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THE QUANTIFICATION OF THE SOCIO-ECONOMIC IMPACT ON GEOMORPHOLOGY

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QUANTIFICAZIONE DELL'IMPATTO SOCIO- ECONOMICO SULLA GEOMORFOLOGIA

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Dedicated to all geomorphologists/ecologists/ economics/ sociologists worldwide

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After these three years of research work, I gradually understand that research actually is to demonstrate your ideas with scientific methods and present it to the public. It's unnecessary to convince everyone as long as you firmly believe it. Being a Ph.D. candidate is not that cool, instead, you need to complete piles of work every day, read substantial pieces of literature and cultivate your own critical thinking based on other's views. You don't have to be brilliant or smart, but you have to be diligent, self-motived, self-disciplined and open-minded, that's the essence of a decent scientist in my dictionary. I feel so lucky there's a bunch of people accompanying me during my exploring and I would like to give my special thanks to them.

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SUMMARY

It is acknowledged that the Earth's surface was shaped by natural processes such as tectonic uplift, erosion and sediment movement. Nevertheless, recently, the human society as a new force to reshape the landscape has been perceived by the scientific community. The Anthropocene working group (AWG), which is a part of subcommission on Quaternary Stratigraphy – International commission on Stratigraphy of International Union of Geological Science (IUGS) proposed to mark the current geologic time unit as Anthropocene. The AWG declared human beings stepped into an epoch that our societies have become a global geophysical force and the extent of human intervention on geomorphic processes has become comparable to nature, and the trend is accelerating.

Humans act as a geomorphic agent shaping Earth's surface through activities ranging from agricultural tillage, mining, road networks and building constructions. These activities leave significant signatures on the topography, literally and figuratively across millennia and reflecting the socio-economic conditions of the societies that produce them. People tend to live in the surroundings where resources such as food and fuel are cheaper and more accessible, and the economic and social demands of resources drive the land-use changes to meet the demands. As the human population has grown and the power of technology has expanded, the socio-economic demands have scaled up, the landscapes were imprinted by the rapid increase of anthropogenic modification caused by deforestation, agricultural expansion and urban construction to supply the food and energy demands. The Great Acceleration witnessed remarkable explosion of socio-economic development, with significant consequences on the surface topography. It is estimated that humans have shaped around one-third of the landscape through agricultural fields, pastures, or urban landscapes.

However, an empirical computation to link between socio-economic development, land-use changes and the geomorphology alterations is still a gap. Societal-based understanding of anthropogenic geomorphology provides the way of how human

activities involved in natural environmental changes such as soil erosion, floods and tectonic uplifts with the timeline. We synthesized scientific evidence on the emergence, history of present anthropogenic features and illustrated how these features impact the Earth's surface processes. Then we integrated social-geophysical approaches to interpreting a full range of anthropogenic features with identification of remote sensing techniques and reconstruction of the long-term changes by archaeologists, as diagnostic fingerprints of the social processes that formed them. Further, we testified that the natural landscape and anthropogenic landscape present a significant difference in geomorphic signatures, and implied that anthropogenic force shapes the geomorphology in a way different from natural force. Lastly, we used the nighttime light data to represent the socioeconomic status and SLLAC (Slope Local Length of Autocorrelation) metrics to measure the anthropogenic modification on the landscape, and then to assess the correlation between socio-economic impact on the geomorphology based on each stratification of a global pattern.

This thesis helps to understand how the features that human left on the topography affect the Earth surface processes, interpret those features as sociocultural fingerprints, demonstrate that the anthropogenic forcing leaves a different topographic signature on the surface from the natural forcing, and quantify the correlation between socio-economic development and anthropogenic geomorphology. This research not only fill the gap in why people shape the landscape through a diversity of activities; it also presents a possible correlation between socio-economic development and anthropogenic geomorphology. This work also provides the possibility towards an empirical estimation of landscape under the human’s impact at a global scale, and underlines that an integrated approach combining social economy, ecology and geomorphology is needed for the future landscape management.

SOMMARIO

È riconosciuto che la superficie terrestre è stata modellata da processi naturali come sollevamento tettonico, erosione e dinamica dei sedimenti. Ma recentemente la società scientifica ha percepito la società umana come una nuova forzante in grado di modellare il paesaggio. Il gruppo di lavoro sull'Antropocene (Anthropocene Working Group - AWG) ha proposto di classificare l'attuale era geologica come Antropocene ed ha dichiarato che gli esseri umani sono entrati in un'epoca in cui la società è diventata una forza geofisica globale, paragonabile alla natura, sempre più impattante.

Gli esseri umani agiscono come agenti geomorfici che modellano la superficie terrestre attraverso attività che vanno dalla lavorazione agricola, alle miniere, alle reti stradali e alle costruzioni edili. Queste attività lasciano firme significative sulla topografia attraverso millenni, riflettendo le condizioni socio-economiche delle società che le generano. Le persone tendono a vivere in un ambiente in cui risorse come cibo e carburante sono più economiche e più accessibili e le esigenze economiche e sociali delle risorse guidano i cambiamenti nell'uso del territorio per soddisfare le richieste. Con la crescita della popolazione il potere della tecnologia si è ampliato, le esigenze socio-economiche sono aumentate, i paesaggi sono interessanti dal rapido aumento delle modifiche antropogeniche causate dalla deforestazione, dall'espansione agricola e dall'edilizia urbana per soddisfare il fabbisogno alimentare ed energetico. La Grande Accelerazione ha visto una notevole esplosione dello sviluppo socio-economico, con conseguenze significative sulla topografia della superficie. Si stima che circa un terzo del paesaggio sia stato modellato dall'uomo attraverso paesaggi agricoli, pascoli o paesaggi urbanizzati.

Tuttavia, una metodologia di indagine che possa mettere in relazione sviluppo socioeconomico, cambiamenti nell'uso del suolo e alterazioni della geomorfologia manca in letteratura. Una comprensione della società basata sulla geomorfologia antropica fornirebbe un modo per comprendere gli effetti delle attività umane sui cambiamenti ambientali naturali come l'erosione del suolo e le inondazioni. In questa

tesi di dottorato viene presentata un’analisi delle attuali caratteristiche antropogeniche della geomorfologia e illustrato come queste caratteristiche possano avere un impatto sui processi della superficie terrestre. Sono stati integrati approcci socio-geofisici per interpretare una gamma completa di caratteristiche antropogeniche con l'identificazione di tecniche di telerilevamento e la ricostruzione dei cambiamenti a lungo termine da parte degli archeologi, come impronte digitali diagnostiche dei processi sociali che li hanno formati. Inoltre, è stato dimostrato che il paesaggio naturale e il paesaggio antropico presentano una differenza significativa nelle firme geomorfiche evidenziando come una forzante antropica possa modellare la geomorfologia in modo diverso rispetto ad una forzante naturale. Infine, abbiamo usato i dati sull’illuminazione notturna da satellite per rappresentare lo stato socioeconomico e la metrica SLLAC (Slope Local Length of Autocorrelation) per quantificare l’impatto antropico sul paesaggio e quindi valutare la correlazione tra impatto socio-economico sulla geomorfologia a livello globale.

Questa tesi aiuta a capire come le forme morfologiche che l’uomo ha lasciato sulla topografia possano influenzare i processi della superficie terrestre, interpretare quelle forme come impronte digitali socioculturali, dimostrare la forzante antropica imprime una firma statistica differente sulla morfologia rispetto dal forzante naturale e infine quantificare la correlazione tra sviluppo socioeconomico e geomorfologia antropogenica. Questa ricerca cerca di chiarire sul perchè perché l’uomo ha modellato il paesaggio attraverso varie attività, ma vuole anche dimostrare che esiaste una possibile correlazione tra sviluppo socio-economico e geomorfologia antropica. Il lavoro offre anche una prima possibile stima dell'impatto dell’uomo su scala globale, sottolineando anche che per la futura gestione del paesaggio è necessario un approccio integrato che combini economia sociale, ecologia e geomorfologia.

CHAPTER 1

INTRODUCTION

1.1 State of the science

Since human has been present on Earth, the pattern and process of the ecosystem have been changed and such alteration started to show an exponential amplification since industrialization. In the nineteenth centuries, human's capacity to change the natural environment has been perceived by scholars (Boussingault, 1845; Marsh, 1864) but less acknowledged by the public.

In modern society, with the increasing of environmental criticalities such as global warming, the studies towards global environment change become a wide trend. The studies focusing on the human impact on the environment have been more perceived by the public and be proven through several fields: human's disturbance on the oceanic biosphere such as sea-level rise, ocean acidification (Brinson, et al. 2006; Crain, et al. 2009; Duarte, et al., 2013; Kirwan & Megonigal, 2013); human perturbation on the atmospheric elements such as carbon, nitrogen as well as chemical compounds (Andreae & Merlet, 2001; Doney, 2010; Yuan, 1981); effects on the terrestrial biosphere leading to habitat loss and decreased biodiversity (Ellis, et al. 2012; Pace & Groffman, 1998; Swift & Hannon, 2010); production of new materials such as plastics which nondegradable and detrimental to the environment (Derraik, 2002; Thompson, et al. 2009). Fig.1 illustrated the human's impact on the terrestrial biosphere which is measured by six indicators and also showcases how it changes over time. We can see that some components have changed much more than the whole human history since 1950.

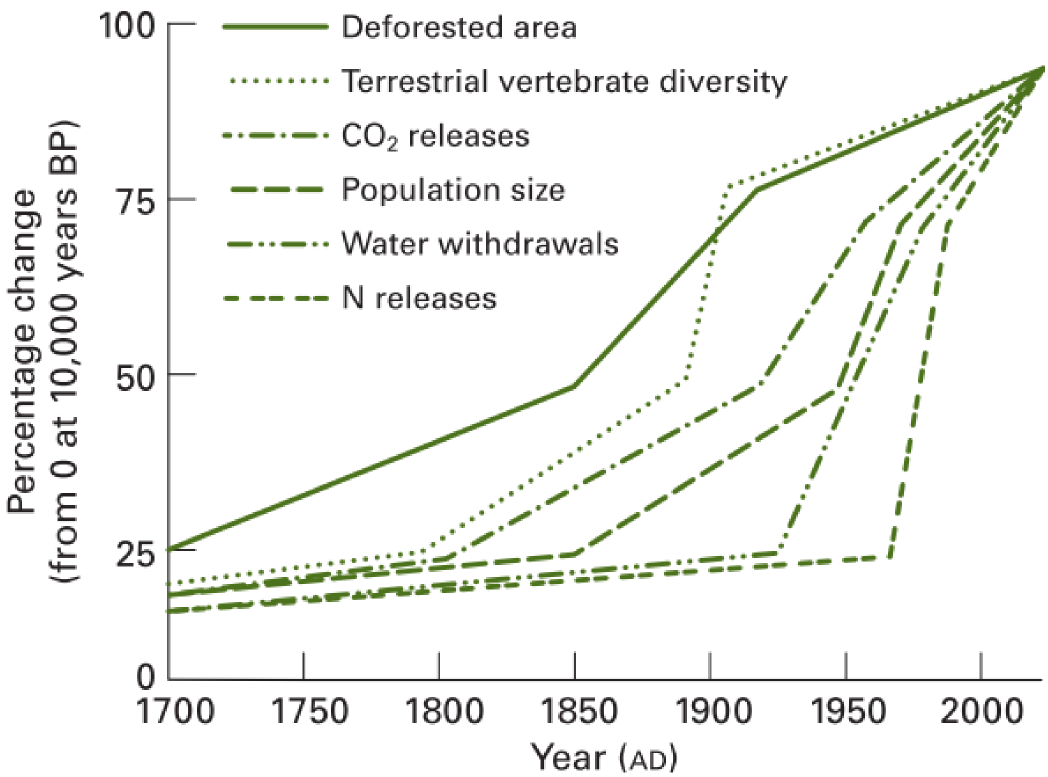

Fig.1 Percentage change (from assumed zero human impact at 10,000 BP) of selected human impacts on the environment (Goudie, 2013)

Among the above alterations that human's impact on the environment, the intensity and extent that human exerts the role across the lands deserve particular attention. Before the emergence of humankind, the main forcing shaping the topography was mainly tectonic uplift, erosion and climate (Tarolli, et al. 2017). But at present, humans dramatically altered Earth's surface locally, regionally and globally. Human reshaped the Earth's ecology, eroded productive soils, diverted water to farms and cities, and eliminated natural habitats at alarming rates through different ways: domestication pastoralism (Clutton-Brock, 1992; Sauer, 1952;), deforestation (Rudel, 2007; Walker, 1993), introductions of flora and fauna (Mills, et al. 2006; Mooney & Drake, 1986; Ricciardi & MacIsaac, 2000; Sofia et al. 2017), clearing of woodland (Martin & McIntyre, 2007; Ward & Cleghorn, 1970) and the draining of marshlands (Kennedy, 2013; Sheppard, 1966), habitat fragmentation (Andrén & Andren, 1994; Lindenmayer & Fischer, 2007; Mouhib et al., 2011), species invasion and extinction (Islands et al., 1997; Sax & Gaines, 2008) and the transformation of landscapes (Hartshorn & Muller, 2010; Knox, 1991) as well as mining (Chen, et al. 2015; Tarolli, Sofia, & Cao, 2017). The question may rise up that to what extent that humans have transformed the Earth's surface. The attempts have been made using the estimation of land has been used or transformed by humans. According to Bai (2008), around 24% of Earth's surface area decreased their ecosystem function and productivity during 1981 to 2003. The human-induced degradation affected 43% of lands all over the world in 1995 (Daily, 1995). Ellis and Ramankutty (2008) revealed that more than 75% of Earth's ice-free land are excluded of wild, and accordin to Sanderson et al. (2002) 83% of the ice-free land area is directly influenced by humans. Smil (2010) made a claim that human activities have transformed one-third of Earth's land surface. He also pointed out that humans have reduced the stock of global terrestrial vegetations around 45% through the agriculture, deforestation, and conversion of grassland and wetlands in the last 2000 years. Furthermore, Hooke (2012) estimated that more than 50 percent of Earth's ice-free land area has been altered by human activities, taking the reference year of 2007. The impacts related to agriculture and forestry occupy over 44 percent (Goudie & Viles, 2016). Fig.2 depicted the historical data and also the forecast based on the estimation of how people utilize the land. The cropland and pasture dramatically increased and the forest decreased over the past 300 years. But in the recent years, all of these three datasets exhibit the declining trend. The urban lands started to expand lately but increased substantially with time.

