MODELLING FIRE-SMART LANDSCAPE MANAGEMENT (FSLM) EFFECTIVENESS IN REDUCING ANNUAL BURNT AREA

MED ITER RE3

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Introduction

List of abbreviations

***Table 1** – List of abbraviations used in the document*

ABBREVIATION	MEANING	DESCRIPTION
AOI	Area of interest	The area of the target landscape. All calculations perfomed with the methodology refer to the AOI
BA	Burnt area	Area struck by fire in at least 1 wildfire event in the target period
FIR	Fire ignition risk	The likelihood of fire ignition, determined by proximity to human infrastructures
FSLM	Fire-smart landscape management	Integrated approach primarily based on fuel treatments aimed to minimize socio--economic impacts of fire maintaining ecological benefits (Fernandes, 2013; Hirsch et al., 2001)
FSR	Fire spread risk	The state of the fuel, that determines the degree of ease of fire spread (the "fire hazard", see Hardy, 2005; Moreira et al., 2011), including terrain features (slope and aspect)
FR	Fire risk	The likelihood that a fire might start and spread
HFIR	High fire ignition risk	The area within 50m from buildings, paved roads and other human infrastructures or 25m metres from dirty tracks and paths
HFSR	High fire spread risk	Corresponds to FSR Class 5 as estimated by the model described by the methodology
HFR	High fire risk	Occurs where HFSR and HFIR overlap
LULC	Land use/land cover	Categorization or classification of human activities and natural elements on the landscape
MFSR	Medium fire spread risk	Corresponds to FSR Class 3 and 4 as estimated by the model described by the methodology

Foreword

The following methodology aims at estimating the FSL effectiveness in reducing the annual BA in target landscapes through publicly available datasets. Therefore, it can be applied for any landscape in Europe (excluding Russia, Belarus and Moldova) and in wider Mediterranean ecoregion (North Africa and Middle East included, excluding Egypt). Part of the methodology is adapted from Carmo et al. (2011) and Sequeira et al., (2021). GIS and modelling expertise is required to apply to the methodology, which can be applied through open-source softwares (e.g. QGIS, R environment).

Key assumptions

- Naturally occurring wildfires account for a small share of the burnt area (~5% of wildfire events, Pérez-Invernón et al., 2021). Thus, they are not considered in this methodology
- Fires ignite and spread from HFIR areas
- HFIR areas are located where there is a higher likelihood of human presence and, thus, of ignition. They are estimated as a function of proximity to human infrastructures (roads, paths, buildings)
- HFIR cannot be mitigated
- FSR can be mitigated through FSLM
- FSLM should be applied to in HFR areas resulting from the co-occurrence of HFSR and HFIR
- For the same size, HFSR areas produce larger fires than MFSR
- Reducing FSR in HFIR areas (HFSR è MFSR) result in annual BA reduction

Dataset

Table 2 *– List of dataset used in the described methodology. All data are publicly available*

VARIABLE	GOAL	SOURCE	DATA TYPE	URL
LULC	FSR estimation	Copernicus Global Land Cover (GLC)	Raster (GeoTIFF, ~100m res.)	https://lcviewer.vito.be/download
TERRAIN	FSR estimation	Copernicus EU-DEM	Raster (GeoTIFF, 25m res.)	https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1
ROADS & BUILDINGS	FIR areas identification	OpenStreetMap (OSM)	Vector (shapefile or osm.pbf)	http://download.geofabrik.de
BURNT AREAS	Locate burnt areas	EFFIS burnt areas	Vector (shapefile)	https://effis.jrc.ec.europa.eu/apps/data.request.form/
AOI	Identify area for calculations	Ecoregions (Dinerstein et al. 2017)	Vector (shapefile)	https://ecoregions.appspot.com/

NB: Further datasets can be used to refine the outputs, if available (e.g. BA at local scale, detailed LULC maps etc.)

Step 1. Estimate FSR in the landscape

Goals

To obtain a FSR map of the target landscape, using LULC and terrain variables (slope/aspect).

