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Automatic characterization of road networks under forest cover: advances in the analysis of roads and geomorphic process interaction

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ABSTRACT

Mountain road networks support rural development, timber harvesting as well as local travel, trade, and tourism. However, roads represent a difficult and pressing environmental challenge because of their impacts on hydrogeomorphic processes in many locations around the world. For this reason, identifying the location and the structure of a road network is crucial. The position of the infrastructures relative to the valley floor and to ridges results in roads working as a sediment sources (inducing erosion/landslides) or sinks (acting as stopping/storage sites). Currently, the identification of roads and the analysis of their interaction with earth surface processes is based mostly on field surveys. To this point, this work tests an automatic approach to characterize the road network configuration (Sofia et al., 2016), and further extends its significance by analysing the interaction between the network morphology and geomorphic processes. The method considers LiDAR topography and specific topographic metrics that measure the homogeneity and the organization of the slope of a landscape (the Slope Local Length of Auto-Correlation –SLLAC, Sofia et al., 2014, and the derived average SLLAC and Surface Peak Curvature –Spc- per square kilometre). The Lookout Creek watershed (western Cascade Range, Oregon, USA) offers the ideal case study. The area is covered entirely by LiDAR topography; a database of roads and slides (debris flows, shallow and deep landslides) locations, including specific information on events connected to the roads, is available for the whole catchment. The results show how it is possible to automatically characterize the road network conformation also under vegetation cover. The procedure successfully detects areas presenting different shapes of the network, and it allows to deepen the analysis of the connection between the network structure and earth surface processes. To this point, given a similar geological domain and without denying the importance that the natural forcing has on geomorphic systems, networks created by short roads with sharp angles might be related to a greater surface instability, if compared to networks having similar densities, but longer roads and fewer road junctions. Further investigation on additional study cases is needed to confirm the effects of the road network configuration on surface processes, to substantiate the hypothesis that there is a connection between network morphology and surface instabilities. Nevertheless, the automatic characterization of road networks, especially under forest cover, represents a great opportunity to advance the science, while solving important environmental and planning problems.

KEY WORDS: LiDAR, forest roads, feature extraction, landslides, erosion.

INTRODUCTION

Among the anthropogenic modifications of a landscape, road networks strongly shape the pattern of territories following two elementary spatial processes, *densification* and *exploration*, which are responsible for increasing the local density of the network and expanding the network into new areas respectively (Strano et al., 2012). Densification networks are created by short roads intersecting at sharp angles; they have a high network density (RD, km/km^2), and a low Network Simplicity (NS -km/pts- given by the ratio between the network density and the number of road junctions and –if present- buildings per km^2, Sofia et al., 2016). Exploration networks, on the other hand, have a network density comparable to the densification one, but they are simpler, having longer roads and fewer junctions.

Mountain roads, in particular, support agricultural development, timber harvesting as well as local travel, trade and tourism. At the same time they present difficult and pressing environmental challenges in many locations around the world (Sidle & Ziegler, 2012). Networks of roads interact with water and sediment flow paths in multiple ways, with effects on erosion, sediment production, and landslide hazard (see Tarolli & Sofia, 2016 for a full review). Currently, the identification of roads and of their interaction with earth surface processes is based mostly on field surveys, whereas few studies integrated field surveyed information with the analysis of high-resolution topographic data (e.g. Tarolli et al., 2013, 2015). The automatic detection of areas having a different road network composition, especially under forest cover, represents therefore a great opportunity to advance the science while solving important environmental and planning problems.

STUDY AREA

The study is carried out on the Lookout Creek watershed in the western Cascade Range, Oregon (USA, Fig. 1). In this area, roads function as both production and depositional sites for mass movements, increasing the basin-wide sediment production (e.g. Swanson & Dyrness, 1975; Wemple et al., 2001).

The considered catchment is covered by forests, meadows, shrub fields, rock outcrops, and quarries. Here roads have been used for years for forestry practices. The watershed is underlain by geological units and associated soils that are markedly different in their susceptibility to slides (Dyrness, 1967). Two landscape-stability units may be identified: an unstable zone in volcanoclastic terrain, and a stable zone in the overlying lava-flow terrain (Swanson & Dyrness, 1975).

For this site, a LiDAR DTM at 1 m resolution is available for free download, in addition to a database of road networks and slides (debris flows, shallow and deep landslides), including specific information on events in proximity to roads (‘*road-related’* slides) (Fig. 1).

