Model of Post Fire Erosion Assessment Using RUSLE Method, GIS Tools and ESA Sentinel DATA

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Abstract. Soil erosion in fired areas is one of the main environmental problem involves degrading the quality of the soil and reducing the productivity of the affected lands. The aim of this work is to implement a procedure that analyzes the change detection of the potential soil eroded in a burned area, and discriminate the amount of potential soil loss. As part of the MESARIP project (in agreement with the Regional Civil Protection) in order to implement the analyses of soil erosion pre and post fire event, using Sentinel 2 data and with the RUSLE (Revised Universal Soil Loss Equation) method in a GIS open source environment, a graphical model has been developed. The application of the RUSLE requires a series of consequential spatial analysis elaborations and, according to this scheme, the model has been developed with the Graphical Modeler. QGIS contains in a single environment a multiplicity of tools and algorithms native to other open source GIS software, such as, for example, SAGA GIS and GRASS GIS. The user interface is very simple and requires basic and thematic input data such as DEM, MASK areas or vegetation indices etc. The advantages in the construction of the model can be identified in the standardization of map algebra operations and also in the speed of execution of the steps. Currently the model has been tested in some burned areas in 2019 located in the northern part of the Apulia Region and will be tested in operational mode during the 2020 summer season.

Keywords: Graphical modeler · RUSLE method · Soil erosion

1 Introduction

Soil erosion is a natural process which is responsible for landscape degradation. Forest vegetation generally is good for soil protection, however, human disturbances may

© Springer Nature Switzerland AG 2020
O. Gervasi et al. (Eds.): ICCSA 2020, LNCS 12253, pp. 505–516, 2020.
https://doi.org/10.1007/978-3-030-58814-4_36

accelerate erosion on territories with high relief energy. This processes represent one of the most serious environmental problem.

Climate change is also responsible for soil loss intensification. Several studies discuss how forestry activities [28] and land use change influence the sediment transport [2–4, 6, 8, 29, 31].

Soil erosion involves the detachment and transport of soil particles from the upper layers of the soil, degrading the quality of the soil and reducing the productivity of the affected lands. In fired areas this phenomenon is more evident as the effects of fire irreversibly degrade these soils.

Removing trees reduces evapotranspiration and rainfall interception leading to increased surface runoff. Furthermore without vegetation, soils become vulnerable to surface erosion. Most of the soil erosion study done by other researchers were based on the USLE/RUSLE [26, 27, 31] as a method to predict the soil loss, RUSLE takes into account several factors such as rainfall, soil erodibility, slope, land cover and erosion control practice for soil erosion prediction.

Remote sensing technologies can provide useful data for fire management, from risk estimation [5, 7, 13, 16, 22, 31], fire detection [18] to post fire monitoring [1, 14, 17] including burn area [4, 5, 27].

Puglia is, among the Italian regions, the least equipped with forests, despite this being among those most affected by incendiary phenomena. According to the estimates of the Regional Civil Protection, about 600 fires have been surrounded by forest police in 2019, of which 464 concern wooded areas.

The project "MESARIP satellite methodologies for the assessment of the risk of fires in the Puglia Region", in collaboration between the CNR IMAA and the Civil Protection Puglia, aims to provide tools and methodologies useful for the prevention, forecast and management of emergencies related to risk forest fires and interface also with the use of satellite technologies. The activities included in the project include that of estimating and studying fire severity and soil erosion in burnt areas.

The aim of this work is to implement a procedure that analyzes the change detection of the potential soil eroded in a burned area, and discriminate the amount of potential soil loss. In order to implement the analyses of soil erosion pre and post fire event, using ESA Sentinel 2 data and with the RUSLE (Revised Universal Soil Loss Equation) method in a GIS open source environment, a graphical model has been developed.

The graphical modeler has been developed using QGIS open source software and allows you to create complex models using a simple and easy-to-use interface.

QGIS contains in a single environment a multiplicity of tools and algorithms native to other open source GIS software, such as, for example, SAGA GIS and GRASS GIS. Thanks to this flexibility, the implemented model consists of elaborations that "point" to different software.