Together with other anthropogenic changes on the landscape, the geomorphological change caused by human is significant but often neglected. However, the impact of human activities on geomorphology presents an unprecedented magnitude and extension. The action in removing or modifying land cover through cutting, bulldozing and grazing accelerated the erosion and sediment rates. For example, agriculture tillage and urbanization construction move enormous quantities of soil accelerating erosion and sediment transport; road construction modifies natural hillslope profiles and sediment flows path. Particularly, the eroded sediment ends up as colluvium on hillslope or in the floodplain and change the land's shape (Abdulazeez, 2014; Mücher, Steijn & Kwaad, 2010).

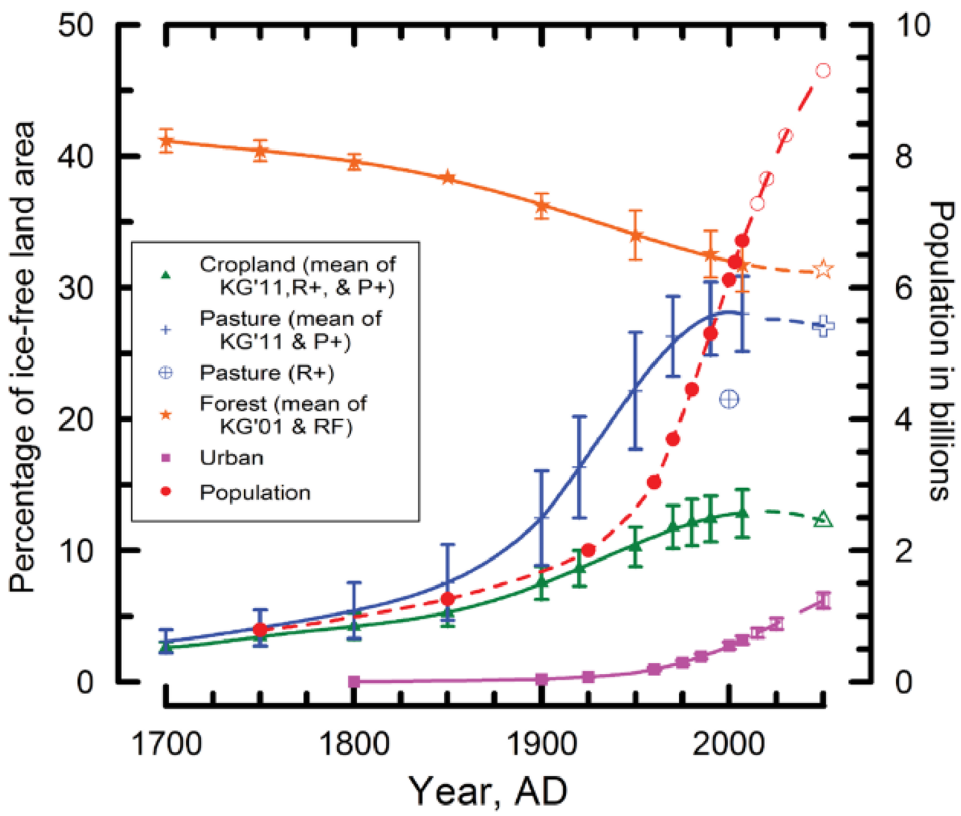

Fig 2. Changes in land use through time with prediction up to 2050 AD (Hook, 2003). Population data and projections are from UNPD (1999)

Since late eighteenth and early nineteenth centuries, the perspective of human's impacts on the landforms and the related processes started to be recognized. Early geomorphologists pioneered on the exploration of anthropogenic geomorphology in different stages (Table.1). Fabre (1797) and Surell (1841) studied the flooding, erosion and channel braiding caused by deforestation occurred in 1837 and 1838 at Alps of Europe. Marsh (1864) expressed the concern in his remarkable book *Man and Nature* that Mediterranean civilization vanished because the environmental degradation through human activities, such as deforestation contributing to the loss of soil productivity. Shaler (1891) and McGee (1911) focused on accelerated soil erosion during the processes of overland flow and subterranean piping in North America. Gilbert (1877) also argued taking man-made impact into consideration when addressing geology problems. Starting from the second half-past century the impacts of human activities on geomorphology became more evident thus geomorphologists started to focus more on this aspect.

Though the substantial alterations that human put on Earth surface perceived by a lot of scholars, the idea that humans are geomorphic agents didn't get sufficient awareness. The breakthrough was made by the concept of "Anthropocene" (Crutzen & Stoermer, 2000; Crutzen, 2002; Paul, 2006; Rockström & Noone, 2009; Steffen, et al. 2007; Waters et al., 2016; Zalasiewicz et al., 2015) to denote that processes on Earth surface are profoundly changed by human activities (Brown et al., 2017; Ellis et al., 2013; Lóczy & Süto, 2011; Tarolli & Sofia, 2016). The proposal of "Anthropocene" stressed the fact that we now live in an epoch where human's impact on the environment has been a dominant part, exceed the forces of nature in influencing the functioning of the Earth System and would be increasingly important in the future (Steffen, 2010).

To justify a "geomorphological case" in the Anthropocene debate, we need to consider the human's significant impact on the modification of geomorphological processes and creating landforms. The most important aspects regarding the operation of geomorphological processes are fluvial, aeolian, coastal and cryosphere processes. Table 1 introduces some cases identified by geomorphologists that showcase the human's role in these processes systems respectively.

Table 1. Human's evident role in geomorphological processes (from Goudie, 1993)

Geomorphological processes	Studies
Fluvial	
Arroyo incision	Cooke and Reeves (1976)
Channel geometry change	Petts (1985)
Clear water erosion	Beckinsale (1972)
Soil erosion	Trimble (1988)
Sediment load change	Trimble (1974)
Aeolian	

Dust storm generation	Goudie and Middleton (1992)
Wind erosion of soil	Chepil and Woodruffe (1963)
Dune reactivation + stabilization	Watson (1990)
Costal	
Salt marsh accretion	Adam (1990)
Delta retreat	Walker et al. (1977)
Erosion and accretion	Hails (1977)
Cryosphere	
Permafrost degradation	Barry (1985)
Glacier melting	Chinn (1988)

Human activities influence the discharge and channel network through land-use change. Sofia et al. (2017) took an example of study area located in the northeast of Italy over 100 years and showed that the prolonged duration of the flood and the numbers of flooded locations increased because the drainage system has been significantly transformed through land-use by human activities. The canals and dam's construction work caused sediment trapped in reservoirs. A significant example to demonstrate this point is the series dam's construction in Colorado. Before the engineering work, the Missouri- Mississippi river system carried around 400 million metric tons of sediment to coastal Louisiana every year. But after the dam construction, it had fallen dramatically as one third as before (Meade and Moody, 2010). The development of urban land also transformed the properties of soil, which reduced its water permeability and the water would be accumulated and lead to flooding easily during intense raining. Mining and road construction affect water pathways, sediment dynamics and radically modify the channel-floodplain connectivity (Mossa & James, 2013; Singer et al., 2013). The erosion, transportation and deposition processes influenced by wind are susceptible in regions with sparse vegetation and lack of soil moisture. Goudie and Middleton (1992) pointed out that human disturbance of susceptible surfaces increases the potential dust storm and soil erosion. For example, the Dust Bowl of the USA in the 1930s and in Mauretania of the 1970s and 1980s happened due to the excessive human pressures and climatic deterioration (Goudie, 1993). The aeolian surface erodibility is increasing also because of the reduction of vegetation cover caused by agricultural or pastoral practices (Chi, et al. 2019; Munson, Belnap & Okin, 2011; Shi, et al. 2004). The typical example is the formation of sand dunes, which is aeolian landforms can be found along most of the world's coast. However, according to Ciccarelli (2014), 70% dune systems in European dunes have been damaged mostly by human activities such as urbanization and tourism activities. Another case revealed that the sand flux decreased substantially with vegetation cover after measuring plots of land varying degree of vegetation against rates of sand transport. Therefore, the related anthropogenic activities such as overgrazing and farming, which reduce the vegetation coverage would potentially increase the sand transport (Beier, Fernandes & Poleto, 2016; Paul et al., 2012; Webb & Pierre, 2018).

Coastal environment is one of the most pervasively modified areas across the world. The high densely human settlement concentration on the coastline generated a great pressure on coastal landforms. These activities modify the coastal environments in many ways: dredging of waterways for shipping and commerce but interfere with sediment transport and flow dynamics; construction work such as jetties, groins and seawalls increase downdrift erosion rates (Davidson-Arnott, 2009). Some anthropogenic activities such as drainage of wetland, groundwater withdrawal and deforestation (decrease the water storage capacity in terrestrial) also may lead to sea-level rise (Andres, et al. 2019; Li, et al. 2017). The most prominent problem under human's intervention is the beach erosion, which accounts for 68% of the coastline erosion in New England and the mid-Atlantic region in the US (Hapke, et al. 2013).

One of the critical issues of the cryosphere processes is permafrost degradation. The permafrost in high latitudes and altitudes recently is affected by human activities through surface vegetation clearance and this tendency would be increased. For example, the tracked vehicles affect the vegetation and further result in permafrost degradation (Addison, et al. 2016; Loranty, et al. 2018). Moreover, human activities disrupted the thermal equilibrium through reducing the insulation offered by vegetation cover or organic soil layers. It leads to a series of geomorphological processes, such as slope stability, soil erosion rates and surface runoff. Furthermore, another cryosphere process under human's impact is the glaciers melting. According to a study that Chinn

(1988) carried out in New Zealand, if temperature rise by 3.6 °C to 6.3 °C, snow lines would move 300 m to 500 m vertically, and several glaciers in the country would disappear. Even though human's role contributing to the melting is not obvious at this stage, but it becomes increasingly important and it could be an indirectly effect of global warming through burning fossil fuels, cutting down rainforests and farming livestock.

Numerous studies in the literature described and analyzed human-created landforms. The most prominent man-made landforms nowadays are agricultural terraces (Acabado, 2009; Ackermann, Svoray & Haiman, 2008; Chen, Wei & Chen, 2017; Tarolli, Preti & Romano, 2014); roads construction (Poulikakos et al., 2017; Tarolli & Sofia, 2016; Tarolli, et al. 2013); city building (Carter, et al. 2015; Stelter, 1982); dams and reservoirs (Di Baldassarre, et al. 2017; Van Cappellen & Maavara, 2016; Wan et al., 2017); canals and channels (Clarke-Sather et al., 2017; Wescoat, et al. 2018); embankment and Levees engineering work (Assani & Leclercq, 2006; Wehr & Thorp, 1997; Yuhi, 2008); mining (Dethier et al., 2018; Rickards, 2015; Wagreich & Draganits, 2018). The most distinguishable anthropogenic modified landforms are land reclamation (Meyer, Williams & Yount, 1995; Runólfsson, 2018; Wang, et al.2014; Wiirzburg & Hubland, 1991; Yang et al., 2011), which is happening all over the world. The artificial islands and reefs built near the sea are also significant cases for man-made landforms (Goudie & Viles, 2015). The other case is bulldozing mountains to cities (Brown et al., 2016; Li, Qian & Wu, 2014) through slope engineering work. Dozens of hilltops have been levelled around China, this is the case of cities such as Chongqing, Shiyan, Yichang, Lanzhou and Yan'an.

Even though the human's impacts on the geomorphology are evident and significant, the quantification of such anthropogenic changes still pose a challenge in geoscience, which requires detailed information on topography. Such quantitative analysis is not an easy task. Hook (1994) proposed to measure the alterations triggered by human activities through the amount of soil movement and the affected land. This argument is based on the idea that the moving soil in construction and mining activities, as well as the unwanted by-products of agriculture, can be representative of the human's alterations on the landscape. He summarized that human's impact on the topography could be described following two classifications based on their purpose:

Direct: excavation (mining), construction, dumpling and farming (tillage, terrace);

Indirect: erosion and sedimentation, ground subsidence, weathering environment, triggering of the mass movement, coastal erosion and deposition.

The direct and deliberate actions are through extraction, transformation, re-use and man-made materials. For example, people remove the materials through tipping, molding, terracing and mining as well as damming and draining work. The indirect actions refer to the activities that modify the topography in an unwilling way by cutting, burning with agriculture, forestry and grazing. These undesirable and inadvertent modifications are of great importance but difficult to measure because of the natural processes involved and it is unachievable to divide from the anthropogenic processes.

The calculation of the earth moved intentionally every year lies on the idea that human geomorphological activities in a country closely correlates to its Gross National Product (GNP) and the energy consumption. Hook regarded agriculture as an unintentional anthropogenic geomorphological activity, though Hook's classification may different from generally accepted categorization (Szabo et al. 2010). In Table 2, we can see that the anthropogenic forcing exceeds the natural processes on modifying the Earth surface. This calculation demonstrated the amount of the earth moved by human activities for the early 1990s. It could be considered as the most persuasive evidence to showcase the Earth's surface mass action triggered by human on a global scale. But it also has some flaws. First, the GNP and the energy consumption are based on the statistical data for the United States, and these two indicators cannot stand for the intentional movement of the geomorphological activities accurately. Second, the unintentional soil moved by anthropogenic activities is not only limited to agricultural ploughing and grazing, there are other human activities such as road construction and mining could also trigger considerable earth movement. Lastly, due to the limited knowledge towards Earth processes and the related effects, the estimation of anthropogenic forcing based on soil movement is not clear enough.

Table 2. The estimated rates of anthropogenic and natural forcing Hooke (1994)

Geomorphological factor	Earth moved (billion t/yr)
Man	
Intentional based on GNP	30
Intentional based on energy	35
Consumption	
Unintentional (agriculture)	99
Total anthropogenic	**129-134**
Rivers	
Long-distance sediment transfer	14
Meandering	39
Glaciers	4
Slope processes	1
Wave action	1
Wind	1
Mountain building	
Continental	14
Oceanic	30
Deep ocean sedimentation rates	7
Total natural	**111**

Recently, the development of new remote sensing technologies such as airborne laser scanner (LiDAR) makes the resolution topographic information very detailed, which provide a useful tool for the quantification of anthropogenic modification on the landforms. Moreover, the large-scale coverage of high-resolution datasets makes the geomorphic features easily to be detected and identified. Likewise, multi-temporal elevation data have been used to map the extent of anthropogenic landforms and quantify the differences by comparison. For example, the volumetric estimation of the soil potentially removed could be calculated through the past and present topographic data (Xiang et al. 2019). However, this method highly relies on the historical data and the interpretation of anthropogenic features. Furthermore, several geomorphologists developed morphometric indexes and landscape metrics to quantify such human impacts. For example, Tarolli et al. (2013) proposed the RPII (Relative Path Impact

Index) to recognize the induced flow direction changes due to the roads and trails construction. Sofia et al. (2014) propose the new metric SLLAC (Slope Local Length of Auto-Correlation) to discriminate the artificial landscape from more natural ones through spatial heterogeneity. These geomorphometric indexes based on high-resolution topography provide an unprecedented insight into the quantification of anthropogenic changes on the Earth surface.