Rationale

FSR results from the characteristics of the fuel (volume, density, humidity, presence of flammable oils etc.), which changes across LULC types in the landscape (e.g. conifers are usually more fire-prone than broadleaves, fire spreads faster in shrublands than in closed forests etc.). In addition, slope and aspect affect the speed of fire spread (i.e. southerly aspects are warmer than northerly aspects, creating more favourable conditions for fire ignition and spread; on steeper slopes fire spread faster due the presence of uplift winds). Combining LULC and terrain features leads to the estimation of the FSR in the landscape.

Methodology

All datasets must be clipped/masked to the AOI. In addition, LULC (100m resolution) must be resampled at the EU-DEM resolution (25m).

Step 1.1 – Prepare layers

LULC. Reclassify Copernicus GLC from the original 22 categories into a smaller set of LULC categories, grouped according to similar FSR (expert-based). An example is provided in Table 3.

Terrain (slope and aspect). Calculate slope (expressed as continuous variable, range 0-90°) and aspect (expressed as continuous variable, range 0-359.9°) from the EU-DEM. Similarly to LULC, reclassify both variable layers in categories. Slope may be reclassified into 7-degree interval categories (e.g. 5 categories, see Table 4). Aspect is reclassified into 8 cardinal points (Table 5). A focal statistic (mean or median) can be applied before the reclassification through a moving window (e.g. 5x5) to both terrain layers, in order to minimise the biasing effect of rugged terrain and to consider these features to a wider context.

Table 3 *– LULC types classified by the Copernicus GLC and a potential reclassification of the 22 classes into 10 (in green) and an example of Manly's indices (see Step 1.2 for explanation)*

CODE	LAND COVER CLASS	DEFINITION ACCORDING UN LCCS	RECLASS TO	MANLY INDEX (e.g.)
121	Open forest, evergreen needle leaf	top layer- trees 15-70 % and second layer- mixed of shrubs and grassland, almost all needle leaf trees remain green all year. Canopy is never without green foliage	1	1.273
123	Open forest, deciduous needle leaf	top layer- trees 15-70 % and second layer- mixed of shrubs and grassland, consists of seasonal needle leaf tree communities with an annual cycle of leaf-on and leaf-off periods		
122	Open forest, evergreen broad leaf	top layer- trees 15-70 % and second layer- mixed of shrubs and grassland, almost all broadleaf trees remain green year round. Canopy is never without green foliage.	2	1.158
124	Open forest, deciduous broad leaf	top layer- trees 15-70 % and second layer- mixed of shrubs and grassland, consists of seasonal broadleaf tree communities with an annual cycle of leaf-on and leaf-off periods.		
125	Open forest, mixed	Open forest, mix of types		
126	Open forest, unknown	Open forest, not matching any of the other definitions		
111	Closed forest, evergreen needle leaf	tree canopy >70 %, almost all needle leaf trees remain green all year. Canopy is never without green foliage.	3	0.236
113	Closed forest, deciduous needle leaf	tree canopy >70 %, consists of seasonal needle leaf tree communities with an annual cycle of leaf-on and leaf-off periods		

CODE	LAND COVER CLASS	DEFINITION ACCORDING UN LCCS	RECLASS TO	MANLY INDEX (e.g.)
112	Closed forest, evergreen, broad leaf	tree canopy >70 %, almost all broadleaf trees remain green year round. Canopy is never without green foliage.	4	0.436
114	Closed forest, deciduous broad leaf	tree canopy >70 %, consists of seasonal broadleaf tree communities with an annual cycle of leaf-on and leaf-off periods		
115	Closed forest, mixed	Closed forest, mix of types		
116	Closed forest, unknown	Closed forest, not matching any of the other definitions		
20	Shrubs	These are woody perennial plants with persistent and woody stems and without any defined main stem being less than 5 m tall. The shrub foliage can be either evergreen or deciduous.	5	1.853
40	Cultivated and managed vegetation/agriculture (cropland)	Lands covered with temporary crops followed by harvest and a bare soil period (e.g., single and multiple cropping systems). Note that perennial woody crops will be classified as the appropriate forest or shrub land cover type.	6	0.592
30	Herbaceous vegetation	Plants without persistent stem or shoots above ground and lacking definite firm structure. Tree and shrub cover is less than 10 %.	7	2.289
60	Bare / sparse vegetation	Lands with exposed soil, sand, or rocks and never has more than 10 % vegetated cover during any time of the year	8	0.000
90	Herbaceous wetland	Lands with a permanent mixture of water and herbaceous or woody vegetation. The vegetation can be present in either salt, brackish, or fresh water.	9	0.276
100	Moss and lichen	Moss and lichen	0	0.153
50	Urban / built up	Land covered by buildings and other man-made structures		
70	Snow and Ice	Lands under snow or ice cover throughout the year		
80	Permanent water bodies	Lakes, reservoirs, and rivers. Can be either fresh or salt-water bodies		
200	Open sea	Oceans, seas. Can be either fresh or salt-water bodies.		