2 Material and Method

The study area covered by this work includes all the areas burned in 2019 in the Puglia region Apulia (see Fig. 1).

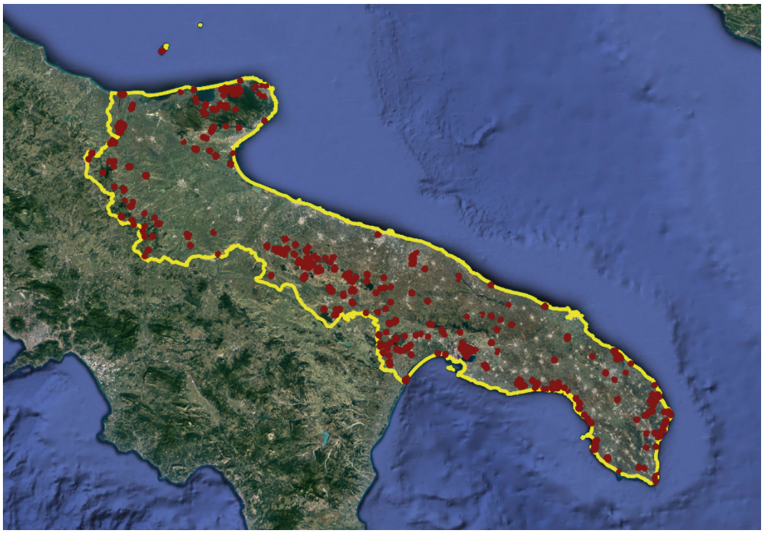

Fig. 1. Geographical localization of fire 2019 areas.

2.1 Fire Severity Assessment and RUSLE Methodology

After the fire, a series of spectrum changes takes place due to the fire consuming the vegetation, destroying the chlorophyll, leaving the soil bare, charring the roots and altering the soil's moisture. The reduction in chlorophyll results in an increase in the visible region of the electromagnetic spectrum and in a diminution in the near infrared region [12]. The NBR (Normalized Burn Ratio) combining information on the near infrared and the mid-infrared regions has been used in the discrimination of burned areas in the Mediterranean, using both a post-fire image and a bitemporal pre-/post-fire difference [12].

The severity of the fire was estimated using Sentinel 2 A and 2 B bands most sensitive to changes in the post-fire reflectance value (Band 8a and Band 12).

In order to assess fire severity degree, dNBR values was categorized. As it is known that dNBR ranges values are basically site-specific, fixed thresholds were not applied but [11] classification approach was adopted. These authors applied an unsupervised clustering algorithm [12] to objectively assign fire severity classes to dNBR on the base of data iterative partitioning [28]. This approach has benefits such as objectivity, possibility of use in case of unavailability of field data and minimizing the issues due outliers. In this study we selected six classes of dNBR: unburned; very low, low, moderate, high and very high. [14].

The dNBR index is used to produce the severity map of the fire on the ground. For each event analyzed, pre and post-fire images very close to the days of the event were used to capture the effects of first-rate fire on the ground. The dNBR index generated several spatial fire severity models related to different fire intensities for each study site. In Figs. 2 and 3, respectively, the images of the preview of the dNBR related to the webgis, the dNBR in grayscale contextualized to the study area, finally the dNBR with

the symbology based on the values assumed by each pixel on a certain portion of the area.

