Human topographic signatures and derived geomorphic processes across landscapes

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25 **Abstract**

26 The Earth's surface morphology, in an abiotic context, is a consequence of major forcings such as
27 tectonic uplift, erosion, sediment transport, and climate. Recently, however, it has become
28 essential for the geomorphological community to also take into account biota as a
29 geomorphological agent that has a role in shaping the landscape, even if at a different scale and
30 magnitude from that of geology. Although the modern literature is flourishing on the impacts of
31 vegetation on geomorphic processes, the study of anthropogenic pressures on geomorphology is
32 still in its early stages. Topography emerges as a result of natural driving forces, but some human
33 activities (such as mining, agricultural practices and the construction of road networks) directly or
34 indirectly move large quantities of soil, which leave clear topographic signatures embedded on the
35 Earth's morphology. These signatures can cause drastic changes to the geomorphological
36 organization of the landscape, with direct consequences on Earth surface processes. This review
37 provides an overview of the recent literature on the role of humans as a geological agent in
38 shaping the morphology of the landscape. We explore different contexts that are significantly
39 characterized by anthropogenic topographic signatures: landscapes affected by mining activities,
40 road networks and agricultural practices. We underline the main characteristics of those
41 landscapes and the implications of human impacts on Earth surface processes. The final section
42 considers future challenges wherein we explore recent novelties and trials in the concept of
43 anthropogenic geomorphology. Herein, we focus on the role of high-resolution topographic and
44 remote-sensing technologies. The reconstruction or identification of artificial or anthropogenic
45 topographies provides a mechanism for quantifying anthropogenic changes to landscape systems.
46 This study may allow an improved understanding and targeted mitigation of the processes driving
47 geomorphic changes during anthropogenic development and help guide future research directions
48 for development-based watershed studies. Human society is deeply affecting the environment with
49 consequences on the landscape. Therefore, establishing improved management measures that
50 consider the Earth's rapidly changing systems is fundamental.

51

52 *Keywords:* geomorphology; anthropogenic signatures; Anthropocene; mining; roads; mountains;
53 floodplains; remote sensing; high-resolution topography

54

55 **1. Introduction**

56 Landscapes are characterized by distinctive morphologies that are mainly caused by major
57 forcings such as tectonic uplift, erosion, sediment transport, and climate that have shaped the
58 Earth's surface and left characteristic topographic signatures. In addition to these processes, biota
59 forcing might play a role in shaping the landscape, but, of course, at a different scale and
60 magnitude than geological forcing. In biotic landscapes, vegetation through its roots influences soil
61 formation and surface erosion. Biota also influence climate and, as a consequence, the
62 mechanisms that control erosion rates and the evolution of the landscape. [Dietrich and Perron](#)
63 [\(2006\)](#) compared the hypothetical frequency of occurrence of landform properties for the present
64 Earth and an abiotic Earth. They suggested that the frequency distributions of measurable
65 landform properties (such as mountain height, steepness, and curvature) could greatly differ,
66 although all observed landform types would be found in both biotic and abiotic worlds (Fig. 1a).
67 The question is, if we can suppose that there is evidence of biota forcing, what is the role of
68 humans? Figure 1b shows a real case study of the relative likelihoods that landform slopes will
69 take a given value (probability density functions, pdfs) in a natural and a terraced landscape (the
70 slope was calculated using high-resolution topography derived from LiDAR data). The result is
71 interesting as their distributions seem to confirm the hypothesis of [Dietrich and Perron \(2006\)](#).
72 Even if all slope values are found in the natural and in the anthropogenic environments, humans
73 actively alter the frequency of occurrence of some specific slope values. In the case presented in
74 Figure 1b, the natural morphology presents a bell-shaped distribution of slopes, with a peak around
75 the average slope ($\sim 35^\circ$). On the other hand, the anthropogenic slope pdf presents two peaks: one
76 around the average value and one around low slope values. These two peaks are caused by the
77 walls (having high values of slopes) and by the benches (low values of slopes) of the terraces.

78

Fig. 1

79 Society developed significantly during the Holocene (from hunting-gathering, to farming, to
80 complex societies and metropolises), and the increase in population was related to a progressive
81 increase in intensive agriculture, raw material demand and urbanization. As a consequence,
82 human activities are leaving a significant signature on the Earth by altering its morphology,
83 processes, and ecosystems (Ellis, 2011). Anthropogenic landscapes cover as great an extent of
84 the Earth's land surface as many other globally important ecosystems (Foley et al., 2005). In
85 anthropogenic landscapes, human alteration is reflected by artificial Earth surface features (e.g.,
86 artificial channels, road networks, agricultural practices and mining activities) that may affect
87 natural processes (Tarolli, 2014). Indeed, the scientific community is now debating the fact that we
88 are living in a new geological epoch, the Anthropocene (Zalasiewicz et al., 2008, 2011a, 2011b,
89 2014; Monastersky, 2015), where human activities leave a significant, if not dominant, signature on
90 the Earth. Whether this is true for the whole of mankind or for only some civilizations (Crist, 2013)
91 and whether human *bioturbation* (Zalasiewicz et al., 2014) constitutes a negligible (Visconti, 2014)
92 or substantial fraction of long-term Earth geological activities are still up for debate. Some authors
93 have highlighted how human impacts are often difficult to separate from naturally driven activities
94 (Fuller et al., 2015), and others have argued that it might be too soon to determine the human
95 impact on geological records (Lewing and Macklin, 2014; Visconti, 2014; Smil, 2015). Aside from
96 this recent ongoing debate, geomorphologists have long investigated the impacts of human
97 societies on Earth surface processes and landform records, without needing the motivation of
98 creating a new geological time interval (Brown et al., 2013).

99

100 1.1. Humans as a geologic agent?

101 Defining humans as a geologic agent might sound a little strange or even a provocation. Further, of
102 course, if we compare human-induced changes to geologic forcing through the millennia, we are
103 looking at a different scale and magnitude. However, humans have the potential to amplify
104 geomorphic processes (Wolf et al., 2014). Bioturbation by humans ('anthroturbation') is a
105 phenomenon without precedent in Earth history and is orders of magnitude greater in scale than

any preceding nonhuman type of bioturbation ([Zalasiewicz et al., 2014](#)). Humans have become the dominant element in many Earth surface processes at different scales ([Steffen et al., 2007](#); [Wohl, 2013](#)), to the point that human activities can be considered distinct from, but comparable to, the effects of climatic or tectonic transformations ([Macklin et al., 2014](#)). According to [Wilkinson \(2005\)](#), humans move increasingly large amounts of rock and sediment during various construction activities, and therefore become a geological agent. They modify the spatial distribution and rates of hydraulic and geomorphic processes ([Fryirs and Brierley, 2012](#)), which might result in land degradation, and geomorphic changes ([Doolittle, 2006](#)). Furthermore, anthropogenic transformations coupled with the natural system can cause geomorphological processes to continue in a 'genetically modified' form ([Lewin, 2013](#)), and the results of this combined forcing might be preserved in long-term geological records, at least in some environments ([Brown et al., 2013](#); [Jefferson et al., 2013](#)).

Unlike natural geomorphic processes, the work done by humans is focused in specific locations with well-defined intent ([Guthrie, 2015](#)), and as a consequence, specific anthropogenic topographic signatures emerge. Looking at the different signatures of humans, we can mention mining activities, road networks and agricultural practices such as terracing and land reclamation. These signatures are very connected to current and future societal changes. In recent years, there has been a rising demand for base metals and industrial minerals, which is also connected to research into new forms of energy production ([Vidal et al., 2013](#)). Populations' needs for food will more than likely push the expansion of arable lands ([D'Odorico and Rulli, 2011](#)). Irrigated lands are also expected to expand ([Foley et al., 2011](#)). Terraced areas are greatly threatened by abandonment ([Tarolli et al., 2014](#)) or, on the other hand, by the intensification and specialization of agriculture ([Cots-Folch et al., 2009](#)). In addition, in the next few decades there may be a progressive increase in transportation networks ([Sidle and Siegle, 2012](#)).

These signatures can cause drastic changes to the geomorphic organization of the landscape, with direct consequences on Earth surface processes (e.g., [Mossa and James, 2013](#); [Sofia et al. 2014c](#); [Tarolli et al., 2014, 2015](#)). Thus, this review provides an overview of the recent challenging

133 theme of the role of humans as a geological agent, specifically as connected to those elements
134 that leave a clear topographic signature on the Earth's surface. The goal is to present the state of
135 the science of the analysis of human bioturbation that can serve as a basis to improve
136 environmental planning, mitigate the consequences of anthropogenic alteration, and provide useful
137 guidelines in the future challenges section. Identifying signals connected to anthropogenic
138 topographic signatures within Earth surface processes might help provide a better understanding
139 of current settings, the future and past steps in the evolution of our planet, and to schedule
140 appropriate environmental planning for sustainable development, to mitigate the consequences of
141 anthropogenic alteration.