Table 4 *- Proposed reclassification table for slope and an example of Manly's indices (see Step 1.2 for explanation)*

FROM	TO	RECLASS TO	MANLY INDEX (e.g.)
0	6.9°	1	0.656
7°	13.9°	2	1.419
14°	20.9°	3	1.226
21°	27.9°	4	1.111
28°	90°	5	0.896

Table 5 *– Proposed reclassification table for aspect and an example of Manly's indices (see Step 1.2 for explanation)*

FROM	TO	RECLASS TO	MANLY INDEX (e.g.)
337.5°	22.4°	N	0.860
22.5°	67.4°	NE	0.722
67.5°	112.4°	E	0.824
112.5°	157.4°	SE	1.478
157.5°	202.4°	S	1.581
202.5°	247.4°	SW	0.897
247.5°	292.4°	W	0.638
292.5°	337.4°	NW	0.640

Step 1.2 – Calculate Manly's index to estimate FSR with respect to each variable and reclassify layers

Manly's index. The methodology used to estimate FSR in target landscapes foresees the computation of selection ratios, a methodology usually proposed for the study of resource selection by animals (Manly et al., 2022) and transposed to application in fire research by Moreira et al. (2001, 2009)
The selection ratio (Mi) for a given LULC or terrain (slope or aspect) class i is an index of selection estimated as

$$M_i = B_i / A_i$$

where B_i is the proportion of burnt land belonging to class *i* (estimated from the EFFIS burnt area dataset) and Ai is the proportion of available land belonging to class *i* in the landscape. If a given class is affected by wildfires proportionally to its availability, then M=1. If M> 1 the class burns more than expected by chance. If M< 1, the class burns less than expected by chance (see examples in Table 3, Table 4, Table 5).

This calculation can be performed by masking each FSR variable (LULC, slope, aspect) with the EFFIS' BA dataset (shapefile), to extract the extent of burnt land for each class and the relative proportion. Then, the proportion is eventually compared to the overall proportion of the extent of each class in the target landscape. For each class, a Manly's index value is calculated.

Reclassify layers with Manly's index to obtain a FSR layer for each variable. LULC, slope and aspect layers are eventually reclassified according to the Manly's index of each class. The Manly's index represents a FSR index. Thus, this step leads to the computation of the FSR for each variable in the target landscape.

Step 1.3 – Compute FSR index map

Scale Manly's index reclassified layers. In order to give equal weight to LULC and terrain in the final FSR estimation, a data normalization function (range 0-1) is applied to each layer. The function is

$$X_{i\,norm} = (X_i - X_{min}) / (X_{max} - X_{min})$$

Sum LULC, slope and aspect normalized layers. Map algebra is eventually applied by summing normalized LULC to the mean normalized slope and aspect as follows

$$FSR = FSR_{LULC} + [(FSR_{slope} + FSR_{aspect}) / 2]$$

The FSR estimation results by summing LULC FSR and terrain FSR. FSR values can range from 0 to 2 (continuous variable).