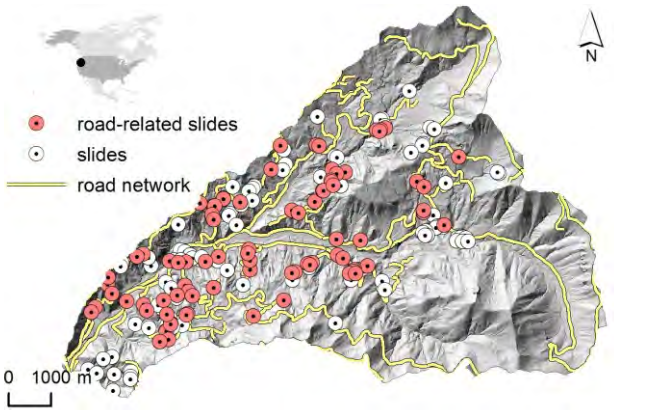

Fig. 1 - Location of the Lookout Creek watershed and available datasets: LiDAR DTM, road network and slides inventory.

METHOD

The work is based on the Slope Local Length of Auto-Correlation (SLLAC) proposed by Sofia et al. (2014), and on the procedure proposed in Sofia et al. (2016) (Fig. 2).

The method starts from a slope map derived from the DTM. The SLLAC is computed using a moving window or kernel (W in Fig. 2a) of 1 ha. At each step the procedure: i) calculates a 2D correlation (Fig. 2b) between W and a slope patch (a square of 100 m^2, T in Fig. 2a) centred at the centre of W; ii) from the 2D correlation, it derives the correlation length (Sofia et al., 2014), as in the horizontal distance of the areal cross-correlation that corresponds to 37% of the correlation maximum value (ISO, 2013) (Fig. 2c). The SLLAC map (Fig. 2e) is further characterized using the Surface Peak Curvature (Spc, Stout et al., 1994) that is the average of the principal curvature of each local maximum (pixel higher than its 8 nearest neighbours) on the SLLAC map. Two further parameters are computed: the average SLLAC (Fig. 2f) and Spc (Fig. 2f) per km^2.

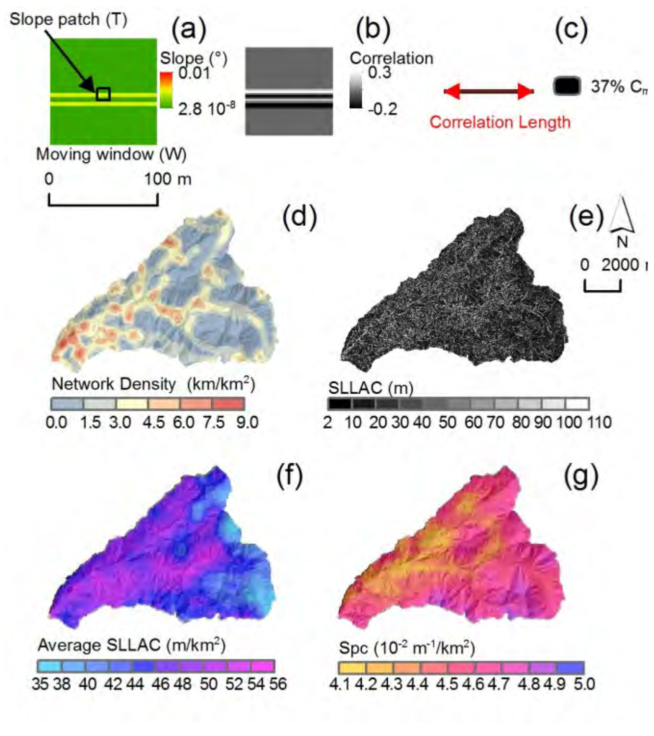

Fig. 2 - Computation of the SLLAC: (a) slope moving window (W), and slope patch (T); (b) cross-correlation between T and W; (c) thresholding at 37% of the maximum correlation and identification of the correlation length. (d) Road network density; (e) SLLAC map; (f) average SLLAC and, (g) average Spc per km^2

According to Sofia et al. (2016), *densification* zones (areas having short roads and lot of junctions) (for example, areas in yellow-to red in Fig. 2d) are expected to be more organized (low Spc per km^2) and at the same time self-similar (high average SLLAC per km^2) respect to a natural landscape. *Exploration* zones having few long roads with fewer junctions (areas having from blue to yellow in Fig. 2d) are expected to be either self-similar (high average SLLAC per km^2), or highly organized (low Spc per km^2). Networks that include both densification and exploration aspects (*mixed* zone), will have either organization or uniformity or both.