142

143 **2. Mining**

144 Recent rapid urbanization in developing countries is spurring the demand for industrial products
145 and infrastructures such as electricity grids, transportation systems and buildings ([Kobayashi et al.,](#)
146 [2014](#)). For developed countries, on the other hand, renewable energy requires infrastructures built
147 with metals ([Vidal et al., 2013](#)). Therefore, more mining is almost unavoidable, and it is predicted
148 that the demand for base metals in 2050 will be several times the current demand ([Halada et al.,](#)
149 [2008](#)). Focusing on the quantities of mined minerals, [Rogich and Matos \(2008\)](#) highlighted that
150 there has been a constant increase over the years in mineral extractions, mostly for construction
151 materials. However, increases in mineral extraction are concomitant with increases in population,
152 and the overall extraction per person in the 1980s was similar to that of the 2000s despite the fact
153 that the gross extraction has been increasing. Given these trends and the trends in our society, it is
154 important to account for the fact that mining can have a significant impact on catchments, during
155 mining and for many years after the cessation of mining ([Hancock et al., 2008](#); [Herrera et al.,](#)
156 [2010](#)), which can influence landscape evolution ([Haigh, 1978](#); [Martín-Duque et al., 2010](#)), sediment
157 transfer ([Macklin and Lewin, 1989](#)) and thus geomorphology as a whole system ([Mossa and](#)
158 [James, 2013](#)). The most recent review about the impact of surface and underground mining on the
159 geomorphic system is by [Mossa and James \(2013\)](#). This section of the paper will focus specifically

160 on surface mining, which leaves an obvious topographic signature on the landscape through the
161 creation of large landforms (Fig. 2) and the addition of mine tailings.

162 Fig. 2

163 Table 1 collects the most significant literature on surface mining and connected geomorphic
164 processes, and it focuses on four main issues: (i) surface mining and consequent erosion, (ii)
165 mining-induced effects such as subsidence, (iii) landslide/debris-flow/rockfall risk, and (iv) effects
166 on runoff. In the following sections, we will focus in detail on the most critical issues connected to
167 these four points.

168 Tab. 1

169 2.1. Mining and erosion

170 Land displacement can be seen as a form of direct erosion on a global scale as the quantity of
171 material mechanically moved within the mines (Fig. 3a). However, mining activities also produce
172 erosion issues at local scales, when large quantities of sediment are transported by water erosion
173 (Fig. 3b).

174 Fig. 3

175 The contribution of construction and mining activities to the excavation and displacement of solid
176 materials on the Earth's surface is important. Quantifying such displacements is not obvious, but
177 some works in the literature allow a first insight. However, the measurement units are not always
178 homogeneous. To allow a comparison, for those works reporting the values of moved material in
179 weight per person, in this section we consider (i) the world or country population at the time of the
180 survey of each referenced work, (ii) the extent of the considered country, and (iii) we also
181 considered that the affected volumes were uniformly distributed over the area analysed, and to
182 account for an overall rate of erosion in mm y^{-1} we assumed a bulk density of 2000 kg m^{-3} for
183 construction/mining together. For those works reporting the values in weight at the plot or
184 catchment scale, we assumed a bulk density of 1500 kg m^{-3} . Hooke (2000) estimated that
185 construction in the past required moving (importing or excavating) 5 m of stone with an average
186 density of 2350 kg m^{-3} per square meter; we assumed a slightly lower value to account for mineral

187 production and excavation (e.g., coal, gravel, sand). At the hillslope scale, mine soils commonly
 188 have higher bulk densities and lower porosities than native soils due to heavy traffic associated
 189 with grading ([Thurman and Sencindiver, 1986](#)), thus we assumed a higher value than that
 190 assumed by [Montgomery \(2007b\)](#) for soil erosion.

191 We are aware that these are a rough simplification of reality and that more information should be
 192 accounted for: however, the transformation of the published values in mm y^{-1} allows for a direct
 193 comparison between the works. The final values should be considered to be only indicative rather
 194 than exact measurements.

195 In the past, large scale mining activities together with construction projects have been estimated to
 196 move approximately $20 \text{ t pers}^{-1} \text{ y}^{-1}$ in industrialised countries ([Luttig, 1987](#)). These numbers seem
 197 to have been confirmed, with an estimated rate of $\sim 16.8 \text{ t pers}^{-1} \text{ y}^{-1}$ in the United States in the
 198 1990s ([Hooke, 1999](#)) and $\sim 16.5 \text{ t pers}^{-1} \text{ y}^{-1}$ in Britain ([Douglas and Lawson, 2000](#)). Other sources
 199 show a global rate of $\sim 9.3 \text{ t pers}^{-1} \text{ y}^{-1}$, with $\sim 15.7 \text{ t pers}^{-1} \text{ y}^{-1}$ in Europe ([Douglas and Lawson,](#)
 200 [2000](#)).

201 Soil erosion rates reported in various units in the literature and converted to equivalent lowering
 202 rates provide an interesting overview. We can estimate the rates of erosion connected to mines
 203 and/or construction activities, which range from $\sim 0.2\text{-}0.3 \text{ mm y}^{-1}$ (USA and industrialized countries
 204 in the 1980s) to $\sim 0.6 \text{ mm y}^{-1}$ in Europe, compared to a natural European erosion of 0.05 mm y^{-1} .
 205 The global estimated erosion rate was $\sim 0.4 \text{ mm y}^{-1}$. Among the industrialized countries, given the
 206 smaller extent of the area, the highest erosion rate apparently was for Britain ($\sim 2 \text{ mm y}^{-1}$). Mining
 207 and construction are also responsible for erosion at the local-scale at the plot and catchment
 208 scales with watershed scale rates that range from 0.1 mm y^{-1} to 3 mm y^{-1} ([Hancock et al., 2006](#);
 209 [Rivas et al., 2006](#); [Meng et al., 2012](#); [Trabucchi et al., 2012](#)). At the hillslope scale, erosion rates
 210 can reach $>10 \text{ mm r}^{-1}$ ([Esling and Drake, 1988](#); [Biemelt et al., 2005](#)). Clearly, local erosion rates
 211 are differently influenced by vegetation, rocks, soils, local slopes, and roughness, and by
 212 subsidence and restoration plans ([Sanchez and Karl Wood, 1989](#); [Nicolau 2002](#); [Choi et al. 2008](#)).

213 The numbers obtained above, although subject to uncertainties, can be compared with different
214 estimates of material transfer by geomorphic agents reported in [Montgomery \(2007b\)](#) (Fig. 4).

215 Fig. 4

216 Keeping in mind that the highest geomorphological effectiveness can be achieved by events of
217 moderate magnitudes that occur more frequently ([Guthrie, 2015](#)), estimates from the literature
218 suggest that the direct or indirect displacement of sediments related to mining activities varies
219 between <0.1 to $>10 \text{ mm y}^{-1}$. This is a relatively high contribution, and it is considerable if
220 compared with sediment production from natural processes; these values, although at different
221 spatial and temporal scales, are in line with those of steep, tectonically active topographies (Fig. 4).

222

223 *2.2. Surface mining and land subsidence*

224 Surface subsidence (Fig. 5) is recognized as a problem in most countries, particularly those with
225 significant mining and other underground resource extraction industries ([Whittaker and Reddish,](#)
226 [1989](#)).

227 Fig. 5

228 In surface mining, land subsidence is mainly induced by the lowering of the water table caused by
229 groundwater withdrawal ([Jambrik, 1995](#); [Wolkersdorfer and Thiem, 1999](#); [Panilas et al., 2008](#);
230 [Woldai et al., 2009](#)), and the rates of withdrawal-induced subsidence have been estimated in some
231 areas to reach 50 mm y^{-1} ([Kircher et al., 2003](#)). Mine-related subsidence causes the permanent
232 inundation of land, aggravates flooding, changes topographic gradients, can induce fault
233 reactivation ([Donnelly, 2009](#); [Woldai et al., 2009](#)) and has direct effects on the natural ([Bell et al.,](#)
234 [2000](#)) and built ([Wolkersdorfer and Thiem, 1999](#)) environment. The significance of mining
235 subsidence as a geomorphic agent is mainly due to its spatiotemporal scale. Considering the time
236 scale, subsidence can occur simultaneously to the mining activities and long after the mines have
237 been abandoned ([Bell et al., 2000](#)) or actively restored. It is usually said that mines are somehow
238 'living creatures' that constantly change, even when their productive life has come to an end,
239 causing subsidence and slope instability phenomena ([Herrera et al., 2010](#)). Regarding the spatial

240 scale, the extent of the subsidence area can range from nearly equal to many times the mining
241 area, where aquifers are dewatered and undergo compaction ([Dunrud, 1984](#)). Modern surface
242 mining operations usually have significant extents, and they can also influence relatively large
243 portions of the terrain adjacent to the crest of the open pit or around the extraction areas. The
244 vertical magnitude of the subsidence itself typically does not cause problems. However, it is the
245 associated surface compressive and tensile strains, curvature, tilts, and horizontal displacements
246 that are the cause of the worst damage to the natural environment, buildings, and infrastructure
247 ([Herrera et al., 2012](#)). The location and extent of the mine as well as the mining techniques in
248 respect to geometrical and geological factors, play a key role in ground subsidence ([Herrera et al.,](#)
249 [2010](#)). However, the accumulation of those effects gives an additional qualification to mining as a
250 geologic agent.