The further question may rise up that why human's imprint on the topography is distinct and what are the driving forces for these modifications? To well understand this point, we should recognize that the land and its inhabitants provide the food, mineral resources, industrial products and other ecosystem services that human being highly dependent on (Foley et al., 2005; Hooke et al., 2012; Ma & Swinton, 2011) and human utilized the land to support the increasing necessity for life systems.

Humans started to exert their functions in this planet since thousands years ago (Brunet et al., 2002; Oppenheimer, 2003). The human's change on the landscape encompasses three phrases. The first phrase is hunting and gathering (Lewin, 2015; Smil, 2010). In the early stage of humankind civilization, their survival mostly depends on fire use, collect food and water where was possible. Therefore, it's hard to estimate the changes they have been made on the Earth surface due to the ancient time and trivial functioning compared to the natural force. The second phrase is domesticated animals, metal working and agriculture. Humankind started to use land for agriculture and settlement more than 10,000 years ago (Goldewijk, et al. 2011; Lal, et al. 2007). Soil structure was damaged through trampling and the grazed lands tended to have lower infiltration capacities. The removal forest for agricultural purpose directly contributed to significant high rates of erosion. Moreover, the agricultural revolution prompts the expansion of population and colonization of new lands. Even though the human impact on the landscape cannot be seen as a simple process of population increasing, still, the growth of population and the need to meet the expansion becomes an essential cause of the transformation of biosphere. This development has accelerated over the appearance of Industrial Era. The latest phrase is modern urban development and industrial society. With the population explosion and technology improvement, humans dramatically changed the configuration of the landscape through engineering work such as roads, dams and building construction to meet the society needs (Harden, 2014; Klaus, 2016; Motesharrei, et al., 2017). A vast number of industrial wastes, minerals and materials (mining) being produced to feed the growing population (Feng, et al. 2017; Graham, 2004). Nowadays, we stand on the brink of a technological revolution that fundamentally shapes the society and the way we live in an unprecedented way. In the Fig.3 we can see that from 1750 to 2010, the socio-economic development which can be represented by the selected indicators are growing at a notable rate. Especially in the most recent decades after 1950, the trends are increasing exponentially. With the development of technologies, people's way of living would change differently and thus have fundamentally different alterations on the landscape. For example, the exploitation of location embedded in geospatial big data would innovate people's daily life and business, and minimizes fuel consumption through the optimal travel time and distance (Lee & Kang, 2015).

The evolutionary trajectory has been imprinted on the landscape through physical changes and it is easy to make a connection between the degraded environment with the burgeoning urban areas and increasing populations. The history of anthropogenic geomorphology can be regarded as the history of human sociocultural civilization (Boivin, et al., 2016; Crumley, et al. 2017; Goudie, 2018).

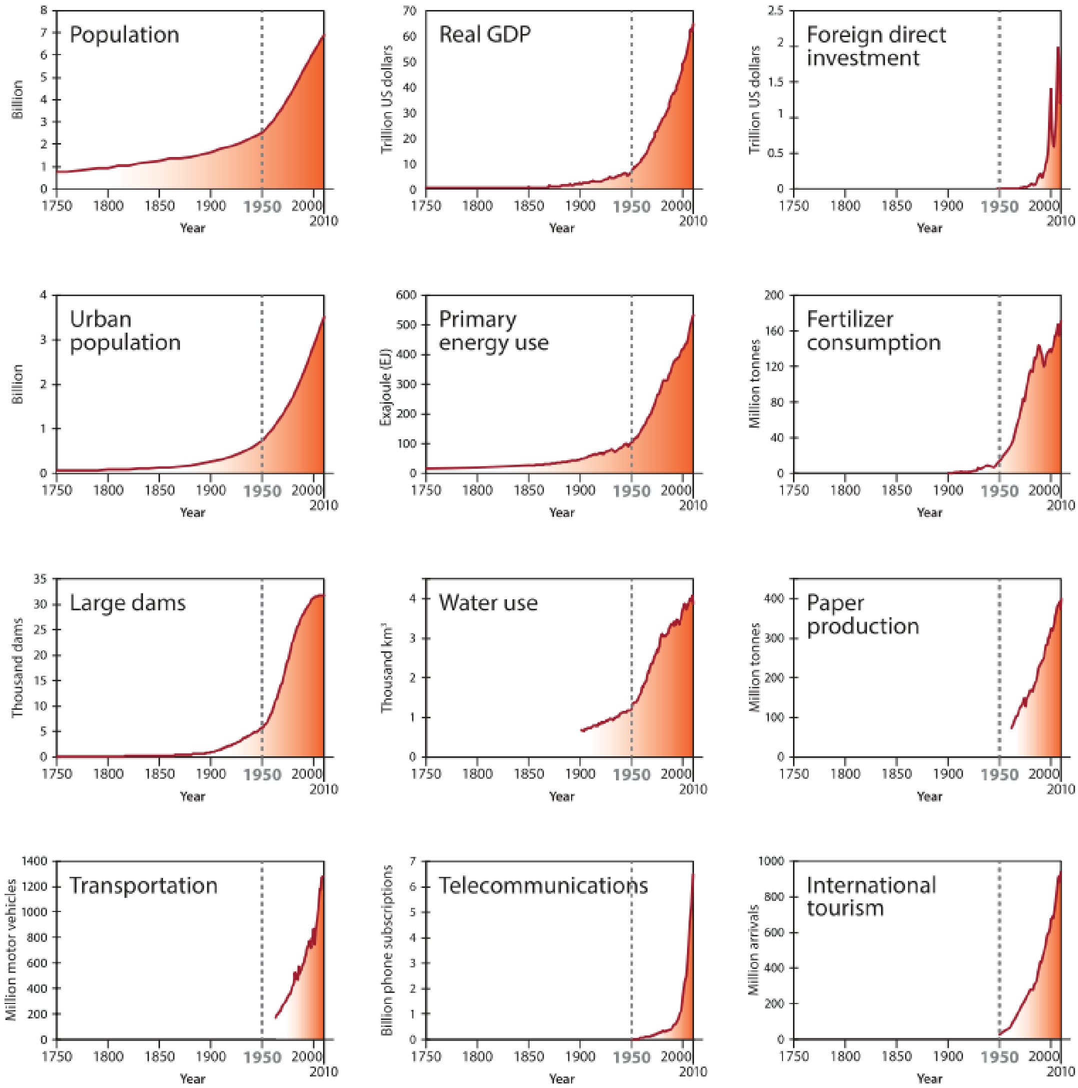

Fig 3. Trends from 1750 to 2010 in globally aggregated indicators for socio-economic development (Steffen, 2015)

Tarolli et al. (2017) mentioned that human activities are leaving significant signatures across Earth driven by increasing population and the upcoming societal needs. Anthony et al. (2014) explored the relationship between economic development in high-revenue urban shores and the fluvial source-to -coastal sink sediment and suggested to develop management strategies between river sediment and urbanization as well as coastal infrastructure. As a consequence, it is possible to argue that this socioeconomic development is the invisible hand in human society to promote civilization through land-use change, and the land-use changes result in geomorphological alterations.

A challenge is the quantification of the socio-economic impacts on the geomorphology. Since the anthropogenic landscape can be calculated through geomorphic parameters, the remain problem is to explore the suitable socio-economic indicators. The most prevalent global geospatial variable that can be used to quantify the socio-economic status is the night-time light data (Addison & Stewart 2015; Elvidge et al. 2017; Falchi et al., 2016; Ghosh 2011; Witmer & O'Loughlin, 2011). Several researches (Fu et, al. 2017; Jean et al., 2016; Mellander et al. 2015; Román et al., 2018; Wu et al. 2018) have revealed that night-time light (NTL) could be the proxy for a wide variety of indicators such as socioeconomic dynamics , development level, urbanization, population density and GDP. Using these advanced data, the prospect of quantifying socio-economic impacts on the geomorphology can be therefore achieved.

1.2 Research questions and objectives

This thesis investigates the hypothesis by assessing whether socioeconomic development in human society would have a significant impact on geomorphology, and how to quantify such impact. Broad evidence from anthropogenic geomorphology suggests that human left substantial features on the landscape during civilization processes, from the first time using the fires to the farming and engineering works, significantly influencing the Earth surface processes. Human's "role" on geomorphology involves fluvial, aeolian, costal and cryosphere processes and also the created man-made landforms. To testify that the anthropogenic forcing on the landforms is exceeding the natural forcing, a detailed quantification of anthropogenic geomorphology is needed. Thanks to the recent technological advances in remote sensing, high-resolution topographic data is now available at large scales. Geomorphologists' endeavor on computing suitable indicators to measure the human's impact on the landforms makes the systematic large-scale anthropogenic geomorphology analysis possible. Despite widespread recognition that the human activities reshaped (and are reshaping) the landscape locally and regionally with unprecedented rate, the driving forcing has yet to be understood as an involved factor. Human utilized the land to support the increasing necessity for life systems. The evolutionary trajectory of human history, started from the use of fires, to the agricultural and the engineering construction, has been imprinted on the landscape through physical changes. Therefore, the socioeconomic development of human society has been the driving force of anthropogenic geomorphology. Measuring the socioeconomic status pose a challenge to economists, sociologist and geographers.

The nighttime light datasets are proven to be the most widespread global covered geospatial datasets and could be the proxy of socioeconomic status. Therefore, there is an unparalleled opportunity to explore the correlation between the modification of anthropogenic geomorphology and the related socio-economic status.

In light of the result presented, four papers have been written following the logic construction of research questions, objectives and the outcomes:

1. What are the features that human left on the topography and how these features affect the geomorphological processes?

Tarolli, P., Sofia, G., Cao, W. (2018). The geomorphology of the human age. *Encyclopedia of the Anthropocene*, 35–43. Della Sala and Goldstein (Eds.), Elsevier, ISBN 9780128135761, doi:10.1016/B978-0-12-809665-9.10501-4.

2. How to observe, identify and interpret the anthropogenic geomorphologic features? How to classify landscapes produced by the long-term forcing of both natural and anthropogenic processes?

Tarolli, P., Cao, W., Sofia, G., Evans, D., Ellis, EC. (2019). From features to fingerprints: a general diagnostic framework for anthropogenic geomorphology. *Progress in Physical Geography: Earth and Environment*, 43, 95–128, doi:10.1177/0309133318825284.

3. Does the anthropogenic forcing leave a statistically different geomorphic signature on the surface if compared to natural forcing?

Cao, W., Sofia, G., Tarolli, P. (accepted). Geomorphometric characterization of natural and anthropogenic land cover. *Progress in Earth and Planetary Science.*

4. Is the socio-economic development being the driving force of anthropogenic modification on geomorphology? How is the correlation?

Cao, W., Ellis. E. Tarolli, P. (ready for submission). A Global assessment of anthropogenic geomorphology.

1.3 General organization

This thesis consists of four papers (chapter from 2 to 5) and the main idea of the thesis is to quantify the socioeconomic impacts on the geomorphology. It started with the introduction of anthropogenic geomorphology and how it relates to the human activities, which is presented in chapter 2. And then we identified and interpreted the anthropogenic geomorphologic features and recognized these features as sociocultural fingerprints across Earth surface, which is presented in chapter 3. Further, we explored if the natural and anthropogenic surface show a distinct geomorphic difference, thus to discriminate the anthropogenic features from the natural signatures, which can be seen in chapter 4. At last, based on a clear understanding of anthropogenic geomorphology, we investigated the driving force and then quantify the correlation between the driving force and the anthropogenic geomorphology, which is demonstrated in chapter 5.

The detailed information of each chapter is introduced below:

The first paper (Chapter 2) titled "The Geomorphology of the Human Age" has been published in *Encyclopedia of the Anthropocene* in 2018. It showed characteristic anthropogenic features (agriculture, mining and transport networks) that human left on the topography and the related Earth surface processes. This paper confirmed that humans have the potential to amplify geomorphic processes, and have become the predominant force in many Earth surface processes at different scales. It stressed the fact that society should find a solution to mitigate the criticalities such as soil erosion and landslides directly or indirectly affected by anthropogenic features. Further, it offered the opportunity for geoscientist to evaluate the extent of human societies reshapes geomorphic processes globally through an extensive inventory for anthropogenic geomorphologies.

The second paper (chapter 3) titled "From features to fingerprints: A general diagnostic framework for anthropogenic geomorphology" has been published in *Progress in Physical geography: Earth and Environment.* It provided a general framework integrating geophysical and archeological approaches to observing, identifying and interpreting the full range of anthropogenic geomorphic features from the past to the present. Further, it underlined the opportunity to recognize these features of sociocultural fingerprints across Earth's land surface using high-resolution remote sensing approaches. Lastly, it pointed out that a sustainable management of the Earth system can be achieved through effectively understanding the long-term dynamics of anthropogenic landscapes.

The third paper (chapter 4) entitled "Geomorphometric characterization of natural and anthropogenic land cover" is accepted in *Progress in Earth and Planetary Science*. This paper considered three geomorphometric indexes (slope, curvature and surface peak curvature), four landscapes (floodplain, plain-to-hilly, hilly, mountainous) covered by 2-meter LiDAR-derived Digital Terrain Models (DTMs) and five types of land covers (based on the CORINE land-cover classification). It characterized the morphology and reveal the underlying features through the frequency distribution of geomorphometric parameters. As a second step, a series statistical analysis (Kruskal-Wallis and two-sample Kolmogorov-Smirnov) were used to test the significance of differences between land covers and if the anthropogenic and natural surfaces show a distinct geomorphic difference. Lastly, it investigated the anthropogenic impacts through different utilization of the same land cover to analyze the magnitude of anthropogenic forcing on the Earth. This study offered a new insight to the geomorphology alterations, land use and humans' activities.

The fourth paper (chapter 5) entitled "A global assessment of geomorphology" is planned to be submitted in winter 2019. It proposed the hypothesis that socio-economic development is the driving force of geomorphology. The paper used a geomorphic parameter to compute the percentage of human-made alterations to terrain through high-resolution DTMs (Digital Terrain Models) and considered the night time light data as the proxy of socioeconomic activities. Further, it selected the global pattern to be the standard of stratification from biomes, anthromes and landforms which got the most fine-scale topographic data covered globally. Then, in each classification, the correlation between anthropogenic geomorphology and the socio-economic activities was computed to achieve the global assessment.

