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The economic value of fire damages in Tuscan agroforestry areas

Claudio Fagarazzi [(1)], Roberto Fratini [(1)], Mara Montanino [(1)], Mauro Viccaro [(2)], Mario Cozzi [(2)], Severino Romano [(2)], Francesco Riccioli [(3)]

The Tuscan Region (Central Italy) spends about 12 million euros every year in the prevention and suppression of forest fires. In this context, this study aims to analyse the economic and environmental benefits derived from fire suppression activities. Starting from a case study of a real fire event in Tuscany, we simulated three hypothetical scenarios (with different fire durations) without fire extinction activities planned by using the open source software FARSITE. Benefits derived from fire extinction activities can be quantified as the avoided damage, which has been calculated through the estimation of the total economic value of forests not destroyed by fire thanks to the extinction action. The avoided damage is represented by the difference between values of forest areas burned by the real fire event and those burned by simulated fire. By providing an economic estimation of avoided damages, our results confirm that forest fire services and forest management have a high impact on both the economy and the environment.

Keywords: Fire Damage, FARSITE, Total Economic Value, Fire Simulation, GIS

Introduction

In the last few decades, changes in land use and society have led to a significant increase in the number of wildfires. This phenomenon has become an important socio-economic and environmental problem that requires great attention, especially in terms of prevention (FAO 2011). Climate change plays an important role in the fire hazard, and a number of studies attempted to analyse this correlation (Garbolino et al. 2019, Syphard et al. 2019). In particular, climate change has a relevant role in the intensity of events, as drying and warming periods have proven to be important determinants for fire hazard. Cammelli & Angelsen (2019) argue that frequency and extent of forest fires have been increasing over the last two decades in the Amazon. Tan et al. (2019) analyse a large wildfire occurred in Fort McMurray, Canada, and related this event to extremely warm and dry weather conditions in spring due to climate change.

The development of urbanized areas and viability in wild and mountainous areas are the main factors of this phenomenon. Indeed, the trigger point of numerous fires is close to the edge of roads and highways (Martínez et al. 2009).

Despite the increase in the number of fires, the surfaces covered by fire are progressively decreasing in extent. In Italy, in the decade between 1995 and 2005, 1,185,000 hectares (ha) of surface burned, while 765,000 ha were destroyed by fire in the previous decade (2006-2015), corresponding to a reduction of 35% (Perelli 2013). The reduction in the area covered by fires in recent years is, above all, the consequence of an improvement in firefighting organization both at regional and national level. In the case of Tuscany, the number of forest fires did actually increase from 2010 to 2015, but the wooded area covered by the fire significantly decreased. During this period, the number of forest fires rose from 243 to 303 per year, while the average area of individual events declined from 1.56 to 0.75 ha (Perelli 2013).

The regional administration of Tuscany invests almost 12 million euro per year in forest fire prevention and repression activities. Despite such significant financial commitment, both the extent of the damage caused to goods and that of the damage avoided thanks to fire prevention and repression are still unclear. Knowing the magnitude of such effects would allow better efficiency and effectiveness of investment planning policies.

Several studies in the literature aimed to assess the damage caused to agroforestry areas by fires (Arca et al. 2009, Di Renzo et al. 2012). This work focus on a methodology aimed to assess the potential evolution of fires in the absence of anthropogenic extinction and to evaluate the resulting avoided damages. Starting from a case study taken from a real event occurred in Tuscany, three different scenarios of wildfire were simulated excluding fire extinction activities. These simulations were implemented in a Geographical Information Systems (GIS) program using the open source software FARSITE (Finney & Ryan 1995) to simulate a fire event (Corona et al. 2014).