251 252 *2.3. Surface mining and landslides/debris-muddy flows/rockfall hazards*

253 Rockfalls and landslides (Fig. 6) in surface mining are among the most critical threats associated
254 with the various types of geological instabilities and also induce risks near the mine (e.g., [Johnes](#)
255 [et al., 2000](#); and Fig. 6b). Some authors have argued that in the mining framework, human beings
256 are an active factor contributing to disasters ([Ramani, 1995](#)); and with the scale of mining
257 extending, landslide disasters on the Earth's surface will become increasingly serious ([He et al.,](#)
258 [2009](#)).

259 Fig. 6

260 Three types of induced-processes can be considered: (i) landslides/debris/rockfalls within the mine
261 itself, (ii) indirect landslides/debris/rockfall hazards exacerbated or induced by mining activities in
262 the surrounding landscape, and (iii) further indirect hazards connected to the movements of the
263 mobilized material in areas away from the mine itself.

264 Concerning direct hazards within mines, surface deformations and slope stability from mining
265 activities have been approached from a modelling point of view because these issues are very
266 important to the mining industry as potential sources of danger to people and equipment. For this

267 type of event, stability analysis and comprehensive treatment methods together with geotechnical
268 data, sliding causes, and characteristics about landslides should be gathered to prevent economic
269 and life loss (Wei et al., 2008; Peila et al., 2011; Li et al., 2012). An interesting aspect from a
270 geomorphological point of view is the effect of mining on landslide/debris/rockfall hazards within
271 the mined catchments. The presence of mining/quarrying activities is apparently responsible for
272 very low frequency, catastrophic events but also for frequent events that recur on a daily or weekly
273 basis (Hearn, 1995) and events that are triggered by medium-intensity rainstorms (Baroni et al.,
274 2000; Cortopassi et al., 2008). In some environments, mining activities have been proven to be the
275 cause of the reactivation of dormant slides (Bentley and Siddle, 1996). Morphologies artificially
276 modified by mining in conjunction with climate inputs (e.g., intense rainfall, Erginal et al., 2008) and
277 geology (e.g., existing geological discontinuities, Laimer and Mulleger, 2012) have also been
278 underlined as a crucial element that contributes to landslides.

279 In addition to landslide processes, mining can produce debris flows and muddy floodwaters from
280 tailings failures, which results in floods (Fig. 7) that are commonly composed of water with high
281 sediment concentrations (Guerrero et al., 2008; Rico et al., 2008a). These events generally occur
282 in active mines and only rarely occur in abandoned ponds (Rico et al., 2008a, b).

283 Fig. 7

284 Without denying the role of natural forcing, the frequency of induced events (daily or weekly basis)
285 and triggering connected with medium magnitude climatic episodes or the exacerbation of events
286 related to intense climatic episodes seem to indicate that anthropogenic pressure can indeed play
287 a contributing role in the overall landscape instability.

288

289 *2.4. Surface mining and runoff*

290 As in the case of subsidence and erosion, the effects of mining on runoff can continue once the
291 extraction activities have stopped. It has been underlined how reclaimed surface-mines cause
292 increased runoff more rapidly than undisturbed areas (Kilmartin, 1989; Negley and Eshleman,
293 2006). This can generally result in higher flood peaks, reduced base flows, shorter lag times

294 between the rainfall and flood peak, reduced groundwater recharge and higher sediment loads in
295 the affected catchments. In addition, the destruction of interfluvies connected to the removal of
296 rocks below the water table can alter the natural groundwater flow paths, which can contribute to
297 the overall increase in flow velocities and the shortening of flow paths (Holmes et al., 1993). Over
298 large areas, surface mining can be correlated to increases in flood extent (Katpatal and Patil, 2010)
299 and magnitude (Ferrari et al., 2009), with greater rates observed for less frequent return intervals
300 (Ferrari et al., 2009). Interestingly, all the above findings seem to indicate that mining leaves the
301 landscape in a condition more similar to urbanized areas than to natural reclaimed landscapes.

302

303 3. Roads

304 Among the anthropogenic modifications of landscapes, road construction has increased
305 dramatically, and new surfaces have appeared in most areas of the world (Jimenez et al., 2013).
306 Networks of roads interact with water and sediment flow paths in multiple ways (Wemple et al.,
307 1996; Jones et al., 2000; Forman et al., 2003). Roads influence a variety of hydrologic and
308 geomorphic processes, which has been well known for a long time (Reid and Dunne, 1984; Luce
309 and Cundy, 1994; Montgomery, 1994; Luce and Wemple, 2001). Among the environmental effects
310 of roads, the effects on water quality, aquatic ecology (Luce, 2002) and ecological processes
311 (Jones et al., 2000; Coffin, 2007) are critical. Table 2 reports the most significant literature
312 regarding roads and geomorphic processes in hilly/mountainous landscapes and issues related to
313 runoff, sediment production, erosion, connectivity and geomorphic processes in flat landscapes.

314 Tab. 2

315

316 3.1. Roads in mountainous / hilly landscapes

317 Roads in mountainous/hilly landscapes support agricultural development, timber harvesting, local
318 travel, trade and tourism, but at the same time they present difficult and pressing environmental
319 challenges in many locations around the world (Petley et al., 2007; Sidle and Ziegler, 2012). Figure
320 8 shows an example of a rural mountain road in Nepal. Interestingly, in 2010 (Fig. 8b) the road

suffered from a series of large landslides along its path. Google Earth also provided an image from 2008 (Fig. 8a), which was taken before the road was constructed. In that year, there were no landslides at the same location. It is clear that a landslide can result from the combination of a whole range of natural factors; in this case, however, human involvement is evident.

Fig. 8

3.1.1. Roads, runoff, erosion and sediment production

Roads, tracks and trails in mountainous/hilly landscapes collect runoff from overland flows (Fig. 9a) as well as from rain falling on road surfaces (Fig. 9b). As a consequence, they can produce runoff much more rapidly than the surrounding landscape.

Fig. 9

Roads and geomorphic processes on hillslopes interact in multiple ways: (i) roads lead to a decrease of infiltration due to the rerouted flow paths; thus, they lead to an increase in surface runoff (Wemple and Jones, 2003; Hölzel and Diekkrüger, 2012); (ii) road segments can intercept subsurface flows and reroute them to ditches and previously unchanneled hillslopes, thus increasing the potential for erosion (Wemple et al., 2001; Borga et al., 2004; Ziegler et al., 2004; Tarolli et al., 2013, 2015); (iii) roads act simultaneously to rainfall events; thus, erosion is controlled both by the road and by the rainfall characteristics (MacDonald et al., 2001; Wemple et al., 2001; Sudgen and Woods, 2007; van Meerveld et al., 2014); (iv) they enhance the effects of other forcings (e.g., vegetation removal) (Harr et al., 1975; Eisenbies et al., 2007); and (v) the relative position of the road with respect to the landscape, road slope and maintenance status have impacts on soil erosion (Sudgen and Woods, 2007; Bochet et al., 2010; Brown et al., 2013; Butzen et al., 2014).

As a consequence of the above interactions, roads can initiate debris slides that increase the rate of mass wasting (Swanson and Dyrness, 1975), and they affect hydrological processes and water pathways (Fig. 10a) (Luce, 2002), floods and debris flows (Jones et al., 2000). In addition, roads can function as both production (Sudgen and Woods, 2007; Jordan-lopez et al., 2009) and depositional sites for sediments (Fig. 10b), contributing to basin-wide production (Dunne and

348 Leopold, 1978; Reid and Dunne, 1984; Ziegler and Giambelluca, 1997; Fu et al., 2010; Collins et
349 al., 2010).

350 Figure 10

351 Some authors have emphasized that despite predicted increases in sediment yields from road
352 surfaces, annual sediment yields at the catchment scale appeared to be within natural levels
353 (Fransen et al., 2001). Other authors have emphasized how the net effect of roads was an
354 increase in basin-wide sediment production, highlighting the simultaneous importance of natural
355 hydrologic factors (Wemple et al., 2001; Wemple and Jones, 2003). Scale, however, matters. Road
356 effects on streams vary depending on the scale; low-order headwater streams can be heavily
357 influenced by roads, whereas this effect might be masked in higher-order catchments (Thomaz et
358 al., 2014). Additionally, in small channels, road crossings can produced deposition, width/depth
359 changes and bed fining, whereas larger channels produce different effects (Marion et al., 2014).
360 As a form of erosion, gully initiation is also affected by roads. In this framework, roads can have a
361 greater effect than vegetation or ground cover, for example (Muñoz-Robles et al., 2010). Gully
362 incision can be significant below culverts and near road drains (Wemple et al., 1996; Nyssen et al.
363 2002; Takken et al., 2008), but it can also develop in locations away from the road itself (Nyssen et
364 al., 2002; Jungerius et al., 2002). In fact, roads alter the thresholds for gully erosion (Muñoz-
365 Robles et al., 2010, Katz et al., 2014) and also induce the development of individual gullies and
366 multi-branched gully systems at a watershed scale (Superson et al., 2014).

367

368 3.1.2. Connectivity

369 Due to the induced effects on runoff, flow paths, erosion and sediment transport, roads can have
370 an overall effect on the catchment connectivity. We consider two main effects: direct connectivity
371 through channels and gullies and diffuse connectivity via overland flow paths (Croke et al., 2005).
372 The lack of maintenance of anthropogenic features tends towards higher stability and lower
373 efficiency of morphological processes, connected with a sustained decrease in slope–channel
374 coupling (Latocha, 2014). The road network geometry also plays a key role in connectivity

375 (Pechenick et al., 2014). Independent of scale, the proximity of the road to the stream can be a
376 valuable driver that discriminates the channel conditions, and the shape of the network can create
377 physical connections to the streams through short overland flow paths and gullies (Pechenick et
378 al., 2014). Section 5.1.3 will further examine the connection between road networks and
379 connectivity.

