MODELLING SOIL EROSION IN THE ALPS WITH DYNAMIC RUSLE-LIKE MODEL AND SATELLITE OBSERVATIONS

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ABSTRACT:

Soil water erosion is a creeping natural phenomenon, mostly related to weather and climate, and one of the main hydrogeological risk in Europe. It causes nutrients loss and exposes the environment to landslides, with negative impacts on agriculture, ecosystem services and infrastructures. Conversely, several human activities induce environmental modifications which intensify pressure on soils, thus increasing their predisposition to erosion.
This study describes the integration of satellite observations with a modified version of the well-known Revised Universal Soil Loss Equation (RUSLE) model for estimating soil erosion in an Italian Alpine river basin. Compared to traditional RUSLE formulation, in this study we assigned the cover management factor using a combination of DUSAF land cover classification and NDVI values computed from Landsat time series. Rainfall erosivity was estimated separating liquid precipitation (erosive) and solid precipitation (non-erosive) from hourly data. Soil erodibility for the study area was tuned combining soil maps with total organic carbon (TOC), acidity (pH) and texture (granulometry) from soil samples collected on site. Finally, the slope length and steepness factor was derived using a 30-meter spatial resolution digital elevation model.
Integrating the RUSLE-like model with spectral indices derived from satellite data allows highlighting spatial patterns useful for understanding soil erosion dynamic and forcing. Thus, satellite-derived spectral information, that include both seasonal and long-term land cover changes, opens new ways for modelling the dynamics of soil erosion.

1. INTRODUCTION

1.1 Background and aims

Soil water erosion is a creeping natural phenomenon, mostly related to weather and climate, which leads to loosening, dissolving or removal of earthy or rock materials from the surface. It causes nutrients loss and exposes the environment to landslides, with negative impacts on agriculture, ecosystem services and infrastructures (Boardman and Poesen, 2006). Conversely, several human activities (e.g. land cover changes, agricultural patterns reshaping,intensive grazing and forest management activities) induce environmental modifications which may intensify pressure on soils, thus increasing their predisposition to water erosion.
The European Commission's Soil Thematic Strategy (COM (2012) 46) has identified soil erosion as one of the main hydrogeological risks in Europe. Long dry periods followed by heavy rainfall on steep slopes, make the Southern European countries particularly prone to erosion (Van der Kniff *et al.*, 2000), with the highest soil loss rates in the Alpine region (Panagos *et al.*, 2015b).
With reference to Italy, mass movements and soil erosion are the most widespread forms of soil degradation, which accounts for an annual cost of about 900 million Euros per year (Costantini and Lorenzetti, 2013). Nonetheless, this natural hazard is often underestimated in local planning.

In this scenario, Earth observation offers a unique mean for monitoring land cover and land use changes over large areas, which is extremely useful to understand how those dynamics affect soil erosion processes. This work describes the integration of satellite observations within a modified version of the Revised Universal Soil Loss Equation (RUSLE) model for the estimation of soil erosion in the Italian Alps.

1.2 Study area

The study area is Val Camonica, one of the largest valleys of the central Alps, located in the northern part of Oglio river basin which is embedded in the central alpine and pre-alpine domain of Regione Lombardia (Italy) (Figure 1).
Val Camonica has an area of about 1,800 km^2 and extends from 185 m a.s.l. to 3,585 m a.s.l. of the Adamello Glacier. Almost 90% of the landscape is vegetated (less than 1% crops and 45% forests), highly influenced by altitude variations and rainfall seasonal regime. Precipitation reaches its peak during summer and fall, while snowfall is frequent from October to May and snow cover generally persists at higher altitudes until July.

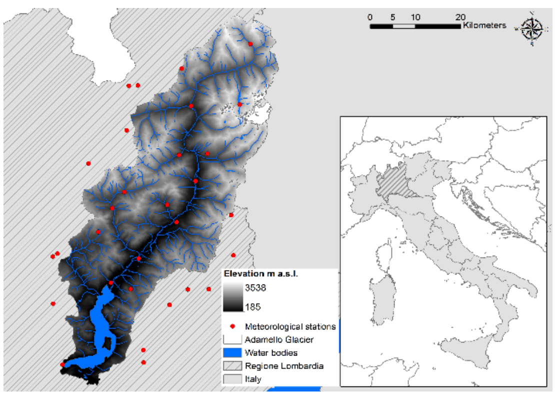

Figure 1. Digital Elevation model of the case study area (Regione Lombardia, Italy).