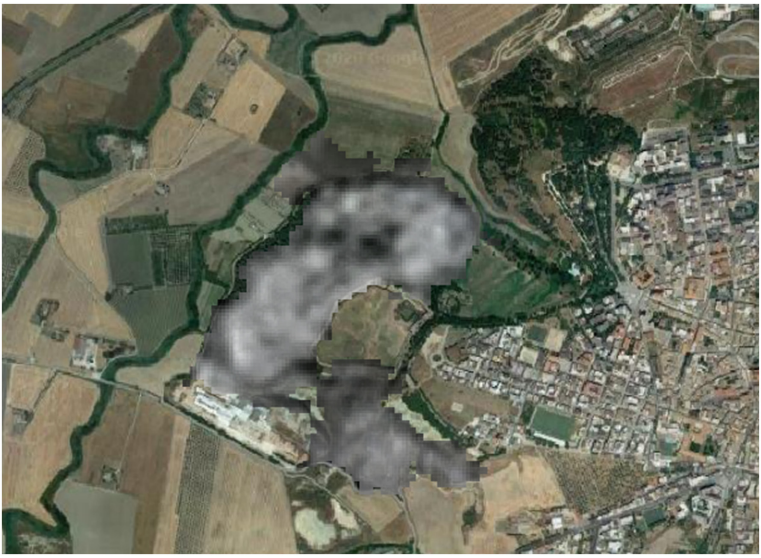

Fig. 2. dNBR Lucera fire in grey scale.

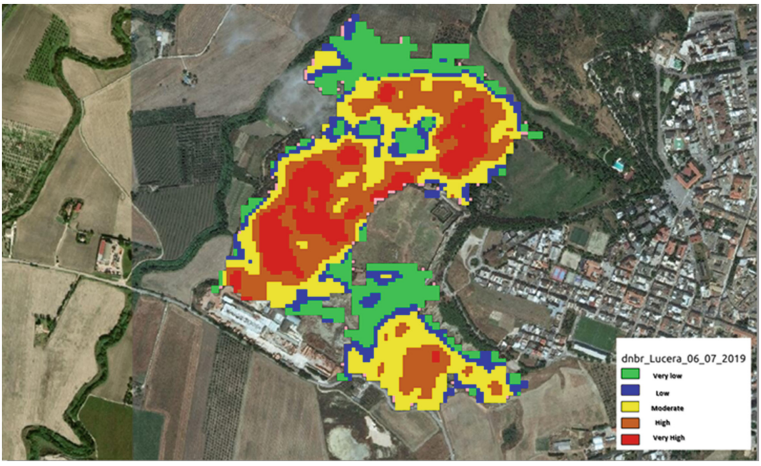

Fig. 3. dNBR Lucera fire.

Many models have been developed in the past to predict areas that are susceptible to soil erosion, to predict soil loss, and to evaluate soil erosion-control practices and RUSLE is one of the most widely used soil erosion model worldwide. For this work RUSLE (Revised Universal Soil Loss Equation) has been applied, this is an empirical

model, based on experimental data, which allows to stimulate the average rate of soil loss due to surface and channeled erosion (erosion of the rill).

The RUSLE [26–28] retains the same six factors of the USLE. The equation used for the calculation of both the USLE and the RUSLE is

$$A = R \times K \times LS \times C \times P \quad (1)$$

Where:

A = annual soil loss (Mg · ha −1 · year −1);
R = precipitation erosion factor (MJ · mm · ha −1 · h −1 · year −1);
K = soil erodibility factor (Mg · h · MJ −1 · mm −1);
LS = slope length factor and slope (dimensionless);
C = crop and cover management factor (dimensionless);
P = cultivation or anti-erosion (dimensionless) practice factor.

The erosion factor of the outflow of rainfall R (MJ · mm · ha − 1 · h − 1 · year-1), constitutes a measure of the rain energy considered as the main erosive agent [28–30]. It is calculated on the basis of the average monthly cumulated rainfall and was determined using the following formula [30]:

$$R = (1163,45 + 4,9 \times H - 35,2 \times NRE - 0.58 \times q) \quad (2)$$

where H (mm • y − 1) is the average value of the annual precipitation, q the altitude of the site (obtained from a DTM with 5 m resolution) and NRE the average annual value of the rainy events. The rainfall values come from the rainfall data of the Functional Center of the Puglia Region on which the average of the values over a few years was subsequently calculated, interpolated to have a value relating to the burnt areas.

K, or the soil erodibility factor (Mg • h • MJ − 1 • mm − 1), is significant of the susceptibility of soil particles to detachment and subsequent transport by rain and surface runoff. By changing the structure of the soil and its permeability, fire leads to a decrease in organic matter and therefore, ultimately, an increase in the K parameter [7]. In the present study, the reference value of the K factor is that obtained from the dataset contained in "Soil Erodibility in Europe High Resolution dataset" [30]. Larsen and MacDonald [17] point out, like other authors, that high severity fires increase the production and transport of sediments by several orders of magnitude. In this work the same criteria applied by [31] in Calabria have been used and therefore K has been multiplied by a factor between 1.6 (very low severity) and 2 (very high severity).