CHAPTER 2

THE GEOMORPHOLOGY OF THE HUMAN AGE[1]

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2.1 Abstract

The Earth's surface morphology is a consequence of dominant forcing such as tectonic uplift, erosion, sediment transport, and climate. Recently, the Earth science community also started to consider biota as a geomorphological agent that has a role in shaping the Earth surface, even if at a different scale and magnitude than that of other major forcings. Human activities directly or indirectly move large quantities of soil, which leave clear topographic signatures on the Earth's morphology. These signatures have the capability to affect Earth surface processes. This work provides an overview of the role of humans as a geological agent in shaping the morphology of the Earth. We consider agricultural landscapes, mining activities, and road networks. We provide examples in different regions of the world. The final section considers concluding observations and open challenges, where we focus on future challenges, related to Anthropocene, in the Earth science community.

Keywords: geomorphology; anthropogenic signatures; mining; roads; agricultural terraces; drainage systems; Anthropocene.

2.2. Introduction

For millennia, natural processes such as tectonic uplift, volcanic, climate, erosion, sediment transport and deposition have shaped the Earth surface. However, in the recent history, a different global force of geomorphic change has risen: humanity (Hooke et al., 2012; Guthrie 2015; Brown et al., 2017; Tarolli and Sofia, 2016; Waters et al., 2016). Human activities ranging from agriculture to mining, road networks, and urbanisation are leaving their fingerprints on the landscapes as evident topographic signatures (Fig.1).

Anthropogenic Landscapes now cover an extent of the Earth's land surface as many other globally important ecosystems (Foley et al., 2005). In these landscapes, human activity creates characteristic geomorphic features (e.g. channels for irrigation, terraced systems on hillslopes, surface mining). These features can significantly affect Earth surface processes (e.g. erosion, runoff, sediment transport and deposition) (Tarolli and Sofia, 2016). The recognition and the analysis of these features, and the related processes represent a challenge for understanding the evolution of the Earth's landscape (Tarolli, 2016). The scientific community is now debating the fact that we are living in a new geological epoch stratigraphically distinct from the Holocene: the Anthropocene (Monastersky, 2015, Waters et al., 2016). However, some authors have highlighted how human impacts are often difficult to separate from naturally driven activities (Fuller et al., 2015), and others have argued that it might be too soon to determine the human impact on geological records (Lewin and Macklin, 2014).

Given such a debate, the question is: can we define humanity as a geologic forcing? Humans have the potential to amplify geomorphic processes (Wolf et al., 2014). Bioturbation by humans ('anthroturbation') is a phenomenon without precedent in the Earth history (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 are a geological agent. Tarolli and Sofia (2016) compared the soil erosion rates of mining operations and agriculture with those collected from gently sloping lowland landscapes (cratons), moderate gradient hillslopes of soil-mantled terrain (soil-mantled) and steep tectonically active alpine topography (Alpine) (Montgomery, 2007).

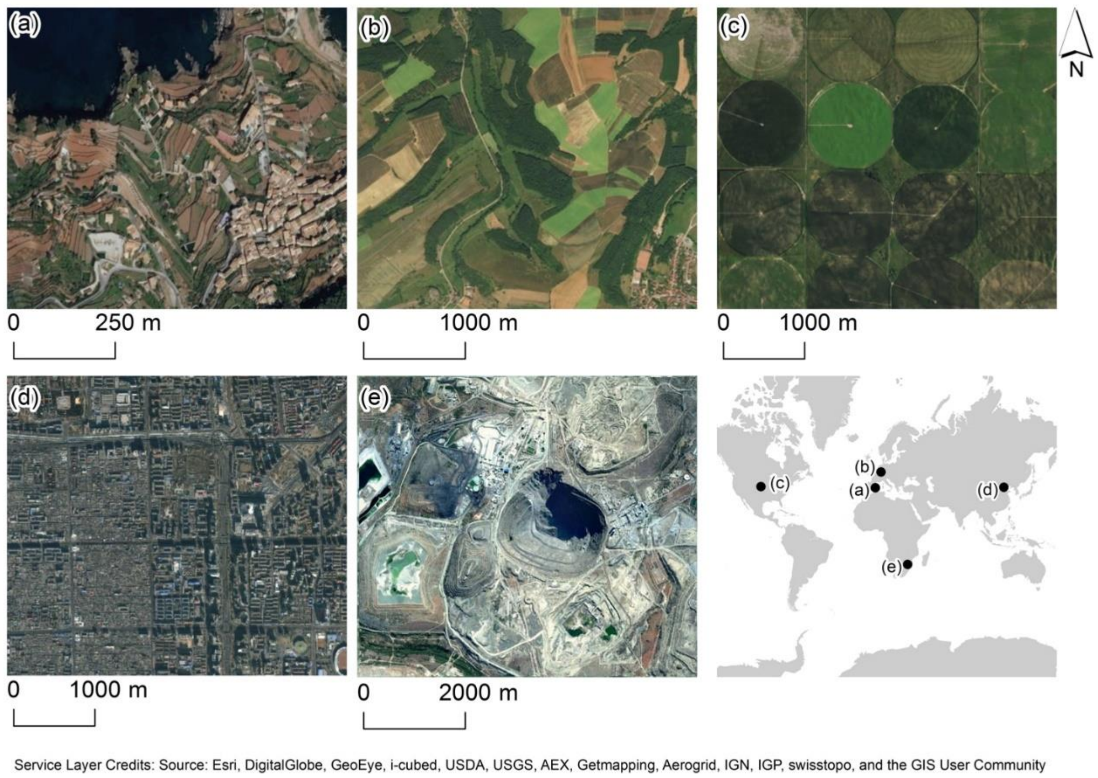

Fig. 1 Geomorphic features of human activities: terraces in Spain (A), agricultural practices in Germany (B), center pivot irrigation agriculture in Kansas (United states) (C), urban area in China（D), and mining in South Africa (E).

In fig. 2 these data are summarised through box-plots. According to this analysis, mining activities and cultivated fields from different regions mostly erode at rates typical of mountainous terrains. These numbers confirm that erosion rates from mining and agriculture that are among the highest rates in general (García-Ruiz and Lana-Renault, 2011; Prosdocimi et al., 2016) can exceed the rates of most natural erosion processes (Massa et al., 2012). Given such results maybe we can partially answer the question whether humanity can be seen as a different geologic forcing. In the following three chapters we summarise the characteristic topographic signatures and the related processes, through examples collected in different regions of the world, related to agriculture practices, mining and transport networks (roads).

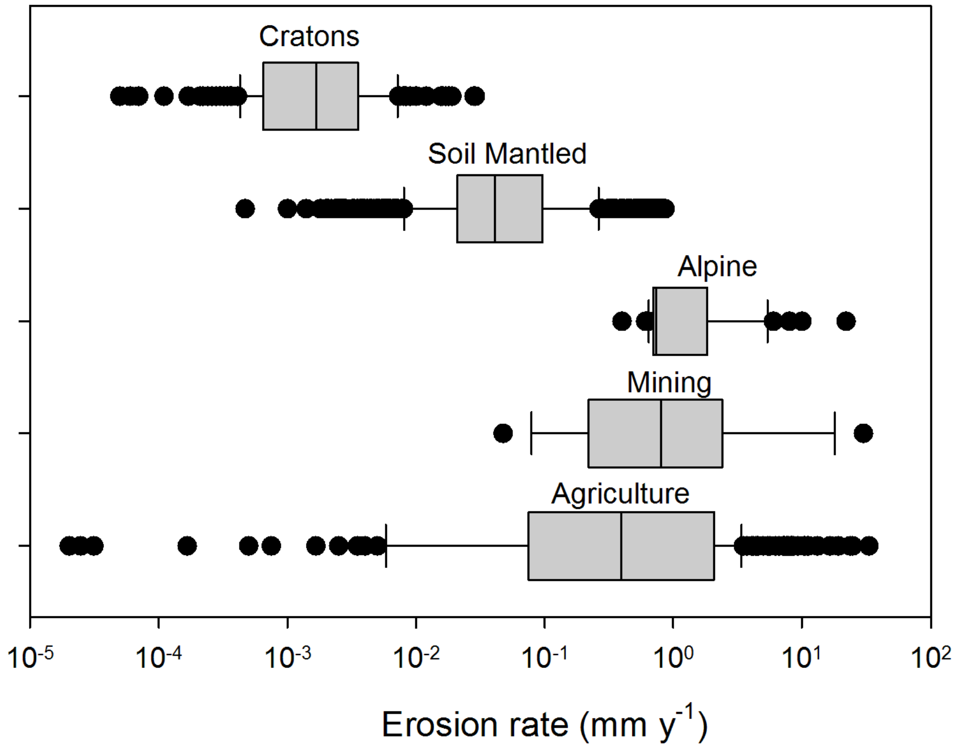

Fig.2 Soil erosion rates for mining landscapes reported in Tarolli and Sofia (2016) converted to equivalent lowering rates and for agriculture reported in Garcfa-Ruiz et al. (2015) converted to equivalent lowering rates (assuming a soil bulk density of 2000 kg m^{-3} for construction/mining together, and 1500 kg m^{-3} for soil erosion at the hillslope scale; and a soil bulk density of 1200 kg m^{-3} for agriculture). These are compared to gently sloping lowland landscapes (cratons), moderate gradient hillslopes of soil-mantled terrain (soil-mantled) and steep, tectonically active alpine topography (Alpine) erosion rate ranges published in Montgomery (2007).

2. 3 Agriculture

2.3.1. Agricultural terraces

Agricultural terraces are among the most evident and extensive signature of humans on different landscapes of the world (Tarolli et al., 2014). Terraces are built to retain more soil and water, to reduce both hydrological connectivity and erosion, and to support irrigation. They reduce the slope gradient and length, facilitating the cultivation on steep slopes, and they increase the infiltration of water in areas with a moderate to low soil permeability, controlling the overland flow and velocity, with positive effects on agricultural activities (Perlotto and D'agostino, 2016). Since ancient times, one can find agricultural terraces in different topographic conditions (e.g., coastal area, hilly and steep slope mountain landscapes) and used for various crops (e.g. grapes, orchards, rice, maize, wheat) (fig.3a).

In few regions, terrace construction and irrigation techniques used in the past continue to be effectively utilised today. In some areas, terraced landscapes can be considered a historical heritage and a cultural ecosystem service. In all Mediterranean basins, terraced landscapes are considered to be among the most important and characteristic anthropological imprints on the relief (Dunjo´ et al., 2003; Trischitta, 2005), and they symbolise an important European cultural heritage (Varotto, 2008; Arnaez et al., 2011). However, one can find ancient terraces also in the Americas, Middle-East and East Asia. In the arid landscape of South America, terrace construction and irrigation techniques used by the Incas are still in use today. Pre-Columbian and current indigenous population developed terraces and irrigation systems to manage the adverse environment (Williams, 2002) better. In the Middle East, thousands of dry stone terrace walls were constructed in the dry valleys by past societies to capture runoff and floodwaters from local rainfall to enable agriculture in the desert (Ore and Bruins, 2012). In Asia, terracing is a widespread agricultural practice. Since ancient times, one can find terraces in different topographic conditions (e.g., hilly, steep slope mountain landscapes) and used for various crops (e.g., rice, maize, millet, wheat).

Fig. 3 Agricultural terraces in Spain and Italy. (a) Well-maintained terrace system for citrus cultivation in Valencia (Spain); (b) terrace failures (white arrow) due to land abandonment in Corniglia, 5 Terre (Liguria, Italy) (photo by P. Tarolli)

Looking at these landscapes, it is clear that agricultural terraces are an integral part of the geomorphology of a region, where the geomorphic features reflect not only tectonic uplift or climate but also human forcing. However agricultural terracing introduced several critical issues: increase of slope failures, and hydraulic erosion processes with consequences on the loss of nutrients and in the redistribution of chemicals. The ancient terraces are often of the bench type with stone walls and require maintenance. Poorly designed and maintained terraces represent significant sediment sources due to terraces collapsing (Brandolini et al., 2016). Agricultural roads also serve terraces, and the construction of these anthropogenic features can also have deep effects on water flows and surface erosion (Tarolli et al., 2015). Land abandonment, which affected several regions of the world during the last half-past century (people moved from farmland to cities where job opportunities were plentiful), has resulted in a progressive increase of land degradation of agricultural terraced landscapes (Tarolli et al., 2014). The result was a gradual change in the spatial distribution of drainage networks, increase in soil erosion and landslide risk with direct consequences to people when these processes were triggered in densely populated areas (fig. 3b).

2.3.2 Erosion in agriculture

Soil water erosion on cultivated lands represents a severe threat to soil resources in the world, and especially in Mediterranean areas, due to their topographic, edaphic and climatic conditions (Prosdocimi et al., 2016). According to Montgomery (2007), cultivated fields from different regions mostly erode at rates typical of Alpine terrains. His results confirmed that erosion rates from conventional agriculture fields are 1–2 orders of magnitude greater than rates of soil production. According to his study, conventional agriculture increased erosion rates enough to be considered an unsustainable practice. García-Ruiz et al. (2015) presented an analysis of published data on soil erosion rates (in units of mass per area and time), considering about 4000 sites worldwide. Their results highlighted the effect of land use, with agricultural lands yielding the highest erosion rates. Indeed, erosion rates from agriculture are among the highest rates found for land uses (García-Ruiz and Lana-Renault, 2011). Among the cultivated lands, vineyards deserve a particular attention because, aside representing one of the most important crops regarding income and employment, they also have proven to be the form of agricultural use that causes one of the highest soil losses (Prosdocimi et al., 2016). Fig. 4 shows an example of soil erosion in a vineyard located in Spain. Erosion from agriculture also has indirect effects on river desiccation, groundwater depletion, water pollution, sedimentation, salinization and salt-water intrusion (Atapattu and Kodituwakku, 2009). Soil eroded in agricultural landscapes can also be delivered to the drainage network (Borselli et al., 2008), with direct consequences on the rates and magnitudes of floodplain sedimentation (Doolittle, 2006;

Knox, 2006).

Fig. 4 Sediments deposited along the road due to soil erosion by water in the surrounding vineyards in Moixent, Valecia province (Spain). Photo by P. Tarolli.

2.3.3 Irrigation in agriculture

Human impacts in floodplain modify the spatial distribution and the rates of hydraulic and geomorphic processes (Fryirs & Brierley, 2012), and this might result in land degradation, and geomorphic changes (Doolittle, 2006). The most rapid stimulation in the agricultural sector was the adoption of irrigation and channel network in the process of farm work (Valipour, 2013) (Fig.5).

Fig. 5 Example of ditch in a typical agricultural landscape of Padana Plain (North of Italy). Photo by P. Tarolli.