Avoided damages are related to forests and the ecosystem services they provide (Viccaro & Caniani 2019), and include benefits such as recreation and tourist functions, biodiversity conservation, timber production, carbon storage, and hydrogeological conservation. These benefits represent the Total Economic Value (TEV) of the forest and consider both private and public environmental functions. Many studies in the literature have quantified these functions (Tao et al. 2012, Marinelli & Marone 2013, Chatzinikolaou et al. 2015, Bottalico et al. 2016). In this study, we have calculated the TEV of the area burned during a real

(1) University of Florence, Department of Agricultural, Food, Environmental and Forestry Sciences and Technologies, p.le delle Cascine 18, I-50144 Firenze (Italy); (2) University of Basilicata, School of Agricultural, Forestry, Food and Environmental Sciences, v. dell'Ateneo Lucano, I-85100 Potenza (Italy); (3) University of Pisa, Department of Veterinary science - rural economic section, v.le delle Piagge 2, I-56124 Pisa (Italy)

@ Francesco Riccioli (francesco.riccioli@unipi.it)

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fire event and the TEV of areas destroyed by simulated fires. Fire extinction activities are planned only in the real event, so the difference between the TEV of simulated events and TEV of the real event represents the avoided damages due to fire extinction activities.

The goal of the paper is to quantify the avoided damage by forecast a burned area by simulating a fire event with FARSITE and calculate the corresponding TEV values.

Material and methods

Case study

The wildfire examined occurred in Verniano, Colle di Val d'Elsa, near Siena (Tuscany, Central Italy) during the period between July 11 and August 3, 2012 (Fig. 1). The affected area was 308.12 ha. The area is mostly hilly (66.5%), with some plains (about 8.4% of the territory) and major mountain ranges (25.1% of the region), and annual rainfall of about 600-700 mm.

The fire was certainly arson and caused by pruning residues burned in a farm near the affected area. The deployment of intervention forces was difficult, due to adverse weather conditions that required complex action plans and the intervention of three Canadair firefighting aircrafts over four days.

The area affected by the fire included mixed stands of conifers and broad-leaved trees, with a prevalence of Mediterranean pines and cypresses (domestic pine, maritime pine, Aleppo pine).

The estimated damage of the real fire event is based on the perimeter delineated by firefighters. For determining the costs of extinction or specific costs of the fight, reference was made to studies conducted by the Italian Academy of Forest Sciences in 2007 (Ciancio et al. 2007). In this study, an intermediate approach was applied, based on the detailed definition of unit costs of personnel and equipment, in relation to the National Collective Labour Contracts of the various operators involved (State Forestry Corps, National Fire Corps, etc.) and the hourly costs of the equipment that can be inferred from service contracts, *Confindustria* (General Confederation of Italian Industry) construction tables and sector bibliography, and technical data sheets. The total cost of fire extinction activities was over 1,222,000 euros.

Simulations of fire

Simulations of wildfire were performed using the software FARSITE (Fire Area Simulator). FARSITE, developed by Finney & Ryan (1995), was integrated using a vector propagation technique for fire perimeter expansion that controls both space and time resolution of fire growth over the landscape. FARSITE is a deterministic fire growth model using a vector propagation technique to simulate fire perimeter expansion over a heterogeneous landscape-where the simulation results can be directly compared to inputs. FARSITE is an efficient tool for simulating fire spread across a landscape as it accounts for the variability of fuel moisture, wind speed and direction over time and space. This is a powerful system suitable to simulate ground and air suppression actions in order to identify a set of comparable scenarios and results. In particular, the FARSITE was recently implemented in the FlamMap software (https://www.firelab.org/project/flammap).

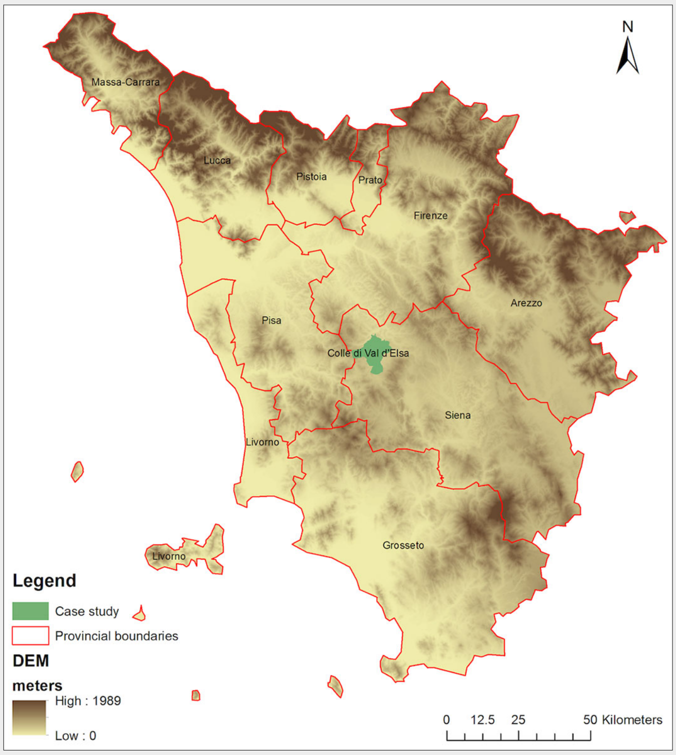

Fig. 1 - The study area in Verniano, Tuscany (Central Italy).