Factors L and S represent the effect of topography on soil erosion rate. The length of the slope (L) in RUSLE is defined as the distance between the point where the runoff begins and the point where sedimentation occurs or where the runoff water is channeled [29]. The increase in the value of eroded soil is proportional to the increase in the length of the slope. The slope steepness factor (S) also allows to consider the increase in erosive phenomena in relation to the angle of inclination of the slope. In fact, a greater slope corresponds to an increase in the flow velocity and, consequently, of the sediments produced and transported. The LS topographic factor was calculated with the support of the QGIS software starting from the DTM with a grid size of 5 m. For the calculation

of the LS factor at a point r located along a hilly slope, the following equation was used [23]:

$$\mathrm{LS(r)} = (\mu + 1)\,[a(r)/a0]\mu \times [\sin b(r)/b0]^{\mathrm{n}} \tag{3}$$

where a (r) [m2 · m − 1] is the area of the basin that contributes to the outflow in the section corresponding to point r per unit of width (specifically in the case studies we have calculated a (r) as a product of the QGIS functions "flow accumulation" and "pixel resolution"), b is the slope in radians, a0 = 22.1 m is the standard length USLE, b0 = 9% is the standard slope USLE while μ en are parameters that depend on the type of flow and the ground conditions. In this study n was assumed equal to 1.2 [14]. The parameter μ, indicative of the relationship between erosion within the grooves (rill) and that along the intermediate slopes (inter-rill), describes the erosive phenomenon which, while inside the impluvium depends on the surface runoff, along the intermediate and furrowed surfaces is a function of the energy with which rainfall impacts the soil. As part of this study, μ was calculated using the formula proposed by [22–24]:

$$\mu = \beta / (1 + \beta) \tag{4}$$

with a value of β varying between 0.5 (unburnt soil, pre-fire condition) and 1.0 (soil covered by fire with very high severity). A correct estimate of these parameters is important as the β value is quickly changed by the fire.

C factor reflects the effects of surface coverage and roofing management on soil erosion [31].

Plant cover and appropriate crop management reduce soil runoff and erosion [21] liby limiting the impact of rain on the soil surface. For non-erodible surface we assume C = 0, while the reference condition refers to bare soil (absence of vegetation) with a value of C = 1. For both the pre-fire and post-fire scenarios, the estimate of the factor C was carried out on the basis of the calculation of vegetation indices derived from satellite. In particular, the SAVI (Soil-Adjusted Vegetation Index) was used. Based on the statistical regression analysis performed by [12] the following equation is used:

$$\mathrm{C} = -\mathrm{a} \times \mathrm{SAVI} + 1 \tag{5}$$

where C is the cover factor and a = 1.18

$$\mathrm{SAVI} = [(\mathrm{NIR} - \mathrm{RED}) \times (1 + \mathrm{L})]/(\mathrm{NIR} + \mathrm{RED} + \mathrm{L}) \tag{6}$$

where L is a correction factor and has been assumed equal to 0.5 while NIR and RED are the reflectance values in the near infrared and red bands. SAVI is calculated using the best Sentinel 2 images acquired pre and post-fire as close as possible, temporally, to the date of the fire. Following this procedure it is possible to expect an overestimation of the post-fire factor C, but considering the underlying operational purposes of this study, we consider this compromise acceptable.

The cultivation or anti-erosion practice factor (P) is an expression of the effects of agricultural management practices aimed at reducing water runoff and consequently soil loss. To determine the value of the P factor, the following equation is applied [3]

exclusively to classes of agricultural vegetation (intensive and continuous arable crops, extensive crops and complex agricultural systems, olive groves, orchards, citrus groves, vineyards).

$$P = 0.2 + 0.03 \times S \tag{7}$$

where S is the slope (%) and the maximum value that P can reach is 1.0.

3 Result and Discussion

The application of the described methodology allowed to elaborate the fire severity maps of the study sites, which were subsequently used as input for the estimation of the parameters of the RUSLE model.