380

381 3.1. Roads in flat landscapes

382 Especially in floodplains, roads can have a significant impact on natural flood patterns and their
383 functions. In floodplains, road construction generally follows two approaches: 'resistance' and
384 'resilience' alignment (Vis et al., 2003). The first approach increases the elevation of the road to
385 create a dyke that prevents flood water from over-flowing the structure. In the second approach,
386 the resilience strategy, roads are developed both by increasing road elevations and the
387 implementation of flow-through structures to allow floodwaters to permeate the road alignment (Vis
388 et al., 2003). In both cases, the flood pathways, extent and duration will be changed by road
389 development (Beevers et al., 2012), with possible effects on erosion as well (Fig. 11)

390

Fig. 11

391 Regarding mountainous environments, the drainage system of roads in a floodplain can have large
392 geomorphic effects. The resistance and the resilience approaches cause two main interactions
393 with geomorphic processes in floodplains: (i) impacts due to bridges, culverts and roadside ditches
394 and (ii) impacts where the road structures act as dams along channels, causing connections or
395 disconnections with the floodplain (Blanton and Marcus, 2009; 2013) or altering the hydrological
396 properties of the landscape (Trizzino, 2015).

397 Regarding floods, culverts can facilitate the excavation of channels and widening of small
398 tributaries (Florsheim et al., 2001). The use of designed flow-through structures maintains
399 inundation patterns, but with increasing levels of road development more impacts are observed to
400 hydraulic components such as water levels, velocities, inundation durations and extents (Beevers
401 et al., 2012). Roads and roadside ditches can also contribute to increasing the drainage density of

watersheds, with effects on floods (Buchanan et al., 2013; Douven and Buurman, 2013). Road-related sediment sources from culverts and road ditches can contribute to rivers and tributaries (Florsheim et al., 2001; Zajac et al., 2002), which make roads an efficient means of transport for pollutants (Buchanan et al., 2013). Road networks act as an anthropogenic ‘barrier’ for water and sediment fluxes across the landscape (Kumar et al., 2014). The presence of a road network can influence the size and duration of inundated areas during floods, fragmenting habitats and drying wetlands (Beevers et al., 2012). Channels near roads can be narrower and simpler in form, and they generally lack depositional elements such as bars and islands (Blanton and Marcus, 2013). Even if they have a localized direct impact on the overall floodplain hydraulics (Douven et al., 2012), small changes in flood dynamics may have large ecological impacts, especially if the cumulative impacts of more road developments are taken into account.

413

414 **4. Agriculture**

Civilizations in floodplains tend to expand rapidly, as long as agriculture in the fertile river valley bottoms allows populations to grow (Montgomery, 2007a). However, as villages expand into cities, the construction of canals, dikes, and earthworks for flood protection, irrigation and reclamation follows (Hooke, 2000). Agricultural activities, among other activities, can significantly alter the geomorphology of large territories over the course of thousands of years and from the use of various tillage methods (Gottschalk, 1945; Costa, 1975). Shifting human geography, especially associated with changes in farming and agricultural activities, is a main factor that drives major soil erosion processes (Boardman and Poesen, 2006), and as a consequence of the exploding world population, there has been an astonishing increase in the geomorphological effects of agriculture. Agricultural lands have been subjected to drastic shifts in land use, characterized by a high diversity of trajectories depending on the local conditions, regional context and external influences (Verburg et al., 2010). In many countries where the economy has shifted from mainly agricultural to industrial, agricultural lands have been reforested (Fig. 12a and b) and lost to urbanization in highly

428 populated areas (Fig. 12c and d), but in other cases, agriculture has intensified (Fig. 12e and f)
429 with changes in agricultural techniques and consequent changes in the drainage system.

430 Fig. 12

431 The interaction between agriculture and geomorphic processes is the result of a combination of
432 factors ranging from small to large scales. At the local scale, tillage practices can influence runoff
433 and erosion (Van Oost et al., 2006), and agriculture can induce structural degradation of the soil
434 (Palmer and Smith, 2013), which results in increases in runoff and transport capacity. At the local
435 and medium scales, terracing practices have a direct effect on processes (Tarolli et al., 2014;
436 Arnáez et al., 2015). Moving to a larger scale, land abandonment (see Sect. 4.2) and land
437 expansion in previously uncultivated lands (Dotterweich, 2013; Dotterweich et al., 2013; Merten
438 and Minella, 2013) can induce or alter geomorphological processes. In addition, hydrologic
439 alteration (Florsheim et al., 2011), which is also connected to the alteration of the drainage network
440 for irrigation purposes, plays a key role in the overall system (See sect. 4.3). However, although it
441 is well known that agricultural activities are directly relevant to watershed hydrology and
442 geomorphology, the specific effects of artificial drainage as contributors to processes are not well
443 understood (Schottler et al., 2014), but sometimes, their effects are critical (Sofia et al., 2014c)
444 (Fig. 13).

445 Figure 13

446 The following two sections, therefore, will focus on the direct effects of agriculture on soil erosion,
447 with a specific focus on land abandonment and the indirect effects connected to changes in
448 drainage systems. Table 3 recalls review papers and specific scientific special issues, focusing on
449 exemplary case studies in different parts of the world and specific cultivations that underline the
450 deep connection between agriculture and surface processes.

451 Tab. 3

452

453 *4.1. Agriculture and soil erosion*

454 Recently, [García-Ruiz et al. \(2015\)](#) offered a detailed analysis of published data on soil erosion
455 rates (in units of mass per area and time) under a large range of climatic conditions and land uses,
456 taken from more than 4000 sites worldwide. Their results revealed a number of general features,
457 including the significant effect of land use, with agricultural lands yielding the highest erosion rates.
458 Similar to the work on mining (Sect. 2.1), the soil erosion rates reported in [García-Ruiz et al.,](#)
459 [\(2015\)](#) for agricultural landscapes were converted to equivalent lowering rates, assuming a soil
460 bulk density of 1200 kg m^{-3} , which provided an update to the ideas of [Montgomery \(2007b\)](#) (Figure
461 14).

462 Figure 14

463 The data from [Montgomery \(2007b\)](#) that were updated using the values of [García-Ruiz et al.,](#)
464 [\(2015\)](#) show how cultivated fields from different regions mostly erode at rates typical of alpine
465 terrains. These numbers confirm what others have found; erosion rates from agriculture are among
466 the highest rates found for land uses ([García-Ruiz and Lana-Renault, 2011](#)), and they can exceed
467 the rates of most natural erosion processes ([Massa et al., 2012](#)). Compared to long-term natural
468 events, however, one should consider that agricultural techniques produce this amount of
469 sediments in shorter periods of time ([Dotterweich et al., 2015](#)). This difference in time scale can
470 become a critical problem, especially considering that the natural production of soil is relatively
471 slow and that soil might not be ‘naturally’ renewable on a societal time scale ([Stockmann et al.,](#)
472 [2014](#)).

473 Erosion from agriculture also has indirect effects on river desiccation, groundwater depletion, water
474 pollution, sedimentation, salinization and salt-water intrusion ([Atapattu and Kodituwakku, 2009](#)). In
475 addition, agricultural erosion can deliver sediment to the drainage network ([Borselli et al., 2008](#)),
476 and it can have consequences on the rates and magnitudes of floodplain sedimentation ([Doolittle,](#)
477 [2006; Knox, 2006](#)). Connected with soil erosion from agricultural lands, floods, especially muddy
478 floods, are also of growing concern in Western Europe ([Biielders et al., 2003; Boardman et al.,](#)
479 [2003, 2006; O’Connell et al., 2007; Evrard et al., 2007; Heitz et al., 2009; Boardman, 2010;](#)
480 [Boardman and Vandaele, 2010](#)).

481

482 4.2. *Land abandonment with special reference to the Mediterranean region*

483 Land abandonment has significant environmental consequences that are not equally relevant in all
484 regions of the world. The most evident effects of farmland abandonment are shown in
485 Mediterranean areas, especially in semi-arid environments, which are primarily affected by erosion,
486 piping and gullying (García-Ruiz, 2010). Specifically on hillslopes, the generalized abandonment of
487 agricultural terraces can favour surface runoff, erosion and soil sliding (Arnaez et al., 2011; García-
488 Ruiz and Lana-Renault, 2011; García-Ruiz et al., 2013; Tarolli et al., 2014, 2015). Land
489 abandonment in Mediterranean environments is expected to increase the overall net soil losses
490 and total erosion and decrease sediment delivery ratios (Debolini et al., 2013). Aside from the
491 direct negative consequences of land abandonment, the recolonization of natural vegetation can
492 also result in a reduction in soil loss and the progressive improvement of soil characteristics
493 (García-Ruiz and Lana-Renault, 2011). However, such evolution can also result in changing
494 stream morphologies, especially narrowing and incision, and a decline in sedimentation levels in
495 Mediterranean reservoirs (García-Ruiz and Lana-Renault, 2011).