To confirm these hypotheses, and to verify the effects of road networks on geomorphic processes: i) the average SLLAC and Spc will be compared with the road network density in terms of Pearson’s coefficient (P_c), and the significance of the relation will be tested with a two tailed t-test at *p-value*<0.5; ii) the areas that maximize the SLLAC and minimize the Spc simultaneously (*Exploration*), and the areas that maximize the SLLAC or minimize the Spc or both (*Mixed*) will be compared with areas having different field-surveyed network simplicities, and the overlapping between estimated zones and actual road networks will be measured according to the Cohen’s k index (Cohen, 1960). This agreement will be considered as *slight* (k<0.2), *fair* (0.2≤k<0.4), *moderate* (0.4≤k<0.6), *substantial* (0.6≤k<0.8) and *almost perfect* agreement (k≥0.8) (Landis & Koch, 1977); iii) each zone will be compared with the number of slides within that area considering both the overall number of events and the events actually related to roads.

RESULTS

AUTOMATIC DETECTION OF ROADS

There is a strong and statistically significant inverse proportionality between the average Spc per km^2 and the road network density (P_c= -0.8), confirming what already proven in Chen et al. (2015) and Sofia et al. (2014, 2016): the more anthropogenic the landscapes, the lower the Spc. The average SLLAC has a strong statistically significant direct proportionality with the road network density (P_c=0.7). Both proportionalities underline what Sofia et al. (2016) showed: complex networks with high density have simultaneously low Spc and high average SLLAC.

The area that maximizes the average SLLAC and simultaneously minimizes the Spc (AND, in Fig. 3), has a

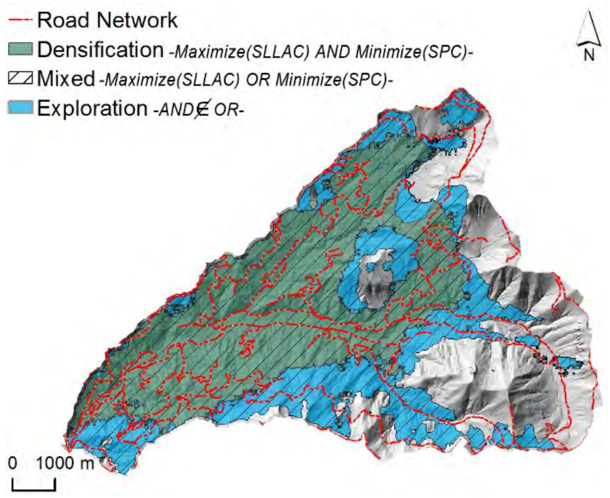

Fig. 3 - Automatically identified *Densification*, *Mixed* and *Exploration* zone.

substantial agreement (k=0.65) with areas covered by densification network (NS <~0.4 km/pts). On the other hand, the area that maximizes the average SLLAC or minimizes the Spc or both (OR, in Fig. 3) has a substantial agreement (k=0.61) with areas covered by both densification and exploration network (NS > ~0.4 km/pts). This confirms the idea of Sofia et al. (2016): densification networks tend to create more organized (low Spc) and uniform (high SLLAC) slopes, while exploration networks result in slopes that are either organized (low Spc) or uniform (high SLLAC).

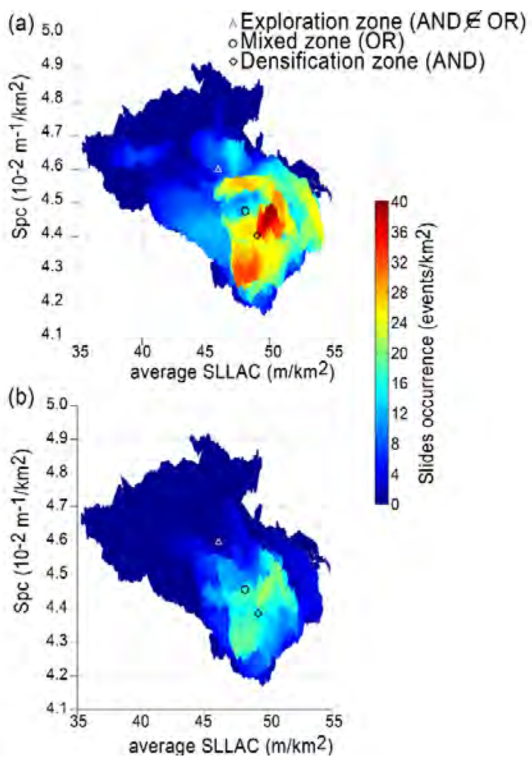

Fig. 4 - SLLAC derived parameters (Spc and average SLLAC) compared to (a) the overall number of sliding events and (b) road-related events. Average values of the parameters for the automatically defined *Densification*, *Exploration* and *Mixed* zone are also shown.