The study has been conducted using a modeling approach, already developed in the 70s–80s of last century (RUSLE model), implemented with digital techniques capable of managing and processing a large number of spatial data (GIS) [16, 17, 22, 24, 25], to obtain a cartographic elaborations as output.

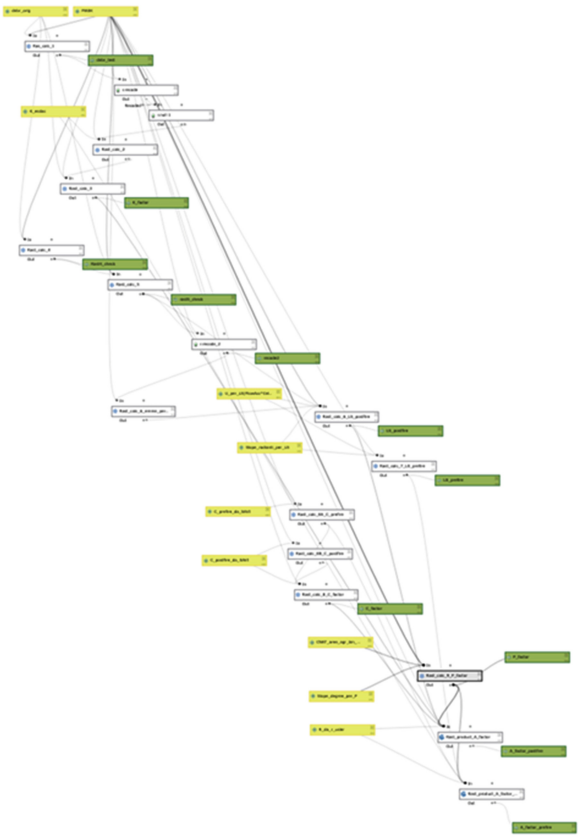

Fig. 4. A RUSLE model scheme made in QGIS.

The main part of the processes useful for obtaining the main maps of the RUSLE model was schematized by means of a spatial analysis workflow (See Fig. 4) in the graphic modeler of QGIS. This, in addition to allowing a clear definition of the sequence of the processes, avoids incurring changes in the fire-to-fire procedure.

Quantitative and semi-quantitative data in this paper has been collected from academic literature and websites. All data has been converted into raster at 10 m grid cell, so that spatial analysis can be done in the same cell size and map projection. In order to use it, it is necessary to create input maps that must be carefully analyzed (See Fig. 5).



Fig. 5. Graphical interface for a RUSLE model made in QGIS.

Specifically, the required input maps are:

- the binary Agricultural Soil Map on the basis of which it is possible to calculate the P factor;
- pre and post fire Factor C maps;
- the original K-factor map;
- the MASK map that defines the perimeter of the fire;
- the map of the R factor that derives from annual rainfall;
- the slope expressed in degrees and in radians (useful for calculating P and LS respectively);
- the U map, which depends on the flow accumulation;
- the dNBR map.

The maps generated in output will be clipped on the perimeter of the fire, based on the mask, and are: K factor (see Fig. 6), LS (pre and post fire) (see Fig. 7), C factor (see Fig. 8), P Factor, A factor (pre and post) (see Fig. 9).

This was done with a view to calculating the effect of fire on erosion in the next summer season in order to make the work more operational. In this regard, in order to quickly locate the fire reports arriving in SOUP, an information entry and recording system has been implemented. The method could be to evaluate the fires that are reported

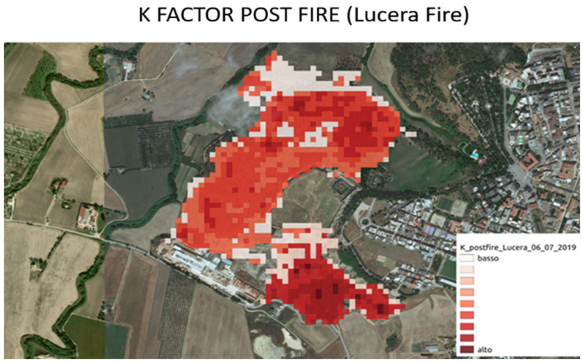

Fig. 6. K factor of Lucera Fire event of 06/07/2019.