Compute FSR index by reclassify into quantiles. A final FSR index (ordinal variable) is eventually computed by reclassifying the FSR map into quantiles. The FSR index map can foresee a 5-value scale (1 = lowest FSR; 5 = highest FSR = HFSR). In this case, quintiles (0.2 intervals of the distribution) are calculated and then used as thresholds to reclassify the "continuous" FSR layer.

Step 2. Estimate the effectiveness of FSLM In reducing ba of wildfire events

Goals

To estimate the effectiveness of decreasing FSR from class 5 (=HFSR) to class 3 or 4 (=MFSR) through FSLM in reducing BA during wildfire events.

Rationale

FSLM aim at reducing FR and therefore the occurrence of wildfires or the BA extent. FSLM should target HFR areas, i.e. where HFSR and HFIR overlap. Observing FSR in HFIR in past BAs helps highlighting the correlation between HFSR and wildfire sizes. For the same size, HFSR areas produce larger fires than MFSR. This step will quantify this difference.

Methodology

Step 2.1 – Compute HFIR areas

Using the OSM dataset, apply a 50m-wide buffer to paved roads and buildings and a 25m-wide buffer to paths. These figures can be modified according to considerations at local scale, or can be applied to other infrastructures (e.g. railroads, powerplants etc.) or specific LULC categories where fire is usually set (e.g. croplands, rangelands). Merge and dissolve the buffers to create a HFIR mask (a "cookie cutter") for the following steps.

Step 2.2 – Estimate effectiveness of FSLM (=reducing FSR from High to Medium) in reducing wildfire events BA through Weighted linear square (WLS) regression

Extract FSR area size in BAs and in HFIR within BAs. Convert FSR index map from raster to vector and intersect it (not clip!) with FSR with the EFFIS' BA layer. This will generate a vector layer of FSR in BAs, where each polygon retains the information of the BA extent of each wildfire event (already included in the EFFIS dataset). Please note that different wildfire events can have occurred on the same area, so overlaid FSR polygons can be generated, each of them attributed to a different wildfire event. Calculate the extent of HFSR and MFSR within each BA. Similarly, use the HFIR mask generated in Step 2.1 on the FSR in BAs to clip FSR in HFIR areas only within BAs and calculate the extent of HFSR (=HFR) and MFSR areas.

Finally, generate a dataset where, for each wildfire event, HFSR and MFSR areas are calculated, both in the whole BA and only in HFIR areas within BAs. Calculate also the relative proportion of the extent of each class in BA with respect to the extent of HFSR and MFSR summed (Table 6).

Table 6 *– Example of dataset to perform WLS. In green, the variables of the WLS (see next paragraph)*

FIRE ID	BA (ha)	FSR CLASS	SIZE IN WHOLE BA (ha)	SIZE IN HFIR ONLY (ha)	PROP. IN BA
	y	x_2		x_1	*weight*
1063	23.12	MFSR	5.22	1.48	0.23
1063	23.12	HFSR	17.93	4.12	0.77
1260	126.40	MFSR	55.05	1.59	0.48
1260	126.40	HFSR	59.00	1.03	0.52
1263	18.19	HFSR	17.83	1.04	1.00
1547	44.96	HFSR	45.01	5.25	1.00
1759	30.81	MFSR	29.45	1.49	1.00
1847	6.81	MFSR	6.59	1.23	1.00
1932	20.88	MFSR	2.75	1.35	0.13
1932	20.88	HFSR	18.16	5.91	0.87
...	...	...	...	...	...

Perform WLS regression. A statistical package is needed to perform a WLS regression to estimate effect of HFSR vs MFSR areas in HFIR (=HFR) on BA size, according to the formula

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_1 x_1 * \beta_2 x_2$$

where

x_1 = HFIR burnt area
x_2 = FSR class
y = Fire BA size
β = regression coefficients
$\beta_1 x_1 * \beta_2 x_2$ = interaction term

The relative proportion of the extent of each FSR class in BA is included as a weight in the regression, to account for the biasing effect of the potential higher share of HFSR in the landscape. The β_2 coefficient can be interpreted as the theoretical effectiveness of FSLM on reducing BA for each wildfire event. In the example shown in Table 7, each hectare where FSR is decreased from High to Medium will reduce the BA by 22.8 ha. An interaction term can be included in the model to highlight the increased effect of HFSR as wildfire BA increases. However, it is advisable to take a conservative approach and discarding the interaction coefficient from subsequent steps.