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2. MODELING SOIL EROSION

2.1 The RUSLE model

The well-known empirical Revised Universal Soil Loss Equation (RUSLE) (Renard, 1997) estimates the annual potential soil erosion rate A [t ha^{-1} yr^{-1}] as the product of the following quantities:

i) Rainfall erosivity (R-factor) [MJ mm ha^{-1} h^{-1} yr^{-1}]. This is the driving force of erosion and is a function of precipitation rate, air temperature and snow cover dynamics;
ii) Soil erodibility (K-factor) [t ha h ha^{-1} MJ^{-1} mm^{-1}]. This quantity describes the soil properties (i.e. soil structure and organic matter content) that influence the predisposition of soil to erosion;
iii) Topography of the area (LS-factor) [dimensionless]. This parameter mainly depends on slope length and steepness that can further increase soil erosion;
iv) Cover management factor (C-factor) [dimensionless]. This parameter takes into account how land use and land cover management practices protect soils from erosion. Lower C-factor values correspond to higher protection, thus to lower erosion.
v) Control practice factor (P-factor) [dimensionless]. This factor is representative of the capacity of soil conservation practice to reduce the erosion potential of runoff. In this study we assumed the P-factor equal to 1.

2.2 Modification of the RUSLE model

RUSLE is usually applied at yearly scale, neglecting the partitioning between solid precipitation (non-contributing to erosion) and liquid precipitation (active in erosion) and the sheltering effect of snow cover with respect to soil erosion. Besides, the land cover/land use parameter is generally set as a static variable, even when using RUSLE to project future scenarios.
In this study we adopted a RUSLE-like approach which incorporates remotely sensed multispectral images for the dynamic updating of C-factor and estimates rainfall erosivity, as described in Section 2.3. In formal terms, we retained the same equation of RUSLE.

2.3 Data and methods

With respect to traditional RUSLE, the R-factor was estimated as function of liquid precipitation intensity (Sun *et al.*, 2002) and snow presence/absence over the soil; the partitioning between liquid and solid precipitation is a function of air temperature (Aiello *et al.*, in press). Hourly precipitation and air temperature data were recorded from 2003 to 2017 by 26 meteorological stations spread over the study area. The observed meteorological data were spatialized through an inverse distance squared weighting algorithm to compute hourly R-factor on a 30-m grid.
The soil erodibility factor was tuned on the study area, by verifying the agreement between the information extracted from the available soil map and analytical measurements of total organic carbon (TOC), acidity (pH) and texture (granulometry) from a set of soil samples collected on site. Then, each textural class of the soil map were assigned a K-factor value as function of the TOC according to Fantappiè *et al.* (2014).
The LS-factor was derived from a 30-meter spatial resolution digital elevation model, through the method proposed by Desmet and Govers (1996), which captures complex topography and takes into account the upslope contributing area.

Dynamism and seasonality of land cover was introduced in the C-factor using satellite multi-temporal surveys. C-factor values were assigned to each land class using a combination of NDVI computed from Landsat-5, -7 and -8 time series images from 2002 to 2017 and the official thematic maps of the DUSAF (*Destinazione d'Uso dei Suoli Agricoli e Forestali*) for 2000, 2007 and 2015 made available by Regione Lombardia.
Satellite data were pre-processed with standard radiometric calibration and atmospheric correction. All the images were grouped into Summer (from March to August) and Winter (from September to February) subsets and snow cover and clouds were masked before the computation of NDVI. However, Val Camonica has many steep and narrow valleys and during Winter almost half of the study area is completely shadowed or snowed up, thus soil protection from erosion based on NDVI-based C-factor turned out to be an unrealistic estimation (Gianinetto *et al.*, 2018). For this reason, the relationship between NDVI and C-factor was based on Summer NDVI values integrated with DUSAF, while the observed Winter NDVI values were replaced with synthetic values reconstructed from Summer observations and DUSAF land cover classes as follows:
i) For each Winter image, we selected the closest Summer image;
ii) Then, we computed the pixel-based ratio between Winter NDVI and Summer NDVI, excluding shadowed or snowy image pixels;
iii) Next, we computed the average ratio between Winter NDVI and Summer NDVI for each land cover class of DUSAF;
iv) Finally, for each land cover class of DUSAF, we reconstructed the synthetic pixel-based map for Winter NDVI by multiplying the Summer NDVI by the average ratio based computed at the previous step.