ROADS AND GEOMORPHIC PROCESSES INTERACTION

There is a statistically significant inverse correlation (P_c=-0.6) between the organization of the slope (Spc) and the density of slides. The homogeneity of the slope (average SLLAC) is instead positively correlated (P_c=0.6) with the number of slides. If we consider the organization and the uniformity of slope as two parameters influenced by densification or exploration networks, we can understand how different network simplicity can have different effects on erosional processes (Fig. 4).

The area automatically identified as a *Densification* zone (Fig. 3) has a network density of 3 km/km^2 and a network simplicity of <0.4 km/pts. This area presents an overall slide density (rotated square in Fig. 4) of 5.4 events /km^2 and a density of 2.9 events/km^2 of road-related slides. On the other hand, the area automatically defined as *Exploration* zone (OR excluding the AND area, in Fig. 3) has a road density of 2 km/km^2, and a higher network simplicity (0.5 km/pts). This area is also characterized by a slide density (triangle in Fig. 4) that is more than halved respect to the overall *Densification* zone (1.9 events/km^2) and reduced to ~10% for the slides actually surveyed as road-related (0.3 events/km^2). The area classified as *Mixed* zone (including both exploration and densification networks) (Fig. 3) is characterized by average values of network density (2.6 km/km^2) and network simplicity (0.4 km/pts). As well, it is characterized by an average number of slides (4.1 events/km^2 overall, and 2.0 events/km^2 considering only the road-related slides) (circle in Fig. 4). From these empirical data, it appears that more complex networks (*Densification*) might be related to a larger occurrence of geomorphic processes, if compared to zones of exploration networks.

Slides data and road networks have also been analyzed according to the underlain geological units considering the catchment stable and the unstable region (Swanson & Dyrness, 1975) separately (Table 1).

			Slide occurrences (events/km^2)	
Unstable	Road density (km/km^2)	Network Simplicity (km/pts)	Overall	Road-related
Densification	3.23	0.39	5.68	3.1
Mixed	3.19	0.39	5.56	2.8
Exploration	3.00	0.39	4.80	0.4
Stable				
Densification	2.42	0.41	4.42	2.3
Mixed	2.03	0.54	2.31	1.0
Exploration	1.81	0.62	1.21	0.3

Tab. 1 - Network structure (*densification, exploration, mixed*) related to the slides data, for the stable and unstable zone.

Many of the large storms that triggered slides during the years involved rapid snowmelt in the low and middle elevations of the forest. This hydrologic factor may have contributed to the high levels of slide erosion in the unstable zone (Swanson & Dyrness, 1975). Without denying the importance of geology and hydrology in influencing the geomorphic system, it is interesting to notice that when the geological component is stronger (*Unstable*) the difference in the overall number of sliding events connected to the shape of the network still exists, even if it is less noticeable. When focusing on the slides actually related to roads, the changes in density are more marked. For the stable zone, differences in the number of slides are more marked, and for similar densities (~2km/km^2) the complexity of the network seems to assume a greater importance: zones of densification networks (lower network simplicity) display a greater occurrence of geomorphic processes if compared to exploration networks (higher simplicity).

CONCLUSIONS

This work proposed an approach for the automatic characterization of road networks under forest cover. The results show that there is a strong proportionality between the road network complexity and the slope conformation. Larger network densities result in slopes that are more organized (low Spc) and at the same time more homogeneous (higher SLLAC). The method can actively capture the alteration produced by road networks on surface morphology, also under vegetation cover, and allows to automatically detect areas with different conformation of the road network, identifying exploration and densification areas. The effect of the network conformation on geomorphic processes is also analysed. To this point, without denying the importance of geology and hydrology in influencing the geomorphic system, in geologically stable zones densification networks created by short roads with sharp angles might be related to a larger number of sliding events, if compared to exploration network having similar densities but fewer road junctions. Further study cases are needed to verify the effects of the road network shape on surface processes, corroborating the connection between road networks and erosion. Nevertheless, the automatic characterization of road networks, especially under forest cover, represents a great opportunity to advance the science, while solving important environmental and planning problems.

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