regional data are available. The approach is therefore transferable to other Mediterranean regions ("upscaling"), which is a key aspect of the MediterRE3 project.

The methodology set-out in this protocol is thus suitable for estimating future Burnt Area (BA) and associated Green House Gas (GHG) emissions, under different scenarios of CC and FSL interventions, throughout the Mediterranean. The protocol may help to support:

- Mediterranean countries in addressing the GHG emission cut 2030 target;
- Regions and countries in shifting fire management practices from suppression to integrated landscape fire management systems;
- Access existing financial mechanisms.

The future expansion of fire-prone areas into the north Mediterranean, and into higher-altitude Mediterranean mountain environments, is a growing concern. At these locations, much larger biomass is present and changing climatic variables strongly increase fire danger [**7-9**]. However, in more arid Mediterranean areas the climate-induced BA increases may be limited due to fuel constraints. For example, in Chania, fire danger over the fire season is already very high, with frequent fires and a lower biomass due to less (and open) forest. The impact of CC is therefore more limited.

FSL management will reduce or avoid the projected future increases in BA and GHG emission from wildfires (even under our low-impact management scenarios; much larger decreases are possible). For example, future BA increases are reduced by up to 40-50% for Chania, by 25-50% for Montenegro and 20-35% for the Luberon. Future GHG emissions from wildfires are not increasing (Chania), or the increase is reduced by up to 22-50% (Montenegro). In the case of the Luberon, the decrease is non-significant; however, this is likely an artefact of the very low initial GHG emission values in this target area.

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