Once generated both the Summer and Winter maps of NDVI, we computed the C-factor. To all unvegetated classes of DUSAF we assigned a null C-factor, while for each vegetated class a range of possible values ($C_{min} \leq \mathrm{C-factor} \leq C_{max}$) was given, as suggested by Panagos *et al.* (2015a). Then, for each land cover class we computed the Summer average NDVI (μ_{NDVI}) and its standard deviation (σ_{NDVI}). Finally, for each land cover class we assumed a linear relationship between NDVI (in the range $\mu_{\mathrm{NDVI}} - \sigma_{\mathrm{NDVI}} \leq \mathrm{NDVI} \leq \mu_{\mathrm{NDVI}} + \sigma_{\mathrm{NDVI}}$) and C-factor (in the range $C_{min} \leq \mathrm{C-factor} \leq C_{max}$), both for Winter and Summer. To avoid saturation effects, we assumed $\mathrm{C-factor} = C_{max}$ for $\mathrm{NDVI} < \mu_{\mathrm{NDVI}} - \sigma_{\mathrm{NDVI}}$ and $\mathrm{C-factor} = C_{min}$ for $\mathrm{NDVI} > \mu_{\mathrm{NDVI}} + \sigma_{\mathrm{NDVI}}$.
This method allowed us to: (a) use Winter satellite images despite clouds, shadows and snow cover, (b) link the estimation of C-factor to real land covers, and (c) achieve reasonable estimates for Summer and Winter.

3. RESULTS

3.1 Seasonality in soil erosion rates

Rainfall regime (i.e. R-factor) and land cover variability (i.e. C-factor) are the parameters which convey seasonality within our RUSLE-like model. In our study, we retrieved both annual and seasonal soil loss rates for the simulation period 2003-2017.
While both Summer and Winter show similar spatial patterns of soil erosion, nevertheless during Summer months we simulated slightly lower erosion rates (1.86 [t $ha^{-1}y^{-1}$]) compared to Winter months (2.01 [t $ha^{-1}y^{-1}$]). However, the model is sensitive to the combined effects of seasonality and altitude. As an example, Winter erosion is slightly lower than Summer erosion in the northern section of the basin, which is mainly characterized by the presence of sparsely vegetated areas and moors (Figure 2a-b).

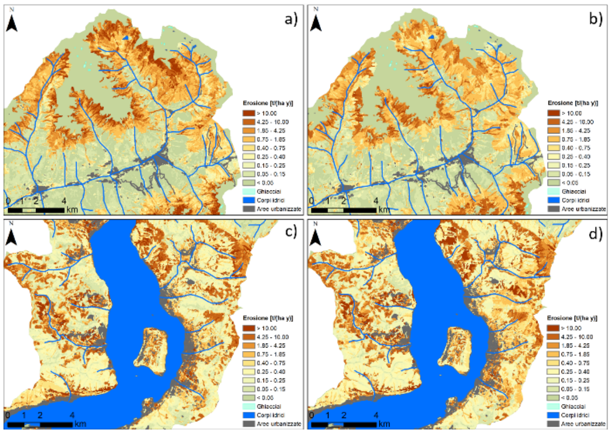

Figure 2. Detail of seasonal soil erosion rates. Top: basin upper section for Summer months (a) and Winter months (b). Bottom: basin lower section for Summer (c) and Winter months (d).

That is probably due to the sheltering effect of snow at higher altitudes. At lower altitudes, where the predominant land covers are broad-leaved and mixed forests, the reduced sheltering effect of vegetation causes higher Winter soil erosion (Figure 2c-d).
The seasonal influence of rainfall and cover management factor on soil erosion was analysed for the most meaningful land cover classes of DUSAF present in the study area. The box-plots of Figure 3a show similar median values for Summer and Winter for the majority of the classes, as the effect of R-factor and C-factor are mostly compensated. A detail of these box-plots for forest classes (311, 312, 313) is presented in Figure 4a. However, this balance is due to a twofold effect:
i) Summer rainfall erosive force exceeds Winter rainfall erosive force, because Summer liquid precipitations are more abundant and more intense (Figure 3b and Figure 4b) but C-factor values are lower due to more prosperous vegetation (Figure 3c and Figure 4c);
ii) On the contrary, during Winter some of the liquid precipitation is replaced by more abundant snowy precipitation (Figure 3b and Figure 4b) and the protective effect of vegetation is attenuated (Figure 3c and Figure 4c).
This compensation effect is also visible in class 333 (Sparsely vegetated areas), which is mainly located at higher altitudes. A similar effect is present in agricultural classes (211, 221, 222, 223) characterized by some of the highest erosion rates. However, it has to be pointed out that the high variability in erosion rates shown by agricultural classes is mostly due to their small size compared to the other classes.