496

497 4.3. *Drainage systems*

498 In many agricultural regions, more than 80% of the catchment basins may be drained by surface
499 ditches and subsurface drain pipes (Blann et al., 2009). Among the environmental impacts caused
500 by agricultural drainage, we can mention habitat loss or alteration, reduced water quality and
501 hydrologic alterations (Blann et al., 2009). Regarding hydrologic alterations, a coarsening of the
502 drainage networks in floodplains might result in significant changes to total groundwater recharge
503 (Krause et al., 2007) as well as changes in the connectivity of the watersheds, which can alter
504 overland flows and create excess water hazards (Kiss and Benyhe, 2015). As a result, the
505 presence of a specific drainage system may also limit the extent to which land cover would ever
506 resemble historic hydrological conditions (Schilling et al., 2008). Connected to the coarsening of
507 drainage networks, the loss of ditches might also result in an exacerbated flood risk (O'Connell et

al., 2007, Wheater and Evans, 2009; Sofia et al., 2014c). This latter effect might be greater for events with shorter return times, with an increase in flood risk for rather frequent rainfall events that are not necessarily associated with extreme meteorological conditions and that are not necessarily associated with worst case scenarios (Sofia et al., 2014c). Furthermore, flows from artificial drainage networks affect stream baseflows and streamflow recession characteristics (Schilling and Helmers, 2008), and they have the potential to alter water budgets on a watershed scale (Schottler et al., 2014). Reduced surface storage and increases in conveyance can also result in increased flows in streams and rivers (Blann et al., 2009), with consequences on sediment transport capacities and increases in the amount of sediments carried downstream (Lenhart et al., 2012). These effects can be so prominent that in some environments, they exceed the effects of precipitation (Sofia et al., 2014c) and land-use changes (Schottler et al., 2014).

519

520 **5. Future challenges**

521 *5.1. Remote Sensing (RS) and High-resolution topography (HRT)*

Remote Sensing and Digital Elevation Models (DEMs) have been used in geomorphology for decades. Researchers in applied geomorphology and geomorphologic surveying and mapping have always relied upon these techniques. However, over the past decade, developments in technology have enabled the general public to be increasingly engaged with technology (Goodchild et al., 2012). Governments and remote-sensing communities inside and outside the scientific world are now seizing opportunities for sharing spatial data (Bernard et al., 2005; Krishnan et al., 2011; Wulder and Coops, 2014), and science-intensive firms are involved with 'open data' initiatives (Perkmann and Schildt, 2014). At the same time, due to the ease of processing and obtaining data, a large amount of interest has arisen in obtaining high-resolution DEMs using flexible and affordable technologies. The recent development of the Structure-From-Motion (SfM) photogrammetric technique (Westoby et al., 2012) and its application on UAVs (Martin-Vide, 2004; Chen et al., 2015; Francioni et al., 2015) and even smartphones (Micheletti et al., 2015; Prosdocimi et al., 2015) has opened new frontiers for the analysis of Earth surface processes and,

535 in particular, anthropogenic processes. Unlike natural geomorphic processes, the work done by
536 humans is focused on specific locations with well-defined intent (Guthrie, 2015). The resulting
537 topographic signatures can be actively modelled only with the global availability of fine-scale,
538 three-dimensional topographies, and today this framework offers a large advantage in terms of
539 spatiotemporal coverage. In this context, the future challenge is the ability to actually model
540 anthropogenic morphologies, quantify them, and analyse the links between anthropogenic
541 elements and geomorphic processes. In addition, the involvement of public authorities, land
542 managers and common users in the creation and dissemination of datasets might slowly allow the
543 transfer the knowledge of geomorphic processes from the scientific to the practical world.
544 Tarolli (2014) and Passalacqua et al. (2015) proposed an overview of how HRT can be useful in
545 engineered landscapes and offered a review of the most important works carried out in this field by
546 researchers. In addition to the literature provided in the previously mentioned reviews, Table 4
547 reports the most recent and interesting works that address HRT and anthropogenic environments.

548 Tab. 4

549 In the following sub-chapters, three examples will be provided regarding how HRT can be useful
550 for the analysis of anthropogenic geomorphologies. The case studies are based on the Slope Local
551 Length of Auto-Correlation (SLLAC) proposed by (Sofia et al., 2014b) and successfully applied in
552 mining landscapes in (Chen et al., 2015) (Chapt. 5.2.1), and in a slightly modified version of the
553 procedure and the technique proposed in (Sofia et al., 2015), to automatically detect anthropogenic
554 areas (Chapt. 5.2). A further example will show the connection between roads and geomorphic
555 processes, which is based on the analysis of the sediment Connectivity Index proposed in Borselli
556 et al., (2008) and Cavalli et al., (2013) on the changes to flow paths induced by roads, measured
557 according to the Relative Path Impact Index (RPII) proposed by (Tarolli et al., 2013).

558 The original SLLAC metric (Sofia et al., 2014b) is based on a 2D cross-correlation between a slope
559 patch and its surrounding areas. From this cross-correlation, it is possible to derive the correlation
560 length as the horizontal distance of the areal cross-correlation that corresponds to 37% of the
561 correlation maximum value. A second parameter, the Surface Peak Curvature (*Spc*), is the

average of the principal curvature of the local maximums on the SLLAC map, where each maximum is defined as a pixel higher than its 8 nearest neighbours. The *Spc* is statistically able to differentiate a terraced area from a natural one; *Spc* increases as the landscape becomes more natural. [Chen et al. \(2015\)](#) furthermore proposed a polynomial (for mining landscapes) that related the value of the *Spc* to the percentage of the terraced area within an analysed site. The connectivity index by [Borselli et al., \(2008\)](#) and [Cavalli et al., \(2013\)](#) is intended to represent the potential connectivity between different parts of the catchment and aims, in particular, at evaluating the potential connection between hillslopes and features, which act as targets or sources for transported sediment. The RPII instead considers the contributing area as a proxy of the flow path distributions, and in a logarithmic form emphasizes areas where the flows are increased due to the presence of anthropogenic features ([Tarolli et al., 2013](#)). See [Sofia et al., \(2014b\)](#), [Chen et al., \(2015\)](#), [Sofia et al. \(2015\)](#) for a full description of the cross-correlation computation and for the measure of the correlation length, [Borselli et al., \(2008\)](#) and [Cavalli et al., \(2013\)](#) for a full description of the Connectivity Index and [Tarolli et al., \(2013, 2015\)](#) for a clear description of the RPII.

577

5.1.1. *HRT for a quick comparison among different areas*

The purpose of the following example is to show the benefit of the availability of free HRT data (in this case LiDAR) to allow a rapid automatic comparison between areas that have different human pressures to associate them with study areas in different parts of the world.

Figure 15 shows the Bingham Canyon Mine (A) (UT, USA) and the Hull-Rust-Mahoning Mine (B) (MN, USA).

584

Fig. 15

The Bingham Canyon mine (A in Fig. 15, Fig. 15a) is one of the largest man-made excavations in the world ([Pankow et al., 2013](#)) and has an open pit that is 0.97 km deep and 4 km wide. In 2013, the mine experienced a massive landslide that moved ~65 million cubic metres of material; this cumulative event was probably the largest non-volcanic landslide in North America in modern

589 times ([Pankow et al., 2013](#)). For this area, the Utah Automated Geographic Reference Center
590 offers a free download of a 2 m DTM collected in 2006 ([AGRC, 2015](#)) (Fig. 15b).

591 The Hull-Rust-Mahoning Mine (B in Fig. 15, Fig. 15d) is one of the widest open pit iron mines in the
592 world; the mine has a 2.5 by ~6 km footprint and a depth up to ~180 m. For this area, the
593 Minnesota Geospatial Information Office of the Minnesota Department of Natural Resources offers
594 a free download of a 1 m LiDAR DTM, which has an accuracy of 0.6 m ([Minnesota Department of
595 Natural Resources, 2015](#)). To ensure homogeneity with the other study site, we generated a
596 reduced-resolution (2 m x 2 m per pixel) version of the Minnesota DTM, where each output cell
597 contained the mean of the input cells that were encompassed by the extent of that cell (Fig. 15e).
598 For the two areas, a SLLAC map was derived ([Sofia et al., 2014b](#)) (Fig. 15c, 15f).

599 It is clear that the open pit areas leave a deep signature on the topography that is captured by long
600 fibres in the SLLAC map and high values of the correlation lengths, which underlines what [Chen et
601 al. \(2015\)](#) found for open-pit mines in China. For the Bingham Canyon mine map, the Spc value is
602 $4.4 \times 10^{-2} \text{ m}^{-1}$, whereas for the Hull-Rust-Mahoning mine, it is $3.9 \times 10^{-2} \text{ m}^{-1}$. These values are
603 statistically similar to Spc values of areas with greater than 10% terrace coverage in [Chen et al.
604 \(2015\)](#) (p -value = 0.2 and 0.8, respectively in a Mann-Whitney test, thus indicating a failure to
605 reject the null hypothesis that the samples come from different populations).