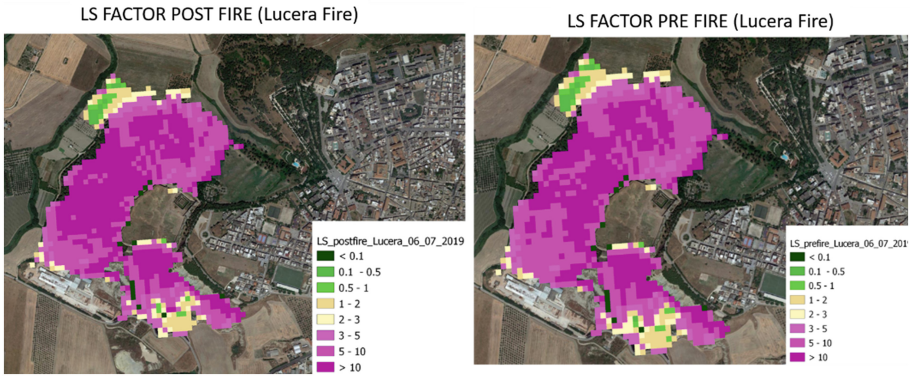

Fig. 7. LS factor PRE and POST of Lucera fire event of 06/07/08.

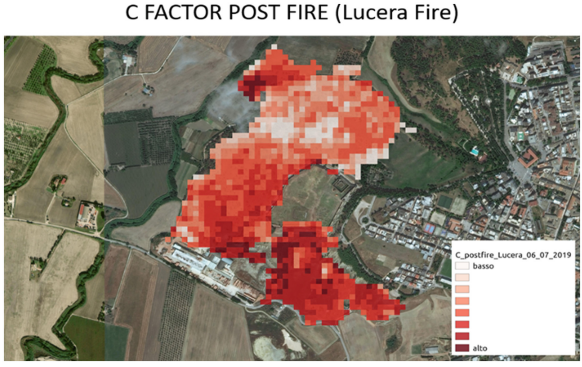

Fig. 8. C factor of Lucera fire event of 06/07/2019.

and recorded in SOUP through the formonline which are thus displayed directly on the webgis.

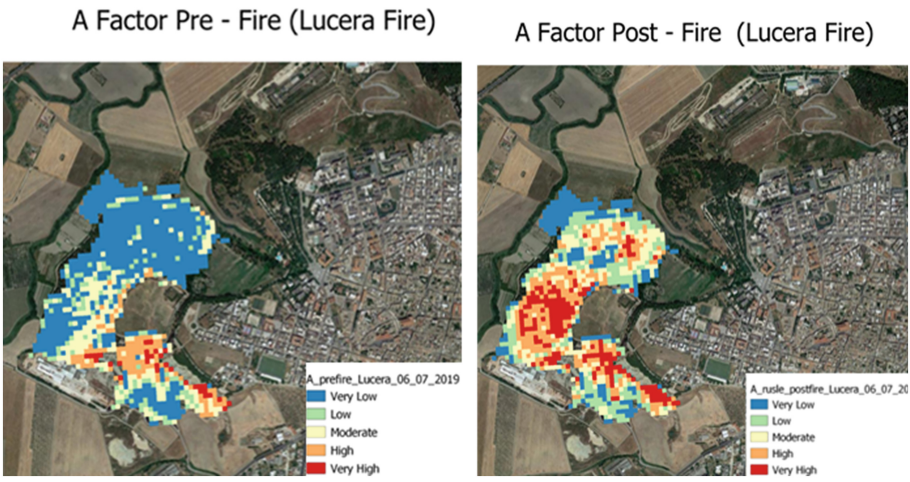

Fig. 9. Fire Lucera: RUSLE A pre and post fire factor. Annual post-fire soil erosion forecast.

4 Conclusions

This work in particular implements the use of the RUSLE model for predicting post-fire eroded soil in applications to different case studies in Apulia Region.