3.2 Comparison with previous studies

The work by Panagos *et al.* (2015b) at the continental scale is a milestone for assessing soil erosion in Europe, thus we used it as reference for comparison. However, they used a 'static' C-factor, derived from the CORINE land cover map of 2006.
The estimation of C-factor through satellite-derived spectral indices, instead of fixed values based on land cover classes, may potentially increase its discretization within different vegetated classes, that may contribute to soil erosion. This is particularly important when studying areas dominated by vegetation, such as on the Alps.
Looking at Figure 5, we can see that hot spots are almost located in the same areas, given the different spatial resolution of the two maps (100-meter (aggregated) for Panagos *et al.*, (2015b) 30-meter for our map), but our fine-tuned modelling suggests that the average potential erosion rate in Val Camonica is only one third (3.87 [t ha^{-1} y^{-1}]) of that estimated with a global modelling (13.71 [t ha^{-1} y^{-1}]).

Our dynamic estimate can help detailing some specific soil loss patterns, particularly when the land cover is subject to natural or artificial changes over time. Besides, our estimate of soil erosion is characterized by a smaller variability with respect to that of Panagos *et al.* (2015b). This holds particularly true for vegetated classes, as shows Figure 6). However, we should mention that Panagos' extremely high variability for classes 332 (bare rocks), 333 (sparsely vegetated areas) and 335 (glaciers and perpetual snow) is biased by the presence of several "no-data" values.

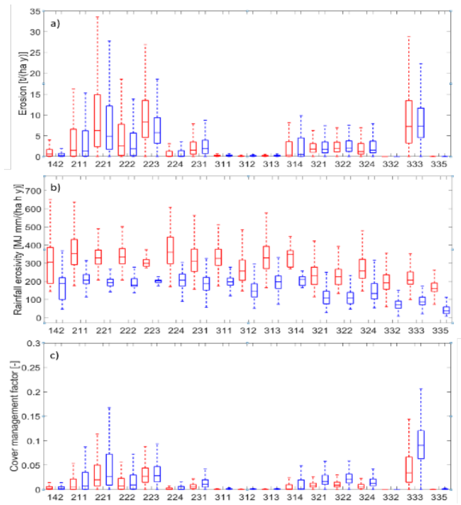

Figure 3. Box-plots of average a) soil erosion rates, b) rainfall erosivity values and c) cover management factor values computed for Summer (red) and Winter (blue). DUSAF land cover classes: 142=Sport and leisure facilities; 211=Non-irrigated arable land; 221=Vineyards; 222=Fruit trees and plantations; 223=Olive groves; 224=Wood arboriculture; 231=Permanent grassland; 311=Broad-leaved forest; 312=Coniferous forest; 313=Mixed forest; 314=Recent reforestation; 321=Natural grasslands; 322=Moors and heatland; 324=Transitional woodland-shrub; 332=Bare rocks; 333=Sparsely vegetated areas; 335=Glaciers and perpetual snow.

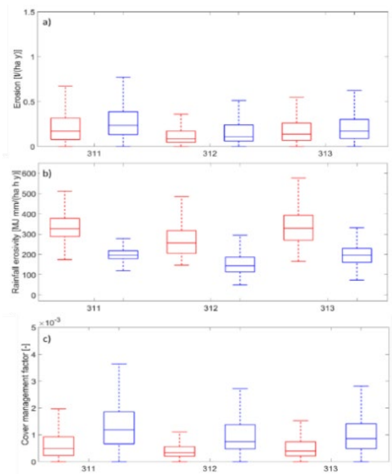

Figure 4. Detail of Figure 3 for the forest land cover classes. DUSAF land cover classes: as in Figure 3 caption.

4. CONCLUSIONS AND FUTURE WORKS

In this study, we proposed a RUSLE-like model based on the integration of traditional on site measures (i.e. meteorological stations), Earth observation (i.e. satellite-derived C-factor), and

on site calibration (i.e. K-factor). The model was tested in central Alps of Italy to study the benefits of a dynamic modelling.
First results shows that a dynamic modelling of soil erosion could highlight different erosive patterns for Summer and Winter, hotspots and land covers which are more susceptible to erosion. Moreover, integrating the erosion model with spectral indices could potentially allow relating phenological and health variations of vegetation with soil loss severity.
This information is required for developing appropriate conservation policies regarding land use and agricultural practices, to avoid irreversible soil loss. Thus, the use of satellite-derived spectral information opens new ways for modelling the dynamics of soil erosion, including both short-term (i.e. seasonal) and long-term land cover changes.
Future steps will include modelling erosion under climate change projections, which foresee relevant changes for the European mountains. Besides, is currently under evaluation the benefit of including Sentinel-2 data in the work flow, both to increase the spatial resolution of the C-factor and to increase the revisit time in Winter, when the cloud cover is higher.