The new FlamMap is able to model the potential fire behavior (spread rate, flame length, fireline intensity, etc.) under constant environmental conditions (weather and fuel moisture). In particular, thanks to the inclusion of FARSITE, the software can compute wildfire growth and behavior for longer time periods under heterogeneous conditions of terrain, type of fuels, fuel moistures and weather.

The FlamMap algorithm calculates the minimum fire travel time between nodes over a gridded landscape relying upon the spatial variability of fuels and topography to drive fire growth. However, FlamMap algorithm is not a complete fire growth simulation model like FARSITE. Despite this limitation, FlamMap will be evaluated to determine if it might offer computational advantages over FARSITE in an operational forecast setting (Finney 2004, 2006).

Furthermore, the FARSITE was recently implemented with FlamMap in the Wildland Fire Decision Support System able to support fire officers in tactical and strategic management decisions in the long-term (up to 14 day). In detail, the model produces vector fire perimeters at specified time intervals; the vertices of these polygons contain information which is then interpolated to produce raster maps of fire behaviour.

The vector modelling approach proved to be a practical technique for incorporating separate models for surface fire, crown fire, acceleration, spotting, and fuel moisture. The model integration was relatively straightforward because the one-dimensional calculations for each model apply directly to the vertices on the fire front.

The semi-empirical propagation model of Rothermel's grazing fire is based on statistical observations of the fire phenomenon under controlled conditions, combined with physical considerations of the combustion event. It derives from the correction of the Frandsen equation of 1971 (Sugihara et al. 2006) and is calculated as the amount of heat received from the vegetal fuel in the numerator, the denominator being the amount of heat necessary to bring the fuel to the ignition temperature (eqn. 1):

$$R=\frac{I_{xig}+\int_{-\infty}^{0}\left(\frac{\partial Z_c}{\partial Z}\right)_{Z_c}dx}{\rho_{be}Q_{ig}} \qquad (1)$$

where R is the quasi-steady state rate of spread, I_{xig} is the horizontal propagating heat flux, the value $(\partial Z_c/\partial Z)_{Z_c}$ represents the gradient of the vertical intensity flux, ρ_{be} is the effective bulk density and Q_{ig} is the heat of pre-ignition.

In the literature, the FARSITE software has been applied to enhance data assimilation capabilities on both fire perimeters and fuel adjustment factors, thus improving the accuracy of fire spread predictions. Srivas et al. (2017) used the "Ensemble Kalman Filter" (EnKF) to extend FARSITE with data assimilation capabilities to up-date both fire perimeters and fuel adjustment factors. Zhou et al. (2019) tested an extension of EnKF called Ensemble transform Kalman Filter (ETKF) which avoids using perturbed observations to eliminate additional sampling errors.

The FARSITE outputs illustrate the strict spatial consequences of fire behaviour by incorporating the models into a two-dimensional simulation. Simplified test conditions show that surface fire growth and intensity conform to idealized patterns. Similarities also exist between simulated crown fires and observed patterns of extreme wind-driven fires. According to Finney & Ryan (1995), the model generates complex patterns of fire growth and behaviour based on spatial and temporal dependencies. On the other hand, the FARSITE model requires uniform conditions (in space and time) of the factors affecting fire (fuels, weather, and topography) over the wildfire area, although these conditions rarely exist in nature.

The input of the model included several data layers which can be grouped in three main categories: (i) landscape data; (ii) weather data; and (iii) fuel data.