Table 7 *– Example of result of the WLS. In yellow, the coefficient used for subsequent calculations (=wildfire events BA reduction by decreasing FSR from High to Medium)*

INDIPENDENT VARIABLES		**ESTIMATE (β)**		**STD. ERROR**	**T VALUE**	**PR(>|T|)**	
	(Intercept)	29.357	(β_0)	12.277	2.391	0.018	**
x_1	HFIR BA size	6.071	(β_1)	0.345	17.615	> 0.001	***
x_2	FSR CLASS (MFSR vs HFSR)	**-22.837**	(β_2)	15.496	-1.474	0.022	*
$\beta_1 x_1 * \beta_2 x_2$	Interaction	-0.972		0.405	-2.403	0.017	*

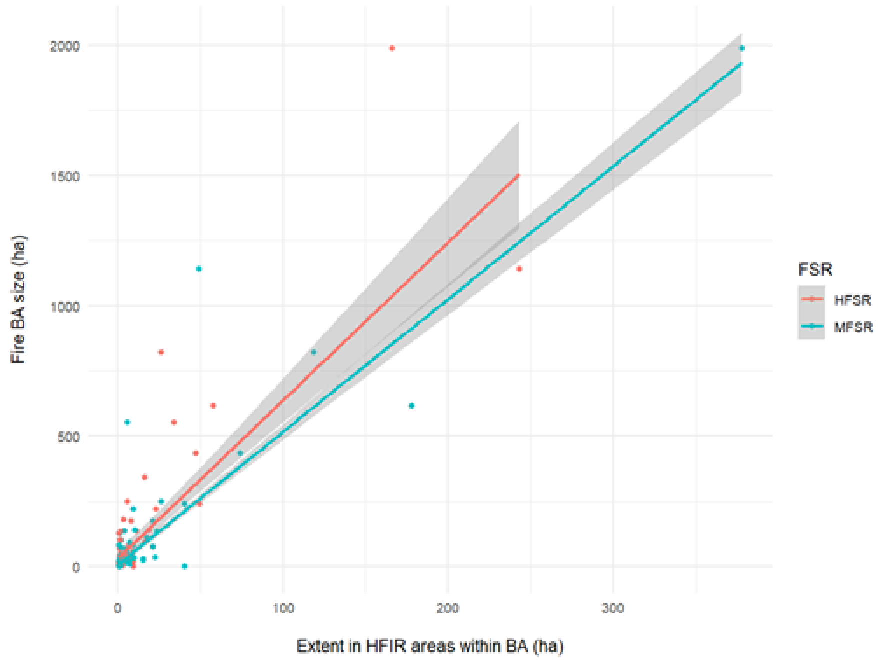

Figure 1 – *WLS regression. Note the different slopes of the regression lines, which denote interaction between* x_1 *and* x_2

Step 3. Estimate the effectiveness of FSLM in reducing BA in the whole landscape

Goals

To estimate the effectiveness of decreasing FSR from High to Medium through FSLM in reducing annual BA in the landscape.

Rationale

In Step 2 the effectiveness of FSLM has been estimated at the scale of wildfire event. This figure is eventually applied at landscape scale by relating it to the annual BA and the extent of HFR areas. Two different scenarios are estimated (FSLM on 2% and 5% of the HFR areas).

Methodology

Step 3.1 – Calculate the extent of the HFR areas in the landscape (=FSLM potential target areas)

Similarly to the Step 2.2, mask (=clip) the FSR index map computed at the end of Step 1 with the HFIR areas, to calculate the extent of each FSR class in the landscape by summarising all areas by class. The overall extent of potentially target areas of FSLM in the landscape are represented by the HFSR extent in HFIR areas.