606 According to the polynomial approach in [Chen et al. \(2015\)](#), the Bingham Canyon mine Spc
607 corresponds roughly to 21% of terrace coverage within the site. The considered DTM is
608 approximately 103 km^2 ; thus, the estimate extent of the anthropogenic surface is approximately 22
609 km^2 . By roughly measuring the extent of the entire mine (not just the open pit), the mine covers
610 approximately 30 km^2 . Therefore, the automatic procedure produced an estimate that is
611 approximately 70% of the actual mine extent. However, by considering the confidence bounds of
612 the [Chen et al. \(2015\)](#) relationship, the actual extent of the mine falls within these bounds. For the
613 Hull-Rust-Mahoning mine, the Spc corresponds to 60% of the anthropogenic surface,
614 approximately 240 km^2 , considering the extent of the analysed DTM. A rough estimate by hand of
615 the extent of the mine, including the areas covered by water, is approximately 110 km^2 . If we

include the footprints of the towns in the study area in the definition of the anthropogenic surface (Hibbing, Keewatin and Chisholm), considering that buildings on LiDAR DTMs leave a clear mark that is captured by the SLLAC (see Fig. 15f), as also underlined by [Chen et al. \(2015\)](#), we measured an actual extent of approximately 250 km², which is very close to the estimated area. In the Hull-Rust-Mahoning Mine case study, it is interesting to see that the mine area itself presents numerous ponds. Clearly, on the LiDAR data these appear as a completely flat surfaces. The SLLAC is based on the normalized cross correlation ([Sofia et al., 2014b](#)), and this measure is an undefined operation in regions where there is zero variance within the analysed area. This is exactly the case for completely flat surfaces derived from water bodies on LiDAR DTMs. A road or a flat field would not be the same as a water body because their surfaces have some roughness and, as a consequence, all the water bodies can be automatically identified as ‘empty’ spaces on the SLLAC maps.

5.1.2. Track/monitor changes over time

Anthropogenic changes follow economic and societal changes and thus occur rather quickly on a geological time scale. The availability of multi-temporal HRT surveys with short revisiting times offers an opportunity to effectively track those changes.

The SLLAC ([Sofia et al., 2014b](#)) is based on the spatial organization of slopes rather than absolute values and can therefore be applied to different topographic supports. As a matter of fact, this technique can potentially be generalized for application to any type of imagery. If we broaden the concept of slope, it is mathematically possible to compute the ‘slope’ (or gradient) of a greyscale image as the directional change in the intensity or colours (Eq. 1):

$$\nabla f = \frac{\partial f}{\partial x} \hat{x} + \frac{\partial f}{\partial y} \hat{y}, \quad (1)$$

where $\frac{\partial f}{\partial x} \hat{x}$ and $\frac{\partial f}{\partial y} \hat{y}$ are the gradient in the x and y direction, respectively, and f is the colour intensity in a greyscale range. Having the image gradient map, it is then possible to feed this input to the cross-correlation evaluation, thus deriving a Gradient Local Length of Auto-Correlation

641 (GLLAC). The following example (Fig. 16) shows a mining area in Spain. For this area, aerial
642 photographs at 2 m resolution are available for 2005 (a) and 2008 (e).

643 Fig. 16

644 From these images, we computed the gradient (b) and (f), and we derived the GLLAC (c) and (g),
645 considering the same parameters presented in [Sofia et al. \(2014b\)](#).

646 Once the GLLAC was derived, we computed the *Spc* and the average GLLAC using a moving
647 window of 1 ha, and we clustered the area into two parts. According to [Sofia et al. \(2015\)](#), the
648 cluster with the lower *Spc* or, alternatively, the higher average SLLAC, can be considered as
649 potentially anthropogenic; thus, we considered the same approach (Fig. 16d and h).

650 Despite limitations due to image illumination/sun exposure that might prevent some elements from
651 being clear on the image, the GLLAC, analogously to the SLLAC, well captured the presence of
652 terraces within the open pit mine and the presence of roads with elongated fibres. Comparing the
653 two maps at two different times, it is possible to detect changes within the study sites and identify,
654 for example, the expanded area of the mine. The area has an *Spc* of 2.08×10^{-2} in 2005 and
655 2.17×10^{-2} in 2008. Despite coming from a different source (GLLAC instead of SLLAC), the two
656 values are statistically similar to the population of the *Spc* values of areas with more than 10%
657 terrace coverage in [Chen et al. \(2015\)](#) (p-value = 0.6 and 0.5, respectively, in a Mann-Whitney test,
658 which indicates a failure to reject the null hypothesis that the samples came from different
659 populations).

660 As in the previous example, using these values and considering the [Chen et al. \(2015\)](#) relationship,
661 we obtained a 17% coverage by anthropogenic structures in 2005 vs. 33% in 2008, which is a gain
662 of ~16% in structures over the complete extent of the considered image. In this case, the image
663 covered approximately 1 km², therefore the estimated change in the areas over time was
664 approximately 16 km². Clearly, the results may have been biased by the image quality and
665 exposure to light, and the capability of tracking anthropogenic structures depends on their visibility
666 on the map (e.g., this would not be possible under vegetation cover). The detection of
667 anthropogenic signatures from a DEM has some confidence bounds (e.g., 10% of terraced areas,

668 according to [Sofia et al. 2014b](#) or $\sim 4 \text{ km/km}^2$ of roads in [Sofia et al., 2015](#)). However, the SLLAC
669 (and GLLAC) derived values, when considering natural or anthropogenic areas, are significantly
670 different, and to our knowledge, there is no other indicator currently in the literature that is able to
671 automatically relate human signatures to specific morphological characteristics. Thus, the flexibility
672 of this image-based approach is promising.

673

674 *5.1.3. Understanding the link between processes and anthropogenic elements*

675 HRT describes the landscape topography, which is both a product and a driver of the activity of
676 geomorphic processes. In the same way, the connectivity of landscape units with respect to water
677 and sediment fluxes can be seen as both a driver and an emergent property of hydrological ([Ali et](#)
678 [al., 2014](#)) and geomorphic processes. Road networks have a large effect both on sediment
679 production and sediment delivery (see Chapt. 3); thus, the availability of HRT can help and provide
680 a better understanding of road-related issues. The site chosen for this application was the Lookout
681 Creek watershed within the Andrew Experimental Forest (OR, USA). In this area, numerous
682 studies have underlined the relationship between roads and erosion (landslides and debris flows)
683 ([Swanson and Dyrness, 1975](#); [Wemple et al., 1996](#); [Jones et al., 2000](#); [Wemple et al., 2001](#)). For
684 this site, the Experimental Forest website offers a free download of a LiDAR DTM at 1 m resolution
685 in addition to a complete database of the slides and road network (Fig. 17a). The watershed is
686 completely covered by vegetation; thus, the road network can be visible only by having either the
687 actual locations of the roads or LiDAR datasets that capture the morphology under the forest
688 cover.

689

Fig. 17

690 For this study, the Connectivity Index ([Cavalli et al., 2013](#)) was evaluated in terms of the (i)
691 sediment delivery across the entire drainage system (as in the potential connection of the sediment
692 between the hillslopes and catchment outlet) (Fig. 17a, 17b, 17h) and the sediment coupling-
693 decoupling between the hillslopes, (ii) main channels (Fig. 17c, 17f and 17i) and (iii) the road
694 network (Fig. 17d, 17g and 17l). The choice of modelling these aspects results from the need to

695 address some primary sediment management issues: (i) what is the probability that sediment from
696 a certain sediment source (in this case, landslide processes) will reach the catchment outlet?; (ii)
697 what is the probability that sediment eroded from the hillslopes will influence the drainage
698 network?; and (iii) what is the probability that a specific event will deliver sediment to the road
699 network.

700 There is no reference theory for the partitioning of the connectivity index into classes, and we
701 therefore adopted a relative classification into four classes (High, Medium-High, Medium-Low and
702 Low) by identifying break points that best grouped similar values and maximized the differences
703 between classes (natural breaks); this has been found to be suitable for alpine watersheds, where
704 the variability in the index ranges from -8 to 2 ([Cavalli et al., 2013](#)). In our study case, the
705 connectivity value assumed similar ranges, therefore we deemed the same classification to be
706 suitable.

707 For this watershed, [Wemple et al. \(2001\)](#) underlined how the roads influenced the overall sediment
708 production in two ways: by producing sediments below the roads and by capturing sediments
709 coming from above the road and delivering them downstream. We therefore selected two case
710 studies: one where the landslides were located in the proximity of a road, but in the downstream
711 direction (Fig. 17e, 17f, 17g), and one where the landslides were located above the roads (Fig.
712 17h, 17i, 17l). In both cases, the roads were built before the landslide events. In the first example,
713 the slides occurred from 1964-1972, but the two roads within the area were built in 1959. In the
714 second example, the landslide occurred in 1953, but the road was built in 1952.

715 In the first example, the analysed slides clearly did not deliver sediment to the road (Fig. 17g). By
716 analysing the connectivity to the outlet (Fig. 17e) and to the network (Fig. 17f) it is possible to
717 understand that the sediment produced by the slides nevertheless could have contributed to the
718 total sediment of the watershed at the outlet. In the second example (Fig. 17h, 17i and 17l), the
719 slide was produced above the road, and it had a high topographic connectivity to the road itself
720 (Fig. 17l), but it was disconnected from the network because the road itself served as an obstacle,
721 or buffer ([Fryirs, 2013](#)) (Fig. 17i). However, the connectivity to the road contributed to the overall

connectivity of the sediment to the outlet (Fig. 17h) because the road itself deviated the flows downstream, thus increasing the probability of delivering the sediment to the watershed outlet. The analysis of the RPII (Fig. 18) for the two above examples gives further interesting insights.