The products generated at the moment meet the minimum requirements assumed in the design phase: quality of the fire identification model, estimation of the parameters and usability of the product. In particular, the integration of the RUSLE model with the Geographic Information Systems and remote sensing provides a reliable estimate of the potential for soil erosion after the fire.

The integration of "classic" spatial data such as aerophotogrammetric data, raster and vector cartography, which have always been used by local authorities, today have a new life thanks to the integration with data collected in the field or acquired remotely (by drone or satellite).

This study point out, in fact, the interoperability of GIS software which allow you to manage data from different sources (satellite images, RUSLE data, cartographic data of the Puglia Region) in a single environment. Furthermore, the use of the model described in this paper presents innumerable advantages such as the speed in carrying out the study and estimation operations of the eroded soil by applying the RUSLE model, uniformity of spatial processes and processes and the standardization of these.

All the operations carried out are being evaluated between CNR researchers and experts from the Puglia Civil Protection to make the model itself easily applicable in near real time in the summer 2020.

The creation of data warehouses, such as the SIT PUGLIA of the Puglia Region (http://sit.puglia.it/portal/sit_portal) greatly enhance the sharing of geographic information and it is important to know them and use them to monitor and plan the actions to be put in place field on the territory.

References

1. Chuvieco, E., Martin, M.P., Palacios, A.: Assessment of different spectral indices in the red-near-infrared spectral domain for burned land discrimination. Int. J. Remote Sens. **23**(23), 5103–5110 (2002)
2. Fu, B.J., et al.: Assessment of soil erosion at large watershed scale using RUSLE and GIS: a case study in the Loess Plateau of China. Land Degrad. Dev. **16**(1), 73–85 (2005)
3. García-Ruiz, J.M., Nadal-Romero, E., Lana-Renault, N., Beguería, S.: Erosion in Mediterranean landscapes: changes and future challenges. Geomorphology **198**, 20–36 (2013)
4. García-Ruiz, J.M., et al.: Flood generation and sediment transport in experimental catchments affected by land use changes in the central Pyrenees. J. Hydrol. **356**(1–2), 245–260 (2008)
5. García, M.L., Caselles, V.: Mapping burns and natural reforestation using Thematic Mapper data. Geocarto Int. **6**(1), 31–37 (1991)
6. Giovannini, G., Vallejo, R., Lucchesi, S., Bautista, S., Ciompi, S., Llovet, J.: Effects of land use and eventual fire on soil erodibility in dry Mediterranean conditions. For. Ecol. Manage. **147**(1), 15–23 (2001)
7. Hall, R.J., Freeburn, J.T., De Groot, W.J., Pritchard, J.M., Lynham, T.J., Landry, R.: Remote sensing of burn severity: experience from western Canada boreal fires. Int. J. Wildland Fire **17**(4), 476–489 (2008)
8. Hartigan, J.A., Wong, M.A.: Algorithm AS 136: a k-means clustering algorithm. J. R. Stat. Soc. Ser. C (Appl. Stat.) **28**(1), 100–108 (1979)
9. Heredia, Á., Martínez, S., Quintero, E., Piñeros, W., Chuvieco, E.: Comparación de distintas técnicas de análisis digital para la cartografía de áreas quemadas con imágenes LANDSAT ETM+. GeoFocus. Revista Internacional de Ciencia y Tecnología de la Información Geográfica **3**, 216–234 (2003)
10. Holden, Z.A., Evans, J.S.: Using fuzzy C-means and local autocorrelation to cluster satellite-inferred burn severity classes. Int. J. Wildland Fire **19**(7), 853–860 (2010)
11. Kuo, K.T., Sekiyama, A., Mihara, M.: Determining C factor of universal soil loss equation (USLE) based on remote sensing. Int. J. Environ. Rural Dev. **7**(2), 154–161 (2016)
12. Lanorte, A., Danese, M., Lasaponara, R., Murgante, B.: Multiscale mapping of burn area and severity using multisensor satellite data and spatial autocorrelation analysis. Int. J. Appl. Earth Obs. Geoinf. **20**, 42–51 (2013)
13. Larsen, I.J., MacDonald, L.H.: Predicting postfire sediment yields at the hillslope scale: testing RUSLE and Disturbed WEPP. Water Resour. Res. **43**(11) (2007)
14. Lasaponara, R., Lanorte, A.: Multispectral fuel type characterization based on remote sensing data and Prometheus model. For. Ecol. Manage. **234**, S226 (2006)
15. Lee, S.: Soil erosion assessment and its verification using the universal soil loss equation and geographic information system: a case study at Boun Korea. Environ. Geol. **45**(4), 457–465 (2004)
16. Lisle, T.E., Napolitano, M.B.: Effects of recent logging on the main channel of North Fork Caspar Creek. In: Ziemer, R.R. [Tech. Coord.]. Proceedings of the conference on coastal watersheds: The Caspar Creek story. PSW-GTR-168. Pacific Southwest Research Station. USDA Forest Service, Albany, CA, pp. 81–85, May 1998
17. Miller, J.D., Nyhan, J.W., Yool, S.R.: Modeling potential erosion due to the Cerro Grande Fire with a GIS-based implementation of the Revised Universal Soil Loss Equation. Int. J. Wildland Fire **12**(1), 85–100 (2003)
18. Mitasova, H., Hofierka, J., Zlocha, M., Iverson, L.R.: Modelling topographic potential for erosion and deposition using GIS. Int. J. Geogr. Inf. Syst. **10**(5), 629–641 (1996)
19. Odeh, I.O.A., McBratney, A.B., Chittleborough, D.J.: Soil pattern recognition with fuzzy-c-means: application to classification and soil-landform interrelationships. Soil Sci. Soc. Am. J. **56**(2), 505–516 (1992)