(i) Landscape data include the digital elevation model, slope, canopy cover, and fuel type. To ensure a good representation of the FARSITE model in the Italian context, we defined the fire growth of individual fuel types by reclassifying land uses as fuel type codes which reflect the susceptibility to burning of each land use. To this purpose, the 1972 Rothermel model was modified in order to match the CLC (Soil Corine Land Cover 2012 level V, ver. 18.5.1) classes and the Rothermel Fuel Model classes (Rothermel 1972).

(ii) Weather data (start-end precipitation, min/max temperature, min/max humidity, etc.) and data of the event (such as ignition point, direction, wind speed, etc.) were obtained from LAMMA (2020). Each parameter was georeferenced using a pixel resolution of 10 meters.

(iii) Fuel files data are related to characteristics of land use such as crown bulk density, crown base height, foliar moisture content, stand height, etc.

Combining the above-mentioned data in the FARSITE input, three different scenarios were simulated which differed in the duration of the wildfire event without fire extinction activities: (i) Simulation 0 = same duration of the real event in Verniano; (ii) Simulation 1 = 7 days more than the duration of the real event; (iii) Simulation 2 = 14 days more than the duration of the real event.

Evaluation of total economic value

Forest produces both private goods (timber production, non-wood products) and public utility services (recreational activities, hydrogeological function, biodiversity protection, CO_2 storage, etc.). Considering fire damages, the multifunctional role of forest introduces a significant problem related to the compensation of two subjects involved: private owners for damage suffered by their incomes, and public owners for damage to ecosystem services. We computed the avoided damage due to fire extinction activities by quantifying the ecosystem function/services provided by the forest. These benefits represent the Total Economic Value (TEV) of the forest considering both private and public environmental functions, including incomes (*e.g.*, climate change mitigation service, wood production, etc.).

Regarding the degree of damage and the intensity of the event, the proposed approach requires to set some initial hypotheses. First, it is assumed that the damage to the forest is total, not partial; second, we hypothesized that the effects on private and public functions are temporary and therefore all functions can be restored after a recovery time.

Several authors in the literature analysed the damage to forests through the quantification of the TEV. Di Renzo et al. (2012) underline that the determination of the damage and its compensation cannot disregard the various components that contribute to the total economic value of the forest area. Specifically, they define the damage of private interest as those ascribable to the forest topsoil, to the structures and infrastructures, while those of public interest are represented by damages to all those goods and resources providing services of public interest which were compromised after the wildfire.

A wide literature provides a schematic classification of TEV. Pearce (2001) and Polelli (2008) divide TEV into two macro-categories (Use Value and Non-Use Value). Moreover, they are subdivided into Direct Value, Indirect Value, Option value, Existence Value and Bequest Value categories. In this study, the approach proposed by Bernetti et al. (2011), Bernetti et al. (2013) and Marinelli & Marone (2013) has been adopted for TEV estimation. These authors provided a quantification of TEV (in euros ha^{-1} per year) by using a territorial approach where the TEV value of all forests in Tuscany have been georeferenced.

The following functions have been considered in this study: (i) tourist-recreational function; (ii) naturalistic function; (iii) hydrological function; (iv) drinking water service; (v) timber production; (vi) carbon sequestration.

The recreational tourist function is given by the sum of recreational tourism activity, hunting activity and mushroom collecting activity. The first activity was estimated using the Travel Cost Method (TCM) with specific logit models for naturalistic areas (Ferrini 2002). The recreational value was obtained using the Random Utility Travel Cost Method (RUTCM) proposed by Ferrini (2002) and considering different variables (*e.g.*, age, education, etc.). This method has been employed to assess multivariate demand functions in protected areas. In this case, the variation of the consumer surplus was evaluated following an increase of 10% of the surface for 19 natural parks in Tuscany (Ferrini 2002). Hunting activities were evaluated based on the willingness-to-pay of hunters, according to Marinelli & Romano (1997). The updated result has been correlated with the number of active hunters in Tuscany, which is equal to 520.77 euros ha^{-1} per year per hunter multiplied by all hunters of Tuscany (111,827) in the year 2012. Finally, the recreational function (mushroom collection) was calculated based on the maximum value for the authorization to mushroom picking (15 euros per day) provided by regional law no. 16/1999. This value was multiplied by the number of persons collecting mushroom (461,093) and the average picking day per person (5).

Natural functions were calculated according to literature reviews (Fisher & Raucher 1984, Boyle & Bishop 1987) based on the willingness-to-pay (in euros per family per year) for biodiversity, ecological value and endangered species.