Step 3.2 – Calculate the annual mean BA ratio of HFSR areas in the landscape

Summarise by year and FSR class the BA extent from the FSR index map intersected with EFFIS' BA layer computed in Step 2.2. Then, calculate each FSR class overall area in the landscape, by summarising by FSR class the overall extent of each FSR class from the FSR index map computed at the end of Step 1. Eventually, calculate the annual mean BA ratio of HFSR area by Dividing the mean annual HFSR BA by the overall extent of HFSR in the landscape.

Step 3.3 – Calculate the overall annual mean BA in the landscape

Calculate the annual mean BA in the landscape, using the dataset computed in Step 3.2.

Table 8 *– BA in AOI summarised per year and FSR class. In the bottom part, figures derived from the calculations are reported. Shaded numbers refer to figures that are eventually not used. Coloured cells highlight figures that are included in the formula used to estimate FSLM effectiveness*

YEAR	BA PER FSR CLASS (HA)					SUM
	1	2	3 (MFSR)	4 (MFSR)	5 (HFSR)	
2001	0.4	12.2	10.6	71.9	223.5	318.6
2002	19.5	32.1	168.0	254.7	194.3	668.6
2003	145.0	112.0	261.5	396.7	260.1	1,175.3
2004	18.4	9.0	40.8	27.8	148.6	244.5
2005	354.2	259.2	542.4	705.7	681.1	2,542.7
2006	17.9	12.5	21.0	57.7	81.1	190.3
2007	18.5	17.5	50.5	93.0	233.6	413.1
2008	1.1	0.7	2.4	8.6	75.5	88.2
2009	3.7	5.5	9.7	22.4	20.6	62.0
2010	0.1	0.2	0.4	2.4	3.2	6.3
2011	0.4	1.9	5.6	27.3	16.4	51.5
2012	41.3	13.1	30.3	44.2	159.2	288.2
2013	5.7	2.8	11.2	5.6	31.6	57.0
2014	2.6	1.9	5.8	13.0	22.8	46.1
2015	8.3	10.2	11.9	11.8	13.8	56.0
2016	16.2	19.0	18.9	33.7	98.0	185.8
2017	93.4	60.0	105.5	320.1	1.329.9	1,908.8
2018	0.5	0.5	2.2	5.9	5.7	14.8
2019	63.8	39.2	50.5	160.5	209.1	523.0
2020	47.5	47.9	38.3	57.6	36.3	227.6
2021	55.5	49.6	31.5	88.0	206.5	431.1
2022	68.1	142.7	205.2	217.5	980.3	1,613.8
ANNUAL MEAN BA	44.6	38.6	73.8	119.4	228.7	**505.2**
OVERALL AREA	197,849.1	176,046.6	188,366.8	183,858.5	186,314.6	932,435.7
ANNUAL MEAN BA RATIO	0.0002	0.0002	0.0003	0.0006	**0.0012**	0.0005
HFIR (HFR) AREA	75,906.2	48,691.0	52,751.4	55,360.6	**42,590.5**	275,299.8

Step 3.4 – Calculate the effectiveness of FSLM in reducing BA in the landscape according to two scenarios

The final estimation of FSLM effectiveness is calculated as follows

$$\boxed{\text{HFR}} * \textit{scenario ratio} * \boxed{\beta\ \textit{FSR class coefficient}} * \boxed{\textit{Annual mean HFSR BA ratio}} = \text{Annual BA reduction}$$

$$\boxed{\textit{Annual BA reduction}} / \boxed{\textit{Annual mean BA}} * 100 = \text{Annual BA reduction percentage}$$

Scenario 1. FSLM on 2% of HFR area

$$\boxed{42{,}590.5} * 0.02 * \boxed{22.837} * \boxed{0.0012} = 23.84 \text{ ha / year}$$

$$23.84 / \boxed{505.2} * 100 = 4.72\ \%\ \text{annual BA reduction in the AOI}$$

Scenario 2. FSLM on 5% of HFR area

$$\boxed{42{,}590.5} * 0.05 * \boxed{22.837} * \boxed{0.0012} = 59.60 \text{ ha / year}$$

$$59.60 / \boxed{505.2} * 100 = 11.80\ \%\ \text{annual BA reduction in the AOI}$$

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