On the one hand, irrigation has contributed significantly to poverty alleviation, food security, and improving the quality of life for rural populations. On the other, the development of drainage system also has a significant effect on runoff production and development (Goudie & Viles, 2016). Floodplains witnessed over the centuries numerous changes in water management and agricultural development (Sofia, Prosdocimi, Fontana, & Tarolli, 2014; Giulia & Tarolli, 2017). Channel engineering and floodplain agricultural improvements determined a profound metamorphosis of the natural river system reshaping channel-floodplain connectivity thoroughly (Brown et al., 2017), to the point that the floodplain system is today nowhere 'fully natural' (Lewin & Macklin, 2010), and can be considered a human-water system (G Di Baldassarre, Kooy, Kemerink, & Brandimarte, 2013; Viglione et al., 2014). The most typical forms established by agriculture are ridges and furrows by ploughing, and irrigation canals and these patterns have great importance in influencing the surface run-off (Kiss & Benyhe, 2015). The spatial organisation of agricultural management, in fact, deeply affect hydrology, especially during flood events (Moussa, Voltz, & Andrieux, 2002). At a plot scale, tillage decreases runoff coefficients and increases infiltration. On the other hand, at the catchment scale, ditch networks extend the runoff production area (Levavasseur, Bailly, Lagacherie, Colin, & Rabotin, 2012), because of inter-field ditches, while the shape of the network controls the flood lag time. Without the presence of such man-made networks, the peak discharge would be lower, and nearly all runoff would be a surface runoff (Carluer & Marsily, 2004). Change in sedimentation rates and sediment sources are also related to the implementation of land drainage (Owens & Walling, 2002) and implementation of embankment systems (Marchetti, 2002). Economic drivers clearly control the development of drainage networks (Krause, Jacobs, & Bronstert, 2007; Sofia, Prosdocimi, Fontana, & Tarolli, 2014; Sofia & Tarolli, 2017), with effects on the hydrological response. When comparing the past to the present, key elements that can enhance or reduce differences in the network response are the antecedent soil conditions and the climate characteristics (Sofia & Tarolli, 2017). Based on the case presented in this article, intense and irregular rainfall events present the higher criticality, especially for frequent storms (Brath, Montanari, & Moretti, 2006; Camorani, Castellarin, & Brath, 2005; Giulia Sofia & Tarolli, 2017).

2.4 Mining

Changes in geomorphology respond to several complex and interdependent factors (Brown et al., 2017). Mines, quarries, urban areas and all types of infrastructure represent an estimated 13% of such changes (Hooke and Martin-Duque, 2012). Mines, however, are responsible for more sediment production than paved road construction, house construction, and agriculture (Hooke, 1999). Compared to other anthropogenic topographies, mining occupies a relatively smaller amount of land worldwide, but it leaves clear signatures on the surface (Tarolli and Sofia, 2016). The main characteristic of such an important topographic signature is its persistence in time. The magnitude of this phenomena is so intense that signs of mining from centuries ago are still visible in the world (Hooke and Martin-Duque, 2012), and so are their effects on the environment. Among mining techniques, opencast mining (surface mining) is an efficient and cost-effective method for the exploitation of mineral resources. However, this modern mining technology has a large impact on the surrounding landscape. The most evident effects are due to the elimination of vegetation and to the permanent alteration of topography, soils and subsurface geological structures, resulting in accelerated runoff and soil erosion (Kilmartin, 1989; Holmes et al., 1993; Osterkamp and Joseph, 2000;

Nicolau, 2002; Hancock et al., 2006; Rivas et al., 2006a; Zhao et al., 2013; Wang et al., 2014).

Mined or reclaimed surface-mined sites provide runoff more quickly than undisturbed areas. Even after reclamation, the landscape is left in a condition more similar to urban areas, rather than to a natural landscape (Ferrari et al., 2009). This results in higher flood peaks, reduced base flow, shorter lag times between rainfall and flood peak, reduced groundwater recharge, and higher sediment loads in affected catchments (Kilmartin, 1989). As well, mining activities modify hardly the natural groundwater flow paths, increasing the flow velocities and shortening the flow paths (Holmes et al., 1993). On an event-basis, if compared to more natural areas, mined/reclaimed watershed produced higher storm runoff coefficients, greater total runoff and higher peaks of hourly runoff rates if compared to more natural watersheds (Negley and Eshleman, 2006).

Mining begins by removing the soil to gain access to deposit. Thus erosion occurs immediately upon beginning the mining, but can continue many years after (Martín-Duque et al., 2010). Local scale erosion also appears in the form of rill system formation or accelerated sheet erosion, mostly controlled by soil compaction, crusting, texture, and chemical composition (Nicolau, 2002). The modification of the regional topography and mobilisation of sediment consequent to erosion can be many orders of magnitude greater than their corresponding natural rates (Rivas et al., 2006b; Tarolli and Sofia, 2016; Redondo-Vega et al., 2017).

Further examples of land degradation from mining are related to landslides (Esling and Drake, 1988; Haque et al., 2016) and slope instabilities, and land subsidence (Meng et al., 2012; Loupasakis et al., 2014; Xu et al., 2014; Zhou et al., 2015; Machowski et al., 2016).

Mining activities are concentrated in areas of specific characteristics, where they can produce rapid geological instabilities. Rockfalls and slope failures are the most critical ones. Slope instabilities in mining activities present a significant issue to the mining industry as a potential source of danger for people and equipment. However, with the extending of mining to larger scales due to mineral demands (Nature Geoscience Editorial, 2011, 2015; Vidal et al., 2013), mining-related disasters in the earth's surface will become more and more severe (He et al., 2009), inducing risk also for the landscapes surrounding the mines (Fig. 6).

In open pit mining areas land subsidenc be induced due to groundwater withdrawal and the lowering of the water table. The subsidence area can range from nearly equal to the mining area, where compaction of re-handled spoil occurs, to many times the mining area, where aquifers are dewatered and undergo compaction (Dunrud, 1984).

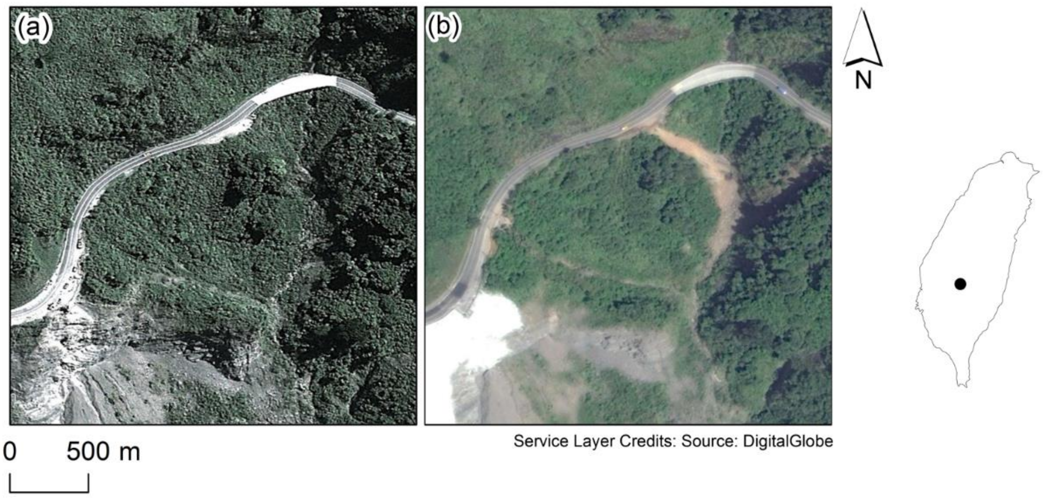

Fig.6. Road induced landslide in Taiwan. Same location as seen in 2013 (a) and after the landslide in 2014 (b).

2.5 Roads

Much more attention has been focused on soil erosion prediction for engineered landforms over the past decade, especially considering roads in mountainous environment (Sidle & Ziegler, 2012), but also in agricultural settings. (Tarolli et al., 2015) and floodplains (Florsheim, Mount, & Rutten, 2001). Road construction has increased significantly worldwide in the last decades to meet the demands of the increasing human population (Jimenez et al., 2013). This increase of road networks resulted in an increase in roads and processes interactions, leading to serious soil erosion problems.

The linear shape of roads, and their tendency to be built across topographic gradients influence the landscape on a scale greater than that one might expect from the surface they occupy (Luce & Wemple, 2001). As a consequence, they influence a variety of hydrologic and geomorphic processes at multiple time and space scales (Luce & Cundy, 1994; Montgomery, 1994; Reid & Dunne, 1984). Transport networks result in the modification of natural hillslope profiles, and the construction of roadcut and fill embankments, and impervious roadbeds influence water, and sediment flow paths in numerous ways (Forman et al., 2003; Jones, Swanson, Wemple & Snyder, 2000; Wemple, Jones, & Grant, 1996).

Road structures have bare and steep gradients that increase runoff generation and sediment yield (Pechenick et al., 2014). In mountain areas, steep gradients increase erosion on these slopes due to reduced water infiltration and increased runoff accumulation (Cerdà, 2007). Roads can also initiate soil erosion through drainage structures diverting water from their impervious surfaces as well as from roadcut embankments. The drainage structures change the runoff from diffuse surface flow downslope to concentrated flow. Thus, the concentration of overland flows can determine the development of small channels and gullies, increasing the watershed drainage density and stream flow flashiness (Montgomery, 1994). As well, extensive surface erosion may occur where this concentrated flow is discharged down-slope at discharge points.

Road networks and paths can alter the landscape distributions of the starting and stopping points of debris flows, and they can modify the balance between the intensity of flood peaks and the stream network's resistance to change (Jones et al., 2000). Road paths can function as both production and depositional sites for mass movements and fluvial processes, creating an increase in basin-wide sediment production (Sofia & Tarolli, 2016; Wemple, Swanson, & Jones, 2001). Such sediment production can appear as a chronic or episodic sources of sediment through surface erosion, or in the form of large-scale mass movements (Swanson & Dyrness, 1975) (Fig.7). By altering the rate and location of erosion and sedimentation, road surfaces may limit infiltration and affect hydrology and geomorphology, as well as negatively impact water quality and aquatic habitat, increasing the rate of fine-grained sediment production in watersheds (Dunne T., 1987; Reid & Dunne, 1984; Ziegler & Giambelluca, 1997). Also, roads may influence sediment production and transport by fluvial processes (Wemple, 2003).

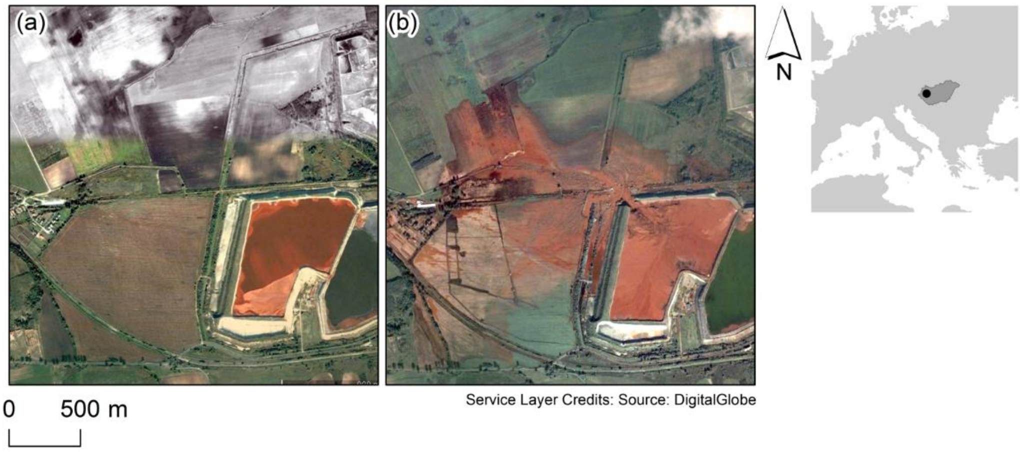

Fig. 7. The Ajka alumina mining in western Hungary (a). In oct. 2010 the north western corner of the dam of the mining reservoir collapsed, freeing approximately one million cubic metres of liquid waste from red mud lakes (b).

In addition, roads can directly alter stream channel geometry at engineered road-stream crossings, and influence water quality and aquatic ecology (Luce, 2002). To this point, road networks interact with stream networks at the landscape scale, and they might affect biological and ecological processes in the stream and riparian systems (Jones et al., 2000). As well, transportation systems, have a broad range of primary, or direct, ecological effects as well as secondary, or indirect, ones on the landscapes and on both abiotic and biotic components of terrestrial and aquatic ecosystems (Coffin, 2007).

Environmental challenges caused by the accelerated soil erosion due to roads have economic ramifications related to soil rehabilitation and water treatment. It is, therefore, important to provide a better understanding of the causes of such process so as to guide future development; and provide the necessary guidance and informed recommendations on possible effective monitoring approaches and erosion control efforts especially in resource-scarce environments.

2.6 Final remarks and open challenges

Human activities are leaving a significant signature on the Earth by altering its morphology, processes and ecosystems. Humans can move large amounts of materials and thus play a similar role, even at a different magnitude and temporal scale, as a geologic agent. At the end of this century, because of the increasing of population and human needs, anthropogenic geomorphology will cover a large part of the Earth. The consequences on Earth surface processes (soil erosion and land sliding related to surface water flow interception by roads; soil erosion and mass movements related to mining activities; runoff and soil erosion associated with land use changes and issues related to anthropogenic drainage systems in agricultural landscapes) will be significant. Society, from a geomorphological point of view, should find solutions to minimise such consequences. The potential to assess the global topographic fingerprints of humanity using high-resolution topography provided by the novel remote sensing techniques (e.g. LiDAR) will be a challenge (Tarolli, 2014). The actual challenges regarding the limited availability of spatial data from small number of resources could be summarized as follow: 1) the quality and accuracy of spatial data; 2） the acquisition of new technologies to collect spatial data effectively; and 3) technical understanding and spatial analysis of datasets. An extensive inventory for anthropogenic geomorphologies would enable geoscientists to evaluate the extent to which human societies reshape geomorphic processes globally. This would facilitate (a) unprecedented insights into the sensitivity of landscapes and their responses to human forcing at a global scale; (b) the development and implementation of strategies and practices to reduce or mitigate the social and environmental impacts of anthropogenic geomorphic change.

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CHAPTER 3

FROM FEATURES TO FINGERPRINTS: A GENERAL DIAGNOSTIC THEORY FOR ANTHROPOGENIC GEOMORPHOLOGY[2]

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3.1 Abstract

Human societies have been reshaping the geomorphology of landscapes for thousands of years, producing anthropogenic geomorphic features ranging from earthworks and reservoirs to settlements, roads, canals, ditches, and plow furrows that have distinct characteristics compared with landforms produced by natural processes. Physical geographers have long recognized the widespread importance of these features in altering landforms and geomorphic processes, including hydrologic flows and storage to soil erosion and deposition. In many of the same landscapes, archaeologists have also utilized anthropogenic geomorphic features to detect and analyze human societal activities, including symbolic formations, agricultural systems, settlement patterns and trade networks. This paper provides a general framework aimed at integrating geophysical and archaeological approaches to observing, identifying and interpreting the full range of anthropogenic geomorphic features based on their structure and functioning both individually and as components of landscape-scale management strategies by different societies, or "sociocultural fingerprints". We then couple this framework with new algorithms developed to detect anthropogenic geomorphic features using precisely detailed three-dimensional reconstructions of landscape surface structure derived from lidar and computer vision photogrammetry. Anthropogenic landscapes are palimpsests produced by the long-term activities of both natural and anthropogenic processes. To understand the geomorphic processes and landforms of the Anthropocene, the science of physical geography must advance towards integrated empirical and theoretical frameworks encompassing the coupled natural and sociocultural forces that now shape Earth surface morphology.