The water flow service was estimated based on the refurbishment costs that would be necessary to pay in order to guarantee the maximum flow rates in the absence of the forest. In particular, considering run-off index and aridity index of each basin (Marinelli & Marone 2013, Riccioli et al. 2019a), a maximum sizing of the expansion tank system was necessary to ensure the disposal of the increase inflow due to the absence of forest and to calculate the total annualized cost of the system of boxes. Finally, this subrogation cost was attributed to each "pixel" of the basins proportionally to the quantity of water governed by the presence of the forest.

The drinking water service was assessed by hypothesizing that the best alternative to groundwater is represented by the water reserves stored in artificial basins and the consequent contribution of forest soils to the production of drinking water calculated using the water balance method. In this case, the values of water storage in the watersheds in Tuscany were defined based on the studies carried out by Civita et al. (1999). The process was achieved in two steps. First, the water balance of a single forest location was calculated using the method of the reversed water balance. Then, to calculate the drinking water service value, the subrogation price per cubic meter was applied.

Timber production was calculated by converting the capital value of the forest, obtained with the classic Faustmann formula, into a yearly value. According to the methodology reported in Fagarazzi et al. (2009) and Fagarazzi & Tirinnanzi (2015), we considered data related to stumpage value (associated to the production processes, the forestry and harvesting activities), the ecological characteristics (increments, type of wood, etc.), and other variables (distance from the market centers, productivity, ma-

Tab. 1 - Total Economic Value (TEV) of each forest function/service calculated over all the Tuscany region (data expressed in euros yr^{-1}).

Function/Service	Value
Recreational/tourist function	219,860,253
Naturalistic function	210,043,738
Water flow control	28,224,320
Drinking water service	59,382,140
Wood production	25,116,257
Climate change mitigation service	59,017,484
TEV	601,644,192

chine costs, etc.).

Finally, the climate change mitigation service was quantified by assessing the carbon stored in the trees (and therefore not released into the atmosphere) which is related to tree growth. The calculation was based on the biomass expansion factor (BEF) to quantify the annual quantity of carbon fixed in the trees (Romano et al. 2015, Riccioli et al. 2019b).

All technical parameters, data source and calculations of each function are available in Appendix 1 of Bernetti et al. (2013).

Evaluation of avoided damage

The economic damage which was avoided thanks to fire suppression activities was quantified using the above-mentioned TEV.

TEV was calculated for each pixel falling within the burned area both during the real event and for each of the three simulated scenarios (see above) as follows (eqn. 2):

$$TEV_{ik} = \sum_{j=1}^{N} F_{jk} \qquad (2)$$

where TEV_{ik} is the TEV of *i*-th event (real event: r, or simulated fire: s) of *k*-th pixel (burned surface), F_{jk} is the value of *j*-th function belonging to the *k*-th pixel (burned surface), and N is the total number of functions examined.

Previous studies have considered separately the different forest functions/services (Romano et al. 2015, Bottalico et al. 2016, Riccioli et al. 2019c). In this work, we made the implicit assumption that the values estimated for each function at each pixel considered can be summed up in eqn. 2, despite different species, stand age, and forest type (coppice or high forest) were included in the analysis.

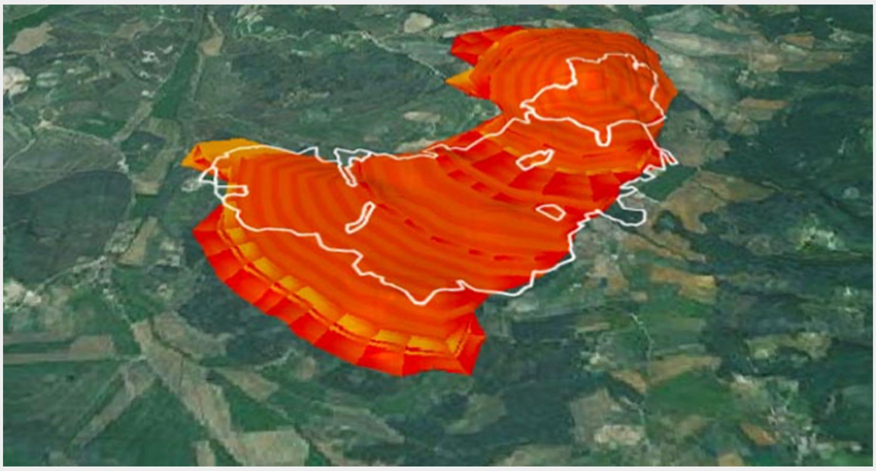

Fig. 2 - Extension of the area burned during the real fire event (in white) and that simulated under the "Scenario 0" (no fire suppression, same duration).