Fig. 18

In the first case (Fig. 18a), the high value of the RPII ($>1\sigma$) indicates that the two landslides (white arrows in Fig. 18a) were probably induced by the presence of the road network. However, it is interesting to see that the deviation of the flows did not start on the road in the immediate proximity of the slides, but on another uphill section of the road network (third white arrow in Fig. 18a).

In the second example (Fig. 18b), the RPII enabled an understanding that the connectivity of the sediment to the outlet (Fig. 17h) was created by the road itself (Fig. 18b). Without the road network, this connectivity would probably not have existed.

The use of the Connectivity Index and RPII on both examples highlights what was found for the same watershed by [Wemple et al. \(2001\)](#) after an extensive field survey and using empirical data. Those authors argued that during extreme events, (i) the roads in the mid-slope positions dominated the production and redistribution of sediment (as underlined by the HRT analyses in Fig. 17e, 17f, 17g and Fig. 18a) and that (ii) a road network may have major impacts on stream channels far removed from the initiation sites (as underlined by HRT analyses in Fig. 17h, 17i, 17l and Fig. 18b). Therefore, in the context of anthropogenic geomorphologies, the use of HRT for the analysis of connectivity and road-induced changes in flows can provide a tool to better address the possible outcomes of sediment production, for example, and the impacts on the watershed in terms of how sediments can be delivered and transported within it. In addition, it would enable an understanding of where engineering efforts should be focused.

5.2. Land planning and management as a function of induced Earth surface processes

According to the latest State of World Population 2014 report from the UN, the global population is predicted to reach nearly 11 billion by 2100. The increase in population and the introduction of new technologies will be inevitably linked to an increase in raw-material demand (e.g., the global

749 production of concrete, steel, aluminium, copper and glass) ([Vidal et al., 2013](#)). In addition, if food
750 production must keep pace with the demands of an ever-expanding global population, arable lands
751 are expected to expand, with the expansion in developing countries being offset by a decline in the
752 developed countries. Lands equipped for irrigation and harvested irrigated lands are also expected
753 to expand ([Alexandratos and Bruinsma, 2012](#)). On the other hand, the results of recent studies
754 suggest that there will likely be significant levels of farmland abandonment in Europe over the next
755 20–30 years ([Renwick et al., 2013](#)). In addition, in the next few decades, there may also be an
756 increase in transportation networks in support of agricultural development, local travel, trade and
757 tourism ([Sidle and Ziegler, 2012](#)). The result will be an increase in anthropogenic forcing with direct
758 consequences on Earth surface processes, especially soil erosion, runoff, hazards and land
759 degradation. A future challenge is to change the perspective of land planning and management:
760 anthropogenic changes in landscapes (mining, agricultural activities and land-use changes) should
761 be controlled and managed as a function of the induced geomorphic processes. Transportation
762 networks need to be better planned and constructed with due attention to minimizing erosion and
763 landslides, so that downstream communities and river systems are adequately protected ([Sidle
764 and Ziegler, 2012](#)). In addition, agricultural policy potentially plays a key role in determining
765 whether land is utilized for agriculture ([Renwick et al., 2013](#)). The same applies for cities. Cities
766 need to be designed and planned with regard to potential runoff, water storage capacity and soil
767 erosion due to the demand on raw and construction materials. The construction of new mining
768 areas and the conversion of existing ones should consider the overall effects on the landscape,
769 keeping in mind that a reclaimed mined area may never function like a natural one, but rather in a
770 condition that is more similar to urbanized areas. Additionally, the rates of erosion that are induced
771 by mining and agricultural activities, despite being on a shorter time scale than natural erosion
772 rates, may become a critical problem considering that the natural production of soil is relatively
773 slow and that soil might not be ‘naturally’ renewable on a societal time scale. Correct land
774 management involving the scientific and land-management worlds is, in principle, an appropriate
775 device to underpin this. Science can inform land-managers by providing evidence-based means for

776 assessing the rates and scales of erosion and can assist land users and policy makers in devising
777 appropriate and effective management techniques and systems. Although natural constraints
778 cannot be influenced but can only be compensated for, degradation processes can sometimes be
779 reversed through technical interventions and research innovations, and the Earth science
780 community will absolutely play a key role in this.

781

782 **6. Final Remarks**

783 Natural processes can leave characteristic topographic signatures on the Earth's surface. Abiotic
784 forcing (e.g., climate and tectonics) have played and will continue to play a significant role across
785 larger time scales in shaping the landscape. However, biota forcing can also affect geomorphic
786 processes. Vegetation, through its roots, influences soil formation and surface erosion. Biota also
787 affect climate, and as a consequence, the mechanisms and erosion rates that control the evolution
788 of the landscape. Humans are part of the biota as well. More than vegetation, human activities are
789 leaving a significant signature on the Earth by altering its morphology, processes and ecosystems.
790 We are looking at a different magnitude and scale with respect to abiotic forcing, however the
791 resulting topographic signatures and related consequences are significant. Humans are able to
792 move large amounts of materials during various construction activities (e.g., urban expansion and
793 raw material demand) and thus play a similar role as a geologic agent. The population of the Earth
794 is increasing; the last estimate debates the fact that we will reach 11 billion people by the end of
795 this century if fertility rates do not drop. The consequences of this will result in an increase in
796 urbanization processes, road networks, mining activities due to demands in raw materials in
797 support of different needs (e.g., houses, smartphones, tablets and cars) and agriculture. At the end
798 of this century, anthropogenic geomorphology probably will cover a large part of the Earth, with
799 direct consequences to Earth surface processes, first to geomorphology but also to climate.
800 Society, from a geomorphological point of view, should find solutions to minimize the following
801 consequences: soil erosion and landsliding related to surface water flow interception by roads, soil

802 erosion and mass movements related to mining activities, runoff and soil erosion related to land
803 use changes and issues related to anthropogenic drainage systems. The new remote sensing
804 technologies (e.g., LiDAR and low cost photogrammetric techniques) and the derived high-
805 resolution topography can greatly assist in the understanding of anthropogenic signatures and their
806 effects on processes. Society also needs to change its vision regarding land use planning and
807 management to find sustainable solutions. Road networks and urban expansion should be
808 controlled and managed as a function of the induced potential for erosion and floods. These will
809 probably be the great challenges of this century.

810

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1466 **Table captions**

1467 Tab. 1. Literature on surface mining and the connected geomorphic processes.

1468 Tab. 2. Literature on roads and geomorphic processes.

1469 Tab. 3. Collection of review papers and journal special issues that underline the deep
1470 connection between agriculture and surface processes.

1471 Tab. 4. Collection of the most recent works dealing with HRT and anthropogenic
1472 environments.

1473 **Figure captions**

1474 Fig. 1. (a) Hypothetical frequency distributions (pdfs) of landform properties for the present Earth
1475 and an abiotic Earth (from [Dietrich and Perron, 2006](#)); (b) pdfs of slope for natural and terraced
1476 landscapes in northern (Trento province) and southern Italy (Salerno province), respectively. Fig.
1477 1b also shows shaded relief maps of the two study areas obtained from 2 m LiDAR DTM.

1478 Fig. 2. Worldwide surface mining from Google Earth imagery: (a) Minnesota (USA), (b) Germany,
1479 (c) Utah (USA), (d) Australia, (e) Chile, (f) Egypt, (g) India, (h) Indonesia, (i) Spain, (l) Italy, (m)
1480 China, (n) Norway, (o) Russia and (p) South-Africa.

1481 Fig. 3. Surface mining in the Rheinald-Pfalz region (Germany) (photo by G. Sofia) (a) and erosion
1482 of tailing piles in a copper mine ([Agency, 1972](#)).

1483 Fig. 4. Soil erosion rates for mining landscapes reported in various units in the literature and
1484 converted to equivalent lowering rates (assuming a soil bulk density of 2000 kg m^{-3} for
1485 construction/mining together, and 1500 kg m^{-3} for soil erosion at the hillslope scale) compared to
1486 gently sloping lowland landscapes (cratons), moderate gradient hillslopes of soil-mantled terrain
1487 (soil-mantled) and steep, tectonically active alpine topography (Alpine) erosion rate ranges
1488 published in [Montgomer \(2007b\)](#).

1489 Fig. 5. Baorixile, Hulunbeir, Inner Mongolia: grassland subsidence due to the lowering of the water
1490 table caused by coal mining ([Greenpeace, 2014](#)). © Lu Guang/Greenpeace

1491 Fig. 6. The Aberfan (UK) Disaster (21 October 1966): a wave of coal deposits from surface mining
1492 slid down the Aberfan Valley. ([Richards, 1966](#))

1493 Fig. 7. Aznalcóllar (Seville, Spain). The tail of a mine broke in 1998 and polluted beyond recovery
1494 almost 5,000 ha of natural land on both sides of a 63 km stretch of river, including a vast swath of
1495 Doñana Natural Park ([Jackson, 2014](#))

1496 Fig. 8. Nepal. (a) Forested landscapes without roads, as seen in 2008 from Google Earth, and (b)
1497 landslides along the newly constructed rural road, as shown in the 2010 Google Earth image.