20. Panagos, P., et al.: Rainfall erosivity in Europe. Sci. Total Environ. **511**, 801–814 (2015)
21. Panagos, P., Borrelli, P., Meusburger, K.: A new European slope length and steepness factor (LS-Factor) for modeling soil erosion by water. Geosciences **5**(2), 117–126 (2015)
22. Panagos, P., Meusburger, K., Ballabio, C., Borrelli, P., Alewell, C.: Soil erodibility in Europe: a high-resolution dataset based on LUCAS. Sci. Total Environ. **479**, 189–200 (2014)
23. Rauste, Y., Herland, E., Frelander, H., Soini, K., Kuoremaki, T., Ruokari, A.: Satellite-based forest fire detection for fire control in boreal forests. Int. J. Remote Sens. **18**(12), 2641–2656 (1997)
24. Renard, K.G.: Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). United States Government Printing (1997)
25. Renard, K.G., Foster, G.R., Weesies, G.A., Porter, J.P.: RUSLE: revised universal soil loss equation. J. Soil Water Conserv. **46**(1), 30–33 (1991)
26. Richards, G.D.: A general mathematical framework for modeling two-dimensional wildland fire spread. Int. J. Wildland Fire **5**(2), 63–72 (1995)
27. Shakesby, R.A.: Post-wildfire soil erosion in the Mediterranean: review and future research directions. Earth Sci. Rev. **105**(3–4), 71–100 (2011)
28. Sorriso-Valvo, M., Bryan, R.B., Yair, A., Iovino, F., Antronico, L.: Impact of afforestation on hydrological response and sediment production in a small Calabrian catchment. CATENA **25**(1–4), 89–104 (1995)
29. Surfleet, C.G., Ziemer, R.R.: Effects of forest harvesting on large organic debris in coastal streams. In: LeBlanc, J. (ed.) Conference on Coast Redwood Forest Ecology and Management, 18–20 June 1996, Arcata, California. Humboldt State University, pp. 134–136 (1996)
30. Terranova, O., Antronico, L., Coscarelli, R., Iaquinta, P.: Soil erosion risk scenarios in the Mediterranean environment using RUSLE and GIS: an application model for Calabria (southern Italy). Geomorphology **112**(3–4), 228–245 (2009)
31. Wischmeier, W.H., Smith, D.D.: Predicting rainfall erosion losses - a guide for conservation planning. U.S. Department of Agriculture, Agriculture Handbook No 537, p. 58, Hyattsville (MD) (1978)