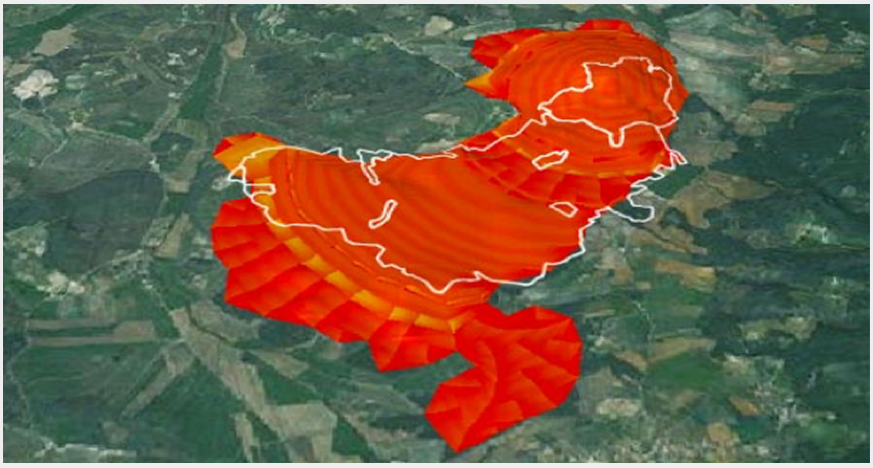

Fig. 3 - Extension of the area burned during the real fire event (in white) and that simulated under the "Scenario 1" (no fire suppression, +7 days duration).

The overall TEV quantified over the Tuscany region is shown in Tab. 1, expressed in euros $year^{-1}$.

The avoided damage (AD) is represented by the TEV calculated only on the areas preserved from fire (unburned) thanks to the fire extinction activities. For this purpose, the fire growth simulation model was run for a duration equal to that of the real fire (as recorded in the intervention sheet) in order to verify which areas have been preserved thanks to fire suppression interventions (Simulation 0). Additional simulations were performed based on the scenario of no fire suppression, with a fire duration of one (Simulation 1) and two (Simulation 2) additional weeks. The avoided damage due to fire extinction activities has thus been estimated by the difference between the TEV of the simulated fire (no fire suppression) and the TEV of the real event (where fire suppression took place), using the following formula (eqn. 3):

$$AD_k = TEV_{sk} - TEV_{rk} \qquad (3)$$

where AD_k is the avoided damage of *k*-th burned surface, $TEVs_k$ is the TEV of simulated fire in *k*-th burned surface (fire extinction activities not planned), and TEV_{rk} is the TEV of real event occurred in *k*-th burned surface (fire extinction activities planned).

Results and discussion

Simulated fires

Fig. 2, Fig. 3 and Fig. 4 show the results of the wildfire simulation model imposing different fire durations. The 3D images highlight how geomorphology and land use heavily affected the evolution of the fire; for matters of comparison, the boundary of the area interested by the real fire event is drawn in white, while the extent of the burned area obtained from the three simulations (Simulation 0: same duration of the real event; Simulation 1: +7 days; Simulation 2: +14 days) are depicted in red.

The surface destroyed by fire in Simulation 0 (Fig. 2) has an extension of 500 ha, almost matching the boundaries of the real event that occurred on the ground. An exception is represented by the area situated in the top part of Fig. 2, which was not interested by the wildfire. In this area, there are residential and tourist buildings that the extinction activities had successfully protected. The surface destroyed by fire in Simulation 1 (Fig. 3) has an extension of 600 ha, while in simulation 2 (Fig. 4) the burned area covers 620 ha; this fire destroyed a large portion of agricultural land, therefore slowing down the flame front.