3.2 Introduction

Before humans left their first footprints on African landscapes, Earth's terrestrial surface was shaped solely by the natural geophysical processes of tectonic uplift, volcanism, and the erosion, transport and deposition of sediments, modified only by the ecosystem engineering activities of microbes, plants, and animals (Erwin, 2008). While these processes continue to operate, human societies have increasingly gained the capacity to act as a novel force of geomorphic change, both adding to and interacting with pre-existing natural biogeophysical forces in shaping landscapes through activities ranging from the clearing of land using fire and the tillage of soils for agriculture, to the construction of settlements, dams, mines, canals, roads and other infrastructures (Brown et al., 2017; Cuff, 2008; Dixon et al., 2017; Ellis and Haff, 2009; Goudie and Viles, 2016; Guthrie, 2015; Hooke and Martin-Duque, 2012; Sauer, 1925; Tarolli et al., 2018; Tarolli and Sofia, 2016; Zalasiewicz et al., 2017). As a result, it is no longer possible to understand the formation and evolution of Earth's landforms without a robust theoretical understanding of the anthropogenic processes that act to cast them.

The science of physical geography and that of geomorphology, in particular, requires new tools and frameworks capable of identifying distinctly anthropogenic features together with the sociocultural processes that have shaped them (Brown et al., 2017b; Erle C. Ellis, 2017; Goudie & Viles, 2010; Tarolli & Sofia, 2016b). Our goal here is to connect existing theories on human sociocultural processes with the observational techniques needed to identify the full spectrum of geomorphic products of these processes, both as individual "anthropogenic features", and their diagnostic interpretation as the geomorphic "sociocultural fingerprints" produced across landscapes by specific human societies. To do this, we integrate archaeological, ecological and geophysical frameworks around theory on sociocultural niche construction (Ellis, 2015; Ellis, Magliocca, Stevens, & Fuller, 2017), building on existing published work on anthropogenic geomorphology (Brown et al., 2017b; Goudie & Viles, 2010; J. Li, Yang, Pu, & Liu, 2017; Szabo, 2010; Tarolli, Sofia, CAO, et al., 2018; Tarolli & Sofia, 2016b).

3.2.1 Anthropogenic landscapes are sociocultural palimpsests

While many species alter their environments to enhance their adaptive fitness, humans are Earth's ultimate ecosystem engineers, engaging in a broader range of more potent environment-modifying behaviours than any other species (Smith, 2007; Smith and Zeder, 2013). By engineering environments using fire, tools of increasingly complex design, domesticated species, and by harnessing nonhuman energy to accomplish these modifications, human niche construction has radically enhanced the adaptive fitness of human individuals, social groups and societies, enabling human societies to increase in scale and to extend their reach across Earth's terrestrial surface (Ellis, 2015; Ellis et al., 2017). Most importantly, human societal capacities to engineer environments are socially learned and enacted (cooperative), enabling collective capacities to accumulate over time and to be enacted at increasing social and spatial scales using increasing amounts of energy over time (Ellis, 2015; Ellis et al., 2017) (Fig.1). Human sociocultural niche construction has evolved, diversified, and scaled up over millennia, from the first use of fire to clear land for greater success in hunting and foraging, to the construction of agricultural landscapes and urban settlements, powered by fossil fuels, to the global networks of exchange infrastructure that have made contemporary human societies the most interdependent in history and have made humanity a global force of nature (Fig. 1 Ellis, 2015; Ellis et al. 2018).

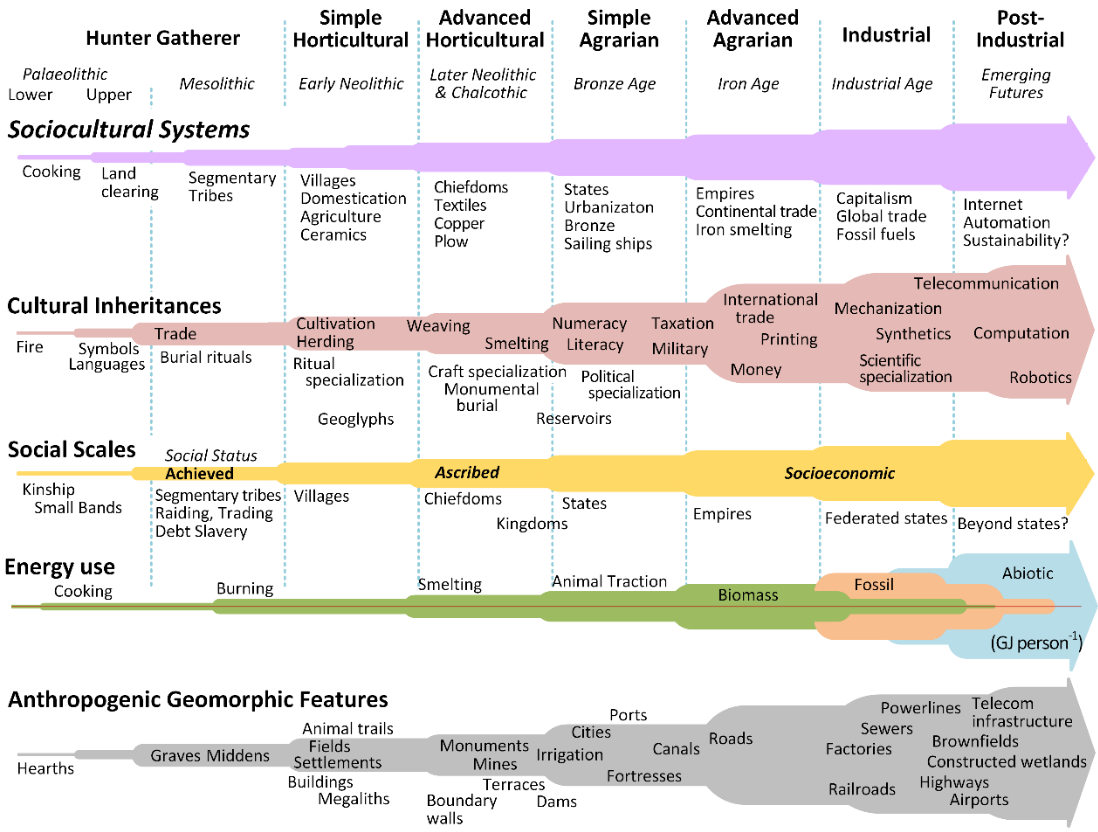

Fig. 1. Long-term changes in sociocultural systems, cultural inheritances, societal scale, energy use, and anthropogenic geomorphic features. Different societies combine different sets of anthropogenic geomorphic features, including both pre-existing and novel, to produce their sociocultural fingerprints across landscapes. This figure expands on Ellis 2015 Fig. 3, Ellis et al. 2018, Fig. 1).

Human modification of landscapes is inherently a social process that has tended to increase in scale and complexity together with human societies (Ellis, 2015). By the Late Pleistocene, opportunistic use of naturally-occurring fire was supplemented by technologies of fire-maintenance and fire-making (Sandgathe & Berna, 2017), amplifying the ability of humans to transform ecosystems over extensive areas, either intentionally or unintentionally. The construction of settlements by sedentary hunter-gatherers and early farmers left more robust geomorphic evidence due to the systematic and deliberate reconfiguration of landscapes, often reflecting distinctive patterns in social behavior and material culture (Fletcher, 2009). As societies scaled up over time, into the first urbanized and then industrial societies, their ecosystem engineering also increased in scale, complexity, durability and in the sheer amounts of material moved (Fig. 1).

Even more significant complexity in anthropogenic landforms has emerged over time, as the geomorphic features engineered in support of one society have come to be overlaid with and overwritten by those of later societies, such that the anthropogenic features and landforms of regions with sustained human occupation represent not the directed efforts of a single society, but the complex sociocultural palimpsests of multiple diverse societies (Bailey, 2007). Moreover, given that natural geomorphic processes continue to act during and after societal processes, the landform palimpsests of anthropogenic landscapes represent the sustained interplay of sociocultural and biogeophysical processes over time (Johnson & Ouimet, 2018).

3.2.2 Anthropogenic features and sociocultural fingerprints

Human societies have been altering ecological, evolutionary and geomorphological processes across Earth for millennia (Cuff, 2008; Edgeworth, 2014; Edgeworth et al., 2015; Ellis, 2015; Foley and Lahr, 2015; Kirch, 2005;). Individual anthropogenic features, as specific human modifications of land surfaces such as an individual grave, building, or road, show a wide variety of forms; in aggregate, however, there is a degree of consistency and regularity to the production of anthropogenic features, and their formation as sociocultural assemblages within a given sociocultural milieu, such as the different sociocultural systems illustrated in Fig.1. Thus, as archaeologists have long recognized, the material cultures of different societies pattern the surface of the Earth in specific ways that produce distinctive and recognizable sociocultural fingerprints (Butzer, 1982; David and Thomas, 2016). In recent years, the availability of high-resolution topographic datasets from sensors such as lidar and through 3D reconstructions using computer vision photogrammetry has spurred renewed interest in the role of social-ecological systems in shaping Earth's surface (Johnson & Ouimet, 2018), ranging from studies of 'archaeological topography' among social sciences (Evans et al. 2013; Opitz and Cowley, 2013) to the study of 'geomorphometry' among geoscientists (Pike, 2000; Sofia, Hillier, & Conway, 2016).

Anthropogenic features represent individual land surface modifications made through individual or collective efforts to remove, transfer, introduce and reshape elements of the physical environment. This social production of space generates a virtually endless variety of physical forms, and we acknowledge at the outset the difficulties in dividing this diversity of physical forms into neat categories according to their perceived function or meaning. Elements of material culture can, of course, be multifunctional, and polysemic, in ways that are arbitrary, unknowable, and subject to variability over time. We argue however that there is practical and heuristic value in structuring the complexity of these physical forms into a generalized ontology of anthropogenic features: symbolic (e.g. graves and monuments), habitation (e.g. housing, villages, cities), transport and exchange (e.g. roads, canals), subsistence (e.g. plow furrows, irrigation networks), mining, refuse disposal, warfare (forts and battlements), among others.

Individual anthropogenic features are readily detectable on Earth's surface (or below) through observations made on their geometric forms, and possibly through a range of other physical or chemical attributes. Smaller scale societies, such as those of the first farmers, tend to produce a relatively narrow range of anthropogenic features. However, even small-scale societies produce a diversity of distinctive anthropogenic features on the landscape within the framework of their material culture. For example, a horticultural society produces building and settlement structures, hand-tilled fields, waste middens, and graves, while the material culture of more complex societies is characterized by large-scale urbanism, plowed fields, irrigation systems, mines and quarries, roads, monuments, cemeteries, and many other anthropogenic features. These individual features are the fundamental elements of material culture at the landscape scale, and considered in aggregate, it is possible to identify the distinctive spatial patterning of a society elaborated across time and space on the surface of the Earth: the sociocultural fingerprints of societies and cultures. The layering of these sociocultural fingerprints over landscapes over time, and their interactions with each other and the natural geomorphic processes that simultaneously shape them, combine to produce the landforms that cover most of Earth’s terrestrial surface today.

3.2.3 Understanding the socioeconomic and sociocultural drivers of anthropogenic landscape evolution

To understand the socioeconomic and sociocultural forces that shape landscapes, it is first necessary to recognize that these operate at the scale of the societies engaging in them (Ellis, 2015). Human societies have long shaped terrain at local and regional scales. Now, human societies numbering in the billions are reshaping landforms globally through global-scale processes enabled by interconnected systems of economic, social, material and energy exchange, increasing levels of technological innovation and rapid socioeconomic development (Fox et al., 2017; Zalasiewicz et al., 2017). Yet, even while the anthropogenic features and fingerprints generated by societies have tended to extend spatially across their areas of influence, their distributions are usually highly heterogeneous within and across these areas. Societal demands for food, minerals, settlements, economic exchange, symbolic communications and other needs are generally expressed unevenly across societal areas of influence to access the distribution of opportunities afforded by natural patterns of resource-use potential, such as fertile soils, level terrain, access to water and other societally perceived patterns defining their suitability for different uses, and also based on pre-existing social structures, such as settlements, transport infrastructures and areas of symbolic significance that define their value and accessibility for societal use (Butzer,1982b; Ellis, 2015). The economic and social demands of globalscale societies are now met through processes that engage with social and environmental differences around the world at regional scales – where land, resources and labor are less expensive and more accessible. As a result, as socioeconomic demands and exchange processes have scaled up, some world regions are experiencing rapid increases in anthropogenic modification caused by deforestation and tillage to meet far-away food demands, road-building to interconnect global supply chains or dam construction to supply energy, while at the same time other regions are experiencing rapid decreases in such modifications and even complete abandonment by human populations (Meyfroidt et al., 2013). While uneven spatial patterns of anthropogenic landscape modification are just as common in small-scale societies, they tend to be produced by very different socioeconomic and sociocultural processes. In general, the forms, extents and distributions of anthropogenic landscape modifications must all be seen as variable across and within societies as a function of both pre-existing natural patterns, largely related to terrain and climate, and to preexisting sociocultural patterns, largely related to the cultural and technological capacities and patterns of social structures in space, and the varying interactions of different societies with these conditions (Butzer, 1982b; Ellis, 2015). Anthropogenic landscape modifications are therefore a combination of cultural forms, technologies and natural environmental patterns, and can involve anthropogenic interventions that accelerate or delay natural geomorphological processes, producing hybrid anthropogenic/ natural features, or engineer entirely distinct anthropogenic features with purely cultural functions. For this reason, anthropogenic landforms vary widely in form and function, in the degree to which they are distinct in their spatial patterning from natural landforms and in the degree to which they may be recognized as the product of a specific cultural milieu. Whereas natural mass flows generally move from high to low positions or from upstream to downstream under the influence of natural forces, and their capacity to move dissipates over distance, landforms engineered through direct human agency are shaped primarily by social and cultural imperatives that produce landforms distinctly different from natural physical processes. Anthropogenic landscape engineering often represents elaborate attempts to subvert natural processes in culturally specific ways – by damming floodplains and diverting sediment-laden floodwaters into walled field systems, for example – which can in turn feed back into natural systems and generate consequential changes within them. To understand human modifications of landscape evolution across multiple scales of time and space, a basic framework for describing and classifying anthropogenic landforms is needed, together with an understanding of the underlying generative principles that produce them, and the nature and degree of their ability to alter the functioning of landscapes.