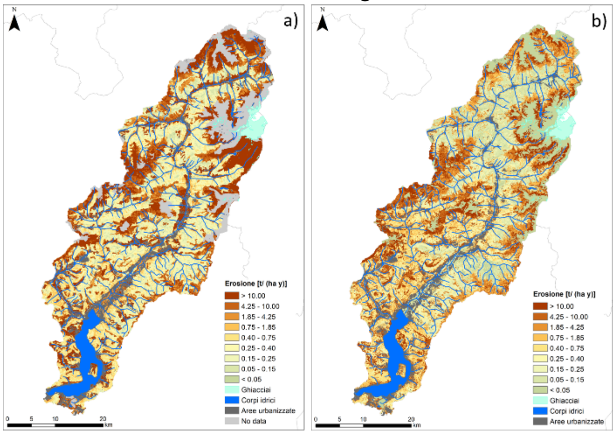

Figure 5. Comparison between (a) the erosion map at European scale by Panagos *et al.* (2015b) and (b) our estimates. While the patterns are similar, our dynamic approach estimates a smaller erosion.

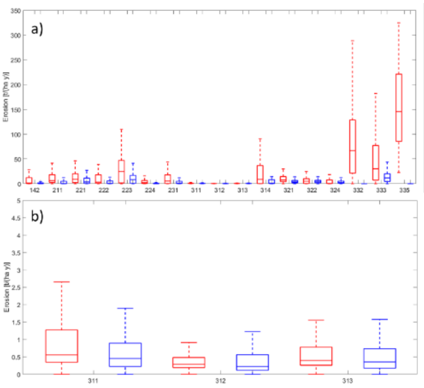

Figure 6. Box-plots of average soil erosion rates. Comparison between the study by Panagos *et al.* (2015b) (red) and our estimates (blue). a) Overall results, b) detail for the forest classes. DUSAF land cover classes: as in Figure 3 caption.

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REFERENCES

Aiello, M., Vezzoli, R. F., Polinelli F., Frassy F., Rota Nodari, Rulli, M.C., Ravazzani G., Corbari C., Soncini A., Chiarelli, D.D., Passera, C., Bocchiola, D., and Gianinetto, M., Analisi di sensitività nella stima dell'erosione di suolo nelle Alpi con misure in situ e serie temporali Landsat, in ASITA 2018 Conference (in press).

Boardman, J. and Poesen, J., 2006. *Soil Erosion in Europe*, John Wiley & Sons Ltd, 855.

Costantini, E.A.C., and Lorenzetti, R., 2013. Soil degradation processes in the Italian agricultural and forest ecosystems. In: *Italian Journal of Agronomy*; 8(28), pp. 233-243.

Desmet, P.J.J., Govers, G., 1996. A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. In: *Journal of soil and water conservation*, 51(5), pp. 427-433.

European Commission, 2012, The implementation of the Soil Thematic Strategy and ongoing activities, COM (2012) 46.

Fantappiè, M., Priori, S., Costantini, E.A.C., 2015. Soil erosion risk, Sicilian Region (1: 250,000 scale). In: *Journal of Maps*, 11(2), pp. 323-341.

Gianinetto, M., Aiello, M., Vezzoli, R., Rota Nodari, F., Polinelli F., Frassy F., Rulli, M.C., Ravazzani G., Bocchiola, D., Soncini A., Chiarelli, D.D., Passera, C. and Corbari C., "Satellite-based cover management factor assessment for soil water erosion in the Alps"., in SPIE Remote Sensing 2018 Conference.

Panagos, P., Borrelli, P., Meusburger, K., Alewell, C., Lugato, E., Montanarella, L., 2015a. Estimating the soil cover-management factor at the European scale. In: *Land Use Policy*, 48,pp. 38-50

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., Alewell, C., 2015b. The new assessment of soil loss by water erosion in Europe. In: *Environmental science & policy*, 54, pp. 438-447.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool D.K., Yoder, D.C., 1997. Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). Washington, DC:United States Department of Agriculture, Vol. 703.

Sun, H., Cornish, P.S., and Daniell, T. M., 2002. Contour-based digital elevation modeling of watershed erosion and sedimentation: Erosion and sedimentation estimation tool (EROSET). In: *Water resources research*, 38(11).

Van der Knijff, J.M., Jones, R.J.A. & Montanarella, L., 2000. Soil erosion risk assessment in Europe. European Soil Bureau, Joint Research Center of the European Commission.