1498 Fig. 9. Road effects on runoff. (a) An agricultural road intercepting snowmelt in the Rheinald-Pfalz
1499 region (Germany) (photo by G.Sofia) (a), and an agricultural road intercepting and concentrating
1500 runoff in Tuscany (Italy) (photo by S.Calligaro).

1501 Fig. 10. Road effects on streams and erosion. (a) Off-highway trail capturing a local stream. (b)
1502 sand building up at a road crossing and washing down into the West Branch of the Sheepscot
1503 River, as indicated by the gully between the third and fourth guard rails ([Klamath Resource](#)
1504 [Information System -KRIS-, 2015](#)).

1505 Fig. 11. Nebraska (USA): receding floodwaters rush through a culvert and tear out the surrounding
1506 earth (a) and an aerial view of the damaged approaches showing the receding flood waters (b).
1507 ([Nebraska State Patrol, 2002](#)).

1508 Fig. 12. Changes in agricultural practices in Italy: (a) terraces in 2006 that were (b) progressively
1509 recolonized by forest in 2014 (Monterosso al Mare, La Spezia, Italy); (c) agriculture in 1945 that
1510 was (d) lost to urbanization in 2015 (Florence, Italy). Changes in crops practices in Kansas (USA)
1511 (e) in 1991 and (f) after the implementation of centre-pivot irrigation in 2014. (Images from Google
1512 Earth).

1513 Fig. 13. Failure of the reclamation network in Veneto (Italy) (a) area as seen on Google Street View
1514 ® in normal condition and (b) after a few hours of rain in Nov. 2014 (photo by G. Sofia)

1515 Fig. 14. Soil erosion rates for agriculture reported in [Garcia-Ruiz et al. \(2015\)](#) converted to
1516 equivalent lowering rates, assuming a soil bulk density of 1200 kg m^{-3} , compared to gently sloping
1517 lowland landscapes (cratons), moderate gradient hillslopes of soil-mantled terrain (soil-mantled)
1518 and steep tectonically active alpine topography (Alpine) erosion rate ranges published in
1519 [Montgomery \(2007b\)](#).

1520 Fig. 15. Bingham Canyon Mine (A) (UT, USA) and Hull-Rust-Mahoning Mine (B) (MN, USA) as
1521 seen from Google Earth (a and d, respectively) and depicted by a 2 m LiDAR DTM (b and d). (c)
1522 and (f) present the SLLAC maps as derived according to the method of [Sofia et al., \(2014b\)](#). The
1523 water bodies are coloured in blue in (f); they are completely flat areas where the cross-correlation
1524 is zero.

1525 Fig. 16. Mining area in Spain in 2005 (a) and 2008 (e); image gradients for the two years (b and f
1526 for 2005 and 2008, respectively) and the derived GLLAC (c) and (g), computed using the same
1527 parameters presented in [Sofia et al., \(2014b\)](#). Figures (d) and (h) show the area automatically
1528 identified as anthropogenic, starting from the GLLAC images.

1529 Fig. 17. Connectivity Index ([Cavalli et al., 2013](#)) for the Lookout Creek watershed (OR, USA). The
1530 connectivity is evaluated in terms of (a, b and h) sediment delivery across the entire drainage
1531 system (as in the potential connection of sediment between the hillslopes and catchment outlet)
1532 and the sediment coupling-decouplings between the hillslopes and main channels (c, f and i) and
1533 the hillslopes and the road network (d, g and l).

1534 Fig. 18. RPII ([Tarolli et al., 2013](#)) evaluated for (a) the areas shown in (Fig. 17e, 17f and 17g) and
1535 (b) the areas shown in (Fig. 17h, 17i and 17l). The arrows in (a) highlight slides that were probably
1536 induced by the presence of the road, and the road caused the flow alteration. The arrows in (b)
1537 highlight the connection of flows induced by the road.

Tab. 1

Surface mining, land displacement and erosion	Luttig (1987) Hooke (1999) Esling and Drake (1988) Sanchez and Karl Wood (1989) Douglas and Lawson (2000) Nicolau (2002) Biemelt et al. (2005) Rivas et al. (2006) Hancock et al. (2006) Choi et al. (2008) Trabucchi et al. (2012) Meng et al. (2012)
Surface mining and land subsidence	Dunrud (1984) Whittaker and Reddish (1989) Jambrik (1995) Scott and Statham (1998) Wolkersdorfer and Thiem (1999) Bell et al. (2000) Kircher et al. (2003) Panilas et al. (2008) Donnelly (2009) Woldai et al. (2009) Herrera et al., (2010)
Surface mining and landslides/debris flows/rockfall hazards	Hearn (1995) Ramani (1995) Bentley and Siddle (1996) Johnes (2000) Baroni et al. (2000) Wei et al. (2008) Erginal et al. (2008) Cortopassi et al. (2008) Guerrero et al. (2008) Rico et al. (2008a) and Rico et al. (2008b) He et al., (2009) Peila et al. (2011) Li et al. (2012) Laimer and Mulleger (2012)
Surface mining, runoff and floods	Kilmartin (1989) Holmes et al. (1993) Negley and Eshleman (2006) Ferrari et al. (2009) Katpatal and Patil (2010)

Tab. 2

Roads in mountainous / hilly landscapes	Luce and Wemple (2001) Croke and Mockler (2001); Fransen et al. (2001); La Marche and Lettenmaier (2001); Madej (2001); Megahan et al. (2001); Tague and Band (2001)
Roads, runoff and erosion/sediment	Harr et al. (1975) Jones et al. (2000) Fransen et al. (2001) Wemple et al. (2001) MacDonald et al. (2001) MacDonald et al. (2001) Luce (2002) Wemple and Jones (2003) Ziegler et al. (2004) Borga et al. (2004) Eisenbies et al. (2007) Sugden and Woods (2007) Jordán-López et al. (2009) Bochet et al. (2010) Fu et al. (2010) Collins et al. (2010) Hölzel and Diekkrüger (2012) Tarolli et al. (2013) Penna et al. (2014) Thomaz et al. (2014) Butzen et al. (2014) Marion et al. (2014) Brown et al. (2013) van Meerveld et al. (2014)
Gully erosion	Wemple et al. (1996) Nyssen et al. (2002) Jungerius et al., (2002) Takken et al. (2008) Muñoz-Robles et al. (2010) Katz et al. (2014) Superson et al. (2014) Dewitte et al., (2015)
Connectivity	Croke et al. (2005) Latocha (2014) Pechenick et al. (2014)
Roads in flat landscapes	Florsheim et al. (2001) Blanton and Marcus (2009) Vis et al., (2003) Beevers et al. (2012) Douven et al. (2012) Douven and Buurman (2013) Blanton and Marcus (2013) Buchanan et al. (2013) Kumar et al. (2014) Trizzino (2015)

Tab. 3

Agriculture and soil erosion	Martínez-Casasnovas and Sánchez-Bosch (2000)
	Biielders et al. (2003)
	Boardman et al. (2003, 2006)
	Van Oost et al. (2006)
	Boardman and Poesen (2006)
	Knox (2006)
	Doolittle (2006)
	O'Connell et al. (2007)
	Evrard et al. (2007)
	Atapattu and Kodituwakku (2009)
	Heitz et al. (2009)
	Cerdà et al., (2009)
	Boardman and Vandaele (2010)
	Boardman (2010)
	García-Ruiz and Lana-Renault (2011)
	Florsheim et al. (2011)
	Massa et al. (2012)
	Tetzlaff et al. (2013)
	Cerda et al. (2013)
	Palmer and Smith (2013)
	Merten and Minella (2013)
	Dotterweich et al. (2013)
	Dotterweich (2013)
	Boardman (2013)
	Lieskovský and Kenderessy (2014)
	García-Ruiz et al. (2015)
	Arnáez et al. (2015)
	Dotterweich et al. (2015)
Land abandonment	García-Ruiz (2010)
	Arnaez et al. (2011)
	García-Ruiz and Lana-Renault (2011)
	García-Ruiz et al. (2013)
	Debolini et al. (2013)
Drainage systems	Tarolli et al. (2014)
	Krause et al. (2007)
	O'Connell et al. (2007)
	Schilling and Helmers (2008)
	Schilling et al. (2008)
	Blann et al. (2009)
	Wheater and Evans (2009)
	Lenhart et al. (2012)
	Sofia al. (2014c)
	Schottler et al., (2014)
	Schottler et al. (2014)
	Kiss and Benyhe (2015)

Tab. 4

Overview	Tarolli (2014)
	Jones et al. (2014)
	Passalacqua et al., (2015)
	Wasklewicz and Scheinert (2016)
Mining landscape	Francioni et al. (2015)
	Chen et al. (2015)
	Hancock et al. (2015)
Road networks	Tarolli et al. (2013)
	Sherba et al. (2014)
	Sofia et al. (2015)
	Sofia and Tarolli (2015)
Agricultural landscapes	Martínez-Casasnovas et al. (2013)
	Tarolli et al. (2014)
	Sofia et al. (2014b)
	Díaz-Varela et al. (2014)
	Tarolli et al. (2015)
	Stöcker et al. (2015)
	Prosdocimi et al. (2015)

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