The simulation results show that the fire slightly extend in south-west direction, while its perimeter remains almost unchanged in the other directions. By comparing the results of Simulations 1 and Simulation 2, it is possible to note that the difference in the burned area is only 20 hectares; this probably reflects the presence of crop fields, which during summer would not have represented a sufficient source of fuel to further support the spread of fire.

Economic evaluation of the avoided damage

The TEV of areas destroyed by the real fire event (which had been controlled by fire suppression activities) is equal to 51,660 euro per year (sum of *j*-th function belonging to the *k*-th burned surface). The TEV of areas affected by the three simulated fires is 66,197 euro per year in the case of simulation 0 (the same fire duration as the real event), 70,671 euro per year in the case of simulation 1 (+7 days fire duration) and 70,700 euro per year in the case of simulation 2 (+14 days fire duration). In all simulated scenarios, fire extinctions activities were not planned.

The avoided annual damage estimated by eqn. 3 were: (i) Simulation 0 = 14,537 euros per year (28.1% of real TEV); (ii) Simulation 1 = 19,011 euros per year (36.8% of real TEV); (iii) Simulation 2 = 19,040 euros per year (36.8% of real TEV).

It is important to note that on the 8^{th} day after fire ignition the fire front reached rocky and clayey areas poor in fuel, thus it seems plausible to hypothesize that the wildfire would likely be estinguished anyway due to fuel depletion.

The recovery time of forest stands and the restoration of ecosystem functions depends on many variables; in particular, it is strongly influenced by the tree species and the turnover of forest management (coppice or high forest). However, during recovery, the annual value of the forest functions is lost. According to Michieli & Cipollotti (2018) and Gallerani et al. (2011), the TEV of areas covered by fires was calculated considering the restoring time and the discount rate for economic estimation of monetary values as follows (eqn. 4):

$$AAD_k = AD_k \frac{q^n - 1}{rq^n} \qquad (4)$$

where AAD_k is the accumulation of avoided damage of *k*-th burned surface in restoring time, AD_k is the annual avoided damage of *k*-th burned surface, $q = 1 + r$, being *r* the discount rate and *n* the restoring time. The results are shown in Tab. 2.

Fig. 4 - Extension of the area burned during the real fire event (in white) and that simulated under the "Scenario 2" (no fire suppression, +14 days duration).

Tab. 2 - Estimated values of damage avoided due to fire suppression activities under different scenarios (different duration of the fire event).

Event	TEV (€ yr^{-1} - eqn.1)	Annual avoided damage (AD, € yr^{-1} - eqn. 2)	Accum. of avoided damage (AAD, € 20yr^{-1} - eqn. 3)
Real	51,660	-	-
Scenario 0	66,197	14,537	237,701
Scenario 1	70,671	19,011	310,857
Scenario 2	70,700	19,040	311,331

As argued by Malczewski (2004), analyses related to natural resources are characterized by a certain degree of uncertainty that is often related to the choice of the market discount rate (Adger et al. 1995, Ciancio et al. 2007). Therefore, in order to choose discount rate and restoring time, a sensitivity analysis has been conducted to assess the accumulation of TEV. The sensitivity analysis was performed considering a fixed discount rate over time and keeping all other factors fixed at their nominal value. Also, the turnover of forest management (restoring time) was considered in this analysis. Setting 2012 as the year zero (the date of fire), five temporal scenarios were considered (20, 40, 60, 80 and 100 years). The different time scenarios are related to the shift (turnover) of the forest species (*Quercus ilex*) and the forest management system used (high forest). For the discount rate, a range between 1% and 8% was considered (Ciancio et al. 2007, Nordhaus 2007, Bottalico et al. 2016.).

Tab. 3 shows the results of the sensitivity analysis carried out considering the annual avoided damage (AD) of the Simulation 0 scenario (14,537 euro per year).

Conclusions and final remarks

The Tuscan Region spends about 12 million euros every year in the prevention and suppression of forest fires. In this context, this study has analysed the economic and environmental benefits derived from the activities of fire suppression.

Regarding the extinction activities, a monetary approach for the quantification of direct damage "avoided" to the environ-

Tab. 3 - Sensitivity analysis of TEV for "Scenario 0" (data expressed in euros).