3.3 The diversity of anthropogenic geomorphic features

Above ground, the legacy of long-term human occupancy and intense activity is identifiable in contemporary landscapes as various types of anthropogenic landforms and features ranging from small (< 1m) to large in size (>1km) (Tab. 1). Here we use the following categories to establish a basic, working framework for the classification of anthropogenic features: (i) symbolic; (ii) habitation; (iii) transport/exchange; (iv) subsistence; (v) minings; (vi) water infrastructure; (vii) waste disposal; (viii) warfare. warfare. These heuristic categories encompass signatures of social functions in space and time. Features identified within these categories cover different spatio-temporal extents, and are affected differently by time-varying processes. As a consequence, the anthropogenic features described within these categories exist across a spectrum of scales in space and time, and also reflect a huge range of societal scales and complexities, from hearth pits to highway networks. The landscapes within which these features are embedded are also a function of spatio-temporal scale, depending on the overall area encompassed by a society (its extent in space) and its historical development (extent in time). When viewed at larger spatial scales, combinations of these features represent fingerprints of societal functions, from agriculture and settlements to industrial development, transport infrastructure and other functions. Even at the level of individual features, which range from small (<1 m) to large (>1 km) in size, it can also be possible to identify specific societies directly from their anthropogenic landforms and features (Fig. 2).

Features	Description	Function	Photos	Sketch	Lidar
Hearth-pits	Bowl-shaped, ash deposits, soil discoloration, shallow (depth generally less than 0.5 m) and small (diameter less than 1 m)	Subsistence: cooking, heat, firing of ceramics, limited metallurgy			
Burial sites	Excavations, mounds, cemeteries including human remains	Symbolic: repository for human remains			
Geoglyph	human rearrangement of earth, stone and other materials to create symbolic anthropogenic landforms	Symbolic: Public and ceremonial spaces, burial sites, funerary customs, animal trapping			
Rock-Shelter	Natural rock formations associated with ancient human habitation, including campfires, remains, debris	Habitation, shelter			
Megaliths	Human-rearranged stones without mortar or concrete	Symbolic: Monumental architecture, ceremonial spaces,			
Buildings	Permanent structures with roof and walls	Habitation, storage, symbolic structures, other functions requiring permanent sites with protection from weather			
Cities	Permanent large-scale human settlement, including infrastructure	Habitation, trade; centers of human social interaction			
Boundary walls	Linear raised features composed of earth, rock, wood, brick and other materials	Protection of settlements, fortresses, and farms from potential aggression			
Roads	Cleared, levelled, sometimes paved, interconnected linear features	Transport: mobility for humans, livestock, vehicles, and exchange of materials among settlements			
Middens	Mounds of domestic refuse containing shells, animal bones and other debris and remains marking sites of prehistoric settlement	Refuse disposal			
Livestock trails	Animal-induced paths trampled into earth, often interconnecting water and shelter	Subsistence: livestock production			
Terraces	Artificially-levelled shelves of land interrupting slopes	Subsistence: facilitating crop production on steep slopes			
Mines	Excavations maintained for mineral extraction	Source of mineral resources, ore for metallurgy, clay for bricks, etc.			
Ditches	Narrow channels excavated around crop fields, buildings and road perimeters	Drainage of settlements, roads, agricultural land, and water transport for irrigation			
Canals	Large-scale, artificial linear excavations	Transport: of materials and people by boat, and water transport for irrigation			
Embankments	Artificial mounds and structures of earth, stone and other materials along waterways	Supporting infrastructure for flood protection from, and access to waterways			
Reservoirs	Artificial lakes	Water infrastructure, water storage, hydraulic power, aquaculture			
Constructed wetlands	Flooded excavations	Drainage, water treatment			
Trenches	Long, narrow excavations	Warfare: protection of military personnel			

Fig. 2. Examples of anthropogenic geomorphic features,their sociocultural functions,and derived fingerprinton topography. From top to bottom: hearth-pit (Shahack-Gross et al., 2014); West Kennet Long Barrow in Avebury, one Wiltshire(UK), of the largest and most impressive Neolithic graves in Britain(3650BC)(ph:©SkyscanBalloon Photography; LiDAR: Survey Open Data UK);

The Long Man of Wilmington on South Downs in Sussex, UK (ph. Steve Slater, LiDAR: Survey Open Data UK); rock shelter (ph. Bernard Gagnon); Stonehenge (UK) (LiDAR: Survey Open Data UK); building in Lugo (Spain) (ph. Luis Miguel Bugallo Sanchez; LiDAR:©Centro Nacional de Informacion Geografica);El Tolmo(Spain),archaeological site showing a continuous time record of ancient civilizations from 3500yr BP onwards (ph.Laclac;LiDAR:©Centro Nacional deInformacion Geografica); Roman wall of Lugo(spain)(phXosema;LiDAR:©Centro Nacional de Informacion Geografica); mountain road (ph. Chell Hill, LiDAR: OpenTopography Facility); shell middens at Mound Key (Florida) (http://www.flpublicarchaeology.org/blog/crc/tag/soil-core/; LiDAR: NOAA National Oceanic Atmospheric Association website); cowtrails (ph.HerziPinki,LiDAR:LiDARLaserscanning-Geodaten Kanton Zu¨rich, Amt fu¨r Raumentwicklung Geoinformation GIS-Produkte); rice terraces in the Philippines (University of the Philippines TCAGP); Bingham Canyon copper mine, UT, USA (ph. Spencer Musick; LiDAR: MNTOPO®); agricultural ditch in the Netherlands (ph. Tup Wanders, LiDAR: Dutch National Spatial Data Infrastructure – PDOK–); the Mittellandkanal, the longest artificial waterway in Germany (LiDAR: Geschaftsstelle des IMA GDI Nordrhein-Westfalen); riverbankinitaly (Google©2017;LiDAR:Italian Mininstry of Environment); LeechLake Minnesota (LiDAR: MNTOPO®); constructed wetland in Northern Italy (Ph Adige Euganeo; LiDAR: Italian Mininstry of Environment); NagiaGrom war trenches in northern italy (ph. Kevin1971; LiDAR: Autonomous Province of Trento)

3.3.1 Symbolic

The first symbolic features of human societies are likely burial sites (Belmonte, 2014). Entombments in ancient times have included caves and underground burials with different designs relating to the wealth and status of the deceased (Cuezva et al., 2016). As societies evolve, so have burial practices, from ground and cave burials to more elaborate constructions (Sidebotham, 2014; Tomczyk, Jedrychowska-Dańska, Płoszaj, & Witas, 2011). In many cultural contexts these funerary structures represent massive investments in reconfiguring the natural landscape, and their sheer size makes them relatively resistant to natural weathering and degradation (Guthrie, 2015). In some instances, for example with geoglyphs, it is clear that landscape-scale transformations of the natural environment have been undertaken in order to encode meaning in geometric patterns (Briones-M, 2006; Tapete, Banks, Jones, Kirkham, & Garton, 2017; Tapete, Cigna, Masini, & Lasaponara, 2013). Geoglyphs can play a role in mortuary practises as well as aiding in the trapping of migratory animals, and serving as cleared areas for camps, houses and animal enclosures (Kennedy, 2011). They are formed of durable materials such as soil, stones, clastic rocks, live trees, gravel and earthworks (Sparavigna, 2010). Prehistoric agricultural societies, especially in parts of Europe also produced large stone structures, or megaliths, including large single standing stones, as part of buildings, as portal dolmens, rotundas and passage graves as well as henges, all of which served diverse but essential societal functions (Beck & Chrisomalis, 2008; Fleming, 1999, 2005; Holtorf, 1998; Midgley, 2010). Historical and contemporary societies also produce a wide variety of symbolic landscape features in parks and gardens, including stylized berms incorporated into artworks, and many shaped to mimic stylized natural landforms, such as those of central park in New York City (Portal, 2017).

3.3.2 Habitation

Early human encampments relied on rock shelters formed by natural processes, such as caves (Farrand, 2001; Judson et al., 2005; Simms & Russell, 1997), whose natural and anthropogenic deposits offer details on human activities, natural environments inside such caves, and their dynamic interactions over time (Courty & Vallverdu, 2001; Farrand, 2001). With the rise of sedentary societies, especially those sustained by agriculture, people began to build more permanent shelters and to concentrate these in ever larger settlements, from seasonal encampments, to villages, towns, cities, and ultimately into interlinked complexes of urban and rural landscapes sustaining large-scale social formations, or states (Goudie and Viles, 2016). As settlements grew in scale, these came to include not only housing but also specialized buildings for governance, crafts production, temples, and other cultural needs, water infrastructure, road networks, and boundary walls or fortifications (Beranek, 1988; Campbell, 2006; van der Spek, 2017). Many early cities prospered, dwindled, and disappeared, such as the Mesopotamian city of Ur, in ruins by 450 BCE (Azara, 2015; Launderville, 2013). Other ancient cities have survived to the present, such as Jericho, one of the oldest inhabited cities in the world, well-known for its protective walls (Issar, 2008). As with Jericho, defensive enclosures are one of the most easily-recognisable components of the archaeological record (Boyce et al., 2015; Cassel, 2012; Rojas, 2010). Other urban forms include the large-scale urban complexes and hydraulic systems that evolved in densely forested landscapes in Asia and Amazonia (Evans et al., 2013; Liu et al., 2017; Roberts, Hunt, Arroyo-Kalin, Evans, & Boivin, 2017). The production of built structures, from walls to housing and those for other specialized purposes induce a variety of geomorphic processes ranging from concentrated excavation to the intensive transport, deposition and restructuring of materials, to the creation of new artificial landforms. All of these intentional structuring processes tend to further enhance other geomorphic processes including water accumulation, the deposition of waste materials in excavated areas, destabilizing of new landforms and underground structures, intensified erosion, and other environmental consequences (Courty & Vallverdu, 2001; Farrand, 2001).

3.3.3 Transport/exchange

Urban development is also accompanied and facilitated by the development of transport networks composed of paths, unimproved and improved roads, railways, and waterways connecting rural resources and people to distant markets and population centers (Bell & Iida, 1997; Kara & Verter, 2004; Morriss, 2003, 2005; Ruiz, 2016; Snead, Erickson, & Darling, 2009). Roads are ubiquitous features of landscapes and different shapes of road network represent different evolution of civilization in times (Strano, Nicosia, Latora, Porta, & Barthélemy, 2012). Road networks can reflect the central or decentralized organization of countries, and provide important pathways for mobility, migration and demographic change. They induce the rural to urban migrations as well as the massive emigration. Additionally, since the Industrial Revolution, railroads have been an important form of transportation (L. Li, 2017; Morriss, 2003), shaping cities and economic growth (Hanedar, 2017; Nerlove, 1966), but also landscape processes (Bell & Iida, 1997; Blanton & Marcus, 2009, 2013; Kumar, Jain, Prasad Babu, & Sinha, 2014; Martinović, Gavin, Reale, & Mangan, 2018). Railways, for example, can induce selective disclosure of the countryside (Antrop, 2004). Villages that received a station in some cases (but not always) developed rapidly into urban-like centers and their surrounding landscape changed accordingly. Developed road networks could also affect new urban development in tourist resort areas that once were remote rural regions with limited access (Petrov, Lavalle, & Kasanko, 2009). The development of both networks (road and rail) is also accompanied by the use or even reshaping of the geomorphologic and topographic setting to create new infrastructure, tunnelling and bridges (Booth et al., 2011; Buchanan & Jones, 1980; Day, 1995; Pratesi, Tapete, Del Ventisette, & Moretti, 2016; Watson, Brigham, Dyson, & Museum of London. Archaeology Service., 2001). More recently, the development of underground tunnels for transport has created extensive subterranean networks in many large cities (Zalasiewicz, Waters, & Williams, 2014).

3.3.4 Subsistence

Together with deposits of stone tools, hearths and other evidence of controlled fire for cooking, warmth and protection from predators are likely the earliest evidence of human transformation of geophysical environments (Roebroeks & Villa, 2011; Smith, 2007; Wrangham, 2009). The earliest intentionally-built fires were little more than controlled burns of woody and other flammable organic materials, but these evolved into hearths constructed of stones and earth, and ultimately into ovens, kilns and other larger-scale fire containing structures. A typical hearth pit of the past formed a bowl-shaped soil discoloration less than 1 m in diameter and less than 0.5 m deep, with evidence of soil or rock exposure to high temperatures (Wandsnider, 1997), with differences in hearth-pit size and shape indicating different functions (Crombé, Langohr, & Louwagie, 2015; Pearson & Pearson, 1999). Human engineering of environments for food production begins in the late Pleistocene with hunter-gatherer modification of landscapes to concentrate and trap game and the use of fire to clear and enhance vegetation growth, followed by the rise of agriculture in the early Holocene, involving the digging of holes for planting, soil tillage, and the construction of livestock pens and fencing; activities continuing to the present day (Ellis, 2015; Ellis et al., 2013; Smith, 2013; Smith & Zeder, 2013). Soil tillage leaves especially clear and widespread geomorphic signatures across landscapes in terms of anthropogenic soils and erosive deposits (Certini & Scalenghe, 2011; Ellis, 2011). The need to exploit steep lands for agriculture also introduced the construction of terraces (Chase et al., 2014; Tarolli, Preti, & Romano, 2014b; Vogel, 1987). Geomorphic features produced by livestock management include animal pens with soils altered by trampling and manure deposits, their surrounding fencing, sometimes constructed using rocks, earth and other durable materials, and the extension of fencing and animal paths across landscapes, often associated with water and shelter, including induced deposition of stones and earth near fences, soil compaction and erosion from paths and disturbance and vegetation removal caused by overgrazing (Amy and Robertson, 2001; Mwendera et al., 1997; Tarolli et al., 2013; Wu et al., 2017; Yong-Zhong et al., 2005; Zhang and Zhao, 2015).