Restoring time	Discount rate 1%	2%	3%	4%	5%	6%	7%	8%
20	262,328.20	237,700.79	216,273.85	197,562.57	181,163.15	166,738.24	154,005.19	142,726.41
40	477,317.83	397,666.60	336,019.44	287,727.55	249,441.64	218,728.02	193,803.05	173,348.10
60	653,511.39	505,319.01	402,319.67	328,877.67	275,175.08	234,938.67	204,087.58	179,917.93
80	797,909.85	577,765.99	439,028.50	347,658.05	284,873.75	239,993.23	206,745.29	181,327.48
100	916,250.81	626,520.74	459,353.29	356,229.17	288,529.07	241,569.27	207,432.10	181,629.89

mental components and anthropic activities has been applied. In particular, the difference between the TEV of fire events simulated by FARSITE and the TEV of the real event represents the avoided damages due to fire suppression activities. For this reason, the fire growth simulation model is particularly important to define the surfaces preserved from fire thanks to the fire suppression intervention. The inclusion of different variables (*e.g.*, land use, meteorological conditions, type of fuel) in the FARSITE models allowed to define the spatial and temporal dynamics of fire in a case study located in the province of Siena (central Italy).

It is important to highlight that the observed results are strictly related to the specific fire event occurred in the case study area, as each wildfire is obviously different. Nonetheless, the methodology applied in this study could be adopted in other contexts in order to map the fire events both in a specific area (municipality, province, region, etc), in a specific period (days, weeks, months, etc.) and/or under specific weather conditions.

All data used in this study have been georeferenced with a high level of detail (pixel resolution: 10 × 10 m) using a Geographical Information System. The use of high-resolution georeferenced data represents a new frontier in spatial territorial planning, as argued by Zandersen & Tol (2009), Bernetti et al. (2011), Baerenklau et al. (2010), Bottalico et al. (2016) and Cozzi et al. (2019).

The main drawback of this study relies in the implicit assumption that the values estimated for each ecosystem function/service at each pixel can be added up together to quantify the TEV. This can be overcome in different ways in future studies. Nonetheless, the monetary quantifications of ecosystem services allowed to analyse fire damages from an economic and environmental point of view. Indeed, we highlighted the potential loss of the economic value of ecosystem services due to fire. Combining the information on the TEV in different fire scenarios based on simulations, we were able to quantify the damage avoided by fire suppression activities, which was equal to 14,537 euros year^{-1} for the Simulation 0 scenario, *i.e.*, 23% of TEV of the real condition.

The sensitivity analysis carried out allowed to forecast the future revenues that could be lost due to fire. This analysis provides different results using different temporal scenarios and different discount rates. The aim is to guide stakeholders towards an optimal planning decision.

In the case study, the fire suppression activities were characterized by a massive use of men and airplanes in the first four days to avoid fire propagation towards an inhabited area, and this justifies the high fire suppression costs. It is important to highlight how public goods have no effect on high suppression costs. The sequence of extinction activities and their intensity is listed in all operating manuals (Anonymous 2011): first protect people, then things (*e.g.*, houses, stables, agricultural outbuildings, etc.), and then forests. Consequently, they are attributed a significant economic and territorial protection value. It is important to stress that, despite the high annual costs of maintenance, the activities of fire prevention and suppression provide economic benefits related to the defense of environmental functions/services as well as private goods, like residential and touristic buildings and farms, which are fairly common in the rural areas of Tuscany.

Regarding the FARSITE model used in this study, the main weakness is the large amount of meteorological data necessary to apply the model to a specific area. However, the model does not consider the "management" choices of the coordinator of fire suppression operations, which deeply affects the fire extinction time and consequently the fire damage.

This study represents a first step to support the economic sustainability of fire extinction activities, and offers a useful basis to further improve the choice of correct planning strategies based on sustainable management of natural areas, as argued by Viccaro et al. (2019) and Riccioli et al. (2020). Future improvements of the methodology applied in this study should focus on the accumulation of the annual TEV of forest considering an accurate restoring time, which could be differentiated by the type of function and silvicultural system (coppice or hight forest). In this way, it will be possible to define the restoring process as a gradual function, whilst in our model the environmental functions/services are completely restored all at once at year 20. Moreover, an extension of the wildfires sampled and an improvement of the fuel model are desirable in future works.

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