3.3.5 Mining

Though mining is as old as the manufacture of stone tools and leaves clear geomorphic signatures, it occupies a relatively small surface area worldwide (Paolo Tarolli & Sofia, 2016b). Mining activity has been driven by a wide variety of objectives, including obtaining materials for making items such as tools, utensils, weapons, ornaments, decoration, currency (Timberlake, 2017). Mining of clay for bricks is also widespread and continues globally (Shakir & Mohammed, 2013). Further mining drivers have been the need for structures, and machinery, and obtaining resources for energy, electronics, nuclear fission (Hartman & Mutmansky, 2002; Herrington, 2013), and for low-carbon energy production (Vidal, Goffé, Arndt, Goffe, & Arndt, 2013). As a consequence, various so-called ‘mining landscapes’ have emerged all over the world since the 19th century. They are characterized by unique excavated, accumulated, and planed landforms (Dávid, 2010) that bear the signature of the material sought. Such signatures can be broadly separated into two classes: surface and underground, although combinations of the two may occur in time and space (Mossa & James, 2013a). The main characteristic is the persistence in time of the landform itself (Hooke and Martin-Duque, 2012) and of the related effects on the environment (Kircher, Roth, Adam, Kampes, & Neugebauer, 2003; Mossa & James, 2013a; Rivas et al., 2006; Toy & Hadley, 1987).

3.3.6 Water infrastructure

Although several forces beyond water management combine to shape societies, the availability of water strongly influenced the trajectory of past societies (Scarborough, 2017). As humans began to settle as farmers during the Neolithic, water wells and water infrastructures began to rise (Angelakis, 2012; Kollyropoulos, Georma, Saranti, Mamassis, & Kalavrouziotis, 2017; Tegel, Elburg, Hakelberg, Stäuble, & Büntgen, 2012). These features leave a distinctive topographic signature that can still be identified on the landscape today, thousands of years later (Yevjevich, 1992). An example of would be Qanat, which are gently sloping underground channels designed to transport water from an aquifer or water well to surface for irrigation and drinking

(Wessels, 2014), originating in the first century and distributed mainly in the Iranian plateau and east of Xinjiang Province in China (Goes, Parajuli, Haq, & Wardlaw, 2017; Harandi & de Vries, 2014; Luo et al., 2014). Another example is the famous hydraulic infrastructure of Pont du Gard in southern France (Dumas, 2011; Vrancic, 2010). Ditches provide further water infrastructure for reclamation purposes, irrigation, drainage alongside roadways or fields (Terry and Hughes, 1978). As well, canals provide water conveyance, navigation and water storage (Swamee & Chahar, 2015). Along water infrastructures, especially in floodplains, humans built embankments, levees and scarps. These infrastructures offer protection from floods, but they also change flood frequency and create disconnectivity between the river landscape and its floodplain (Chin, O'Dowd, & Gregory, 2013; Gregory, 2006; Overeem, Kettner, & Syvitski, 2013; Thoms, Southwell, & McGinness, 2005).

Another example of water control measures is provided by dams and reservoirs, which have increased dramatically in number and scale globally since the 1950s (Chao, 1995). These structures are built for irrigation purposes, water for human consumption, agricultural use, power generation, land drainage and reclamation, flood mitigation and recreational use (Castelletti, Pianosi, & Soncini-Sessa, 2008; FAO, 2001; Gordon & Meentemeyer, 2006; Hall & Shelby, 2000; Le, Nguyen, Wolanski, Tran, & Haruyama, 2007). These functions are, however, accompanied by environmental changes, to the point that water impounded in artificial reservoirs since the 1950s is by far the most significant anthropogenic hydrological change in terms of water volume (Vörösmarty et al., 2004, 2003).

Artificial wetlands have also become ubiquitous in recent decades, and are a distinctive form of water management system created for the purpose of treating municipal or industrial wastewater, greywater or stormwater, to act as a biofilter and remove pollutants from the water, for land reclamation after mining, refineries, or other ecological disturbances (ElZein, Abdou, & ElGawad, 2016; Zhang, Gersberg, & Keat, 2009). Some of the most dramatic anthropogenic transformations of the Earth's surface occur at the interface between terrestrial and aquatic environments, which include massive and elaborate mechanisms for displacing and managing water. Recent advances in engineering technology have allowed for extensive land reclamation and the creation of artificial islands to provide new spaces for development and to achieve political and strategic objectives (Goudie & Viles, 2016; López-Gutiérrez, & Esteban, 2016).

3.3.7 Refuse disposal

Middens are among the first and most prominent examples of physical remnants of resource exploutation activities in the archaeological record, with potential consequences for a range of related physical and chemical characteristics, for example increased soil alkalinity, and in particular increases in levels of nitrogen, calcium, potassium and manganese (Cook-Patton, Weller, Rick, & Parker, 2014). Middens offer an important archive of information about human dispersal and group diversification because they can be created either at the household level or the community level (Trebsche, 2009). They preserve records that are particularly valuable for the development of interdisciplinary approaches in investigating human-environment interaction, social relations and the role of resource exploitation in the developmental trajectory of human groups (Álvarez, Godino, Balbo, & Madella, 2011; Rick, Erlandson, Vellanoweth, & Braje, 2005). They are also suitable for radiocarbon dating (Brady, 2016). Another widespread remnant of past resource exploitation survives in the form of tells, artificial features (mounds) formed from the accumulation of refuse over millennia of settlement activities (Portal, 2017). Their size and shape carry the fingerprint of diverse cultures, and in the most cases, they are representative of earliest settlement systems, beginning in the Neolithic period (Acacus and Art, 2016; Menze et al., 2006). In modern times, middens and tells evolved as landfills used for waste management and processing waste material in the most cost-efficient way (Stirling, 2015). The physical structure of landfills embodies diverse input characteristics such as aspects of terrain, existing land use, aesthetic value, government regulations, and public opinion about the sites themselves (Sharma, 2010).

3.3.8 Warfare

Landform features have also been created for warfare or defence. These features include artificial structures such as fortifications (Ilyés, 2010; Matos-Machado, Bétard, Bilodeau, Jacquemot, & Amat, 2015; Moss & Erlandson, 1992), trenches (Baer & Ashworth, 1981; Houx, 2001; Power, 2009), IED command wires (McDonald & Schumer, 2016), bunkers and missile silos among others, but also existing underground terrain (Eastler, 2004) or rock defences (Moss & Erlandson, 1992). The most famous example of trench warfare is the Western Front World War I, which has become the classic example of stalemate, attrition and futility in modern conflict (Baer and

Ashworth, 1981). However, this class of features also includes direct geomorphological evidence such as bomb and mine craters (Hupy & Schaetzl, 2006; Kiernan, 2015), uranium mining (Blustain, 2016) or landscape modification due to military structures (Yatsko, 2016). Clearly, conflicts leave a significant topographic signature on the landscapes, and they also result in long-term landscape modifications (Bothe, 2007), with impacts on remoteness and naturalness, or on physical phenomena such as geodiversity (geology, landforms, soils and the natural processes that give rise to them) (Kiernan, 2015).

3.4 Methods: Feature detection

Remote sensing is increasingly used for the analysis of landform changes, both contemporary and historical. The concept of anthropogenic landscapes as sociocultural palimpsests composed of the overlapping sociocultural fingerprints of multiple societies provides a theoretical framework through which to interpret anthropogenic geomorphic features in their landscape contexts. The necessary first stage of this interpretation is the identification and labelling of these features. In the last decade, a range of new remote sensing techniques has led to a dramatic increase in terrain information, providing new opportunities for a better understanding of Earth surface processes based on geomorphic signatures (Tarolli, 2014). Technologies such as LiDAR (see Tarolli 2014 for a review), satellite (Purinton and Bookhagen, 2017), and structure from motion –SfM- (see Eltner et al., 2015; Fonstad, et al., 2013; James and Robson, 2012 for a review) have opened avenues for the analysis of anthropogenic signatures and processes thanks to to high-resolution topography (Tarolli, 2014). In this context, one of the actual challenges is the ability to model the anthropogenic morphologies, quantify them, and analyze the links between anthropogenic elements and geomorphic processes. In the following sections, few examples are provided on how remote sensing data can be used to extract and analyze anthropogenic feature and quantify anthropogenic changes on the surface.

3.4.1 Extraction from imagery

Despite the limitation due to shadowing, angle of incidence or lack of topographic information under vegetation cover (Quartulli and Olaizola, 2013; Sowmya and Trinder, 2000; Mostafa and Abdelhafiz, 2017), archaeologists have made use of radar and satellite images to reveal differences in texture, roughness, moisture content, topography, and geometry of features and surfaces reelated to human activities e.g. (Holcomb, 2001; Fowler, 2002; Ricketson et al., 2003; Holcomb and Shingiray, 2006; Moore et al., 2006; Evans et al., 2007). More recently, images from satellite have been used in relation to anthropogenic features in the context of urban studies [see (Ghanea et al., 2016) for a review], for cadastrial boundary extraction (Crommelinck et al., 2016; Wassie et al., 2017), oil spill detection (Brekke and Solberg, 2005), but also to identify target features in ongoing- and post-humanitarian crisis scenarios (Witharana, 2012; Witharana and Civco, 2012). In analyses of this type, image analysis techniques such as wavelets and fusion algorithms, or texture analyses can enhance localize patterns related to human activities, and they can be used to extract features of interest, such as buildings, but also shelters and war/flood/heartquacke damaged structures. To illustrate this point we show in Fig. 3a Pleiades satellite image. The study area is spatially stratified in environmentally similar land units (Fig. 3d) using image analysis techniques (Fig. 3b, 3c), and, thus, it is possible to identify those areas which are most likely to present anthropogenic landscapes (Fig. 3e). Feature extraction from satellite images is, however, limited by shadows (Mostafa and Abdelhafiz, 2017) and other technical issues such as angle of incidence (Quartulli and Olaizola, 2013; Sowmya and Trinder, 2000). Satellite images, furthermore, cannot be used to extract ground features under vegetation cover.

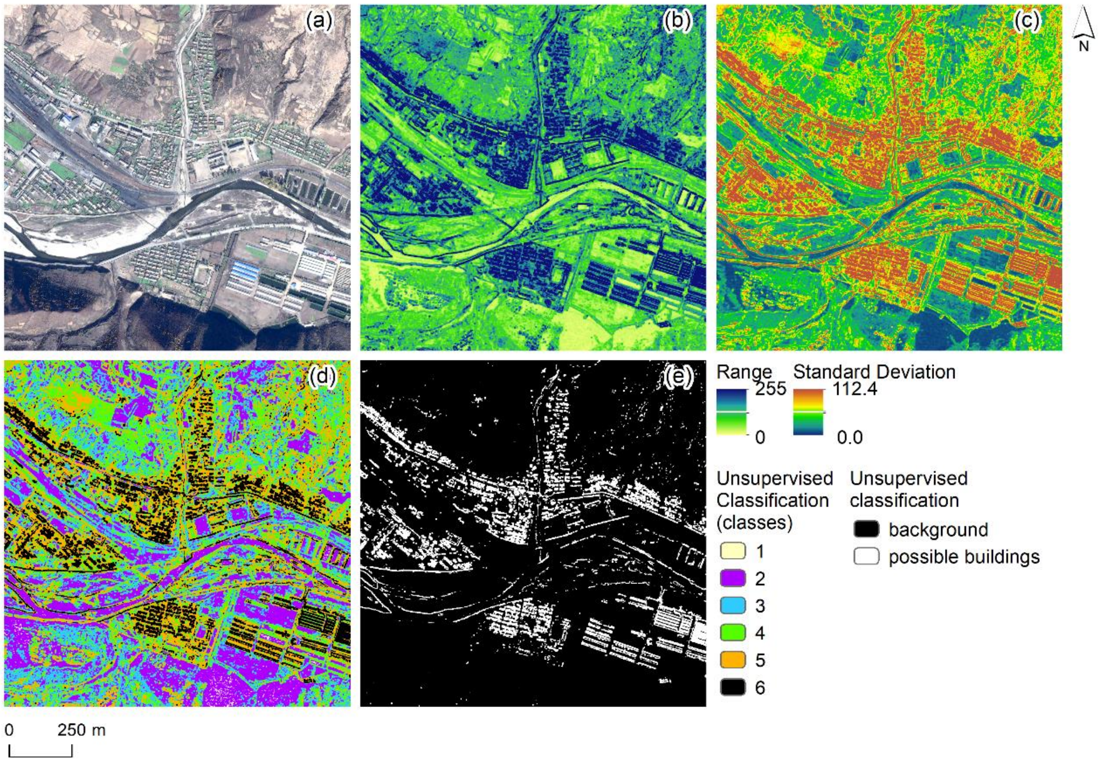

Fig.3.Example of satellite image, derived texture parameters and classification:(a) Pleiades 0.5m satellite image; (b) local range of values (max–min); (c) local standard deviation of values within a 11*11 neighbourhood (Haralick, 1982); (d) iterative optimization clustering procedure implemented by the commercial software ArcGis® (Ball and Hall, 1965; Richards, 2013); (e) extracted buildings.

3.4.2 Extraction from 3D surfaces

A further step in feature extraction is allowed by the availability of 3D models (Digital Terrain Models -DEMs). When DEMs is available, the most straightforward approach to anthropogenic feature analysis is visualization, namely the use of hillshade or shaded-relief maps (Fig.4a) e.g. (Bennett, Welham, Hill, & Ford, 2012; Chase et al., 2014; Deforce et al., 2013; Doneus, Briese, Fera, & Janner, 2008; Golden et al., 2016; Harmon, Leone, Prince, & Snyder, 2006; Johnson & Ouimet, 2016, 2018; Menze, Ur, & Sherratt, 2006; Risbøl et al., 2013; Tapete et al., 2017).

This approach simulates lights and shadows to enhance the presence of features captured by the input dataset. Slightly more advanced techniques, based on compound approaches, have been also developed, such as the sky view factor (Fig.4b) (Bennett et al., 2012; Devereux et al., 2008; Kennelly, 2008; Štular, et al., 2012) or advanced analysis of hillshades (O'Neal, 2012). The advanced use of topographic parameters directly derived from the DEMs allows for the visualization, but also for the classification of anthropogenic features. The most direct and straightforward approach is offered by the so-called “detrending” techniques. Data are filtered using ‘low pass’ filters, resulting in a smoothed surface to subtract from a lidar DEM (Fig.4c), for example (Cazorzi, et al., 2013; Hesse, 2010; Howey, et al., 2016; Luscombe et al., 2015; Schindling and Gibbes, 2014; Sofia et al., 2014). As the *z* values in the detrended data represent the height difference from a smoothed surface, peak values in either the positive or negative domain (depending on the approach) highlight the microtopographic element in the landscape, such as drainage features or pits, or walls. Further useful topographic parameters can be used such as slope (Fig. 4d), e.g. (McCoy, et al., 2011; Riley, 2012), slope and exposure also under water surface (Cappucci et al., 2017), curvature (Fig.4e) e.g. (Drăguţ and Blaschke, 2006; Sofia, et al., 2016; Tarolli, et al., 2014). Recent literature has highlighted how image processing local filters can also be applied to a DEM to detect high-frequency variations (e.g. Laplacian –Fig.4f- , Sobel's filters, SLLAC –Slope Local Length of Correlation-) (Sofia, et al., 2014; Sofia, et al., 2016; Stal et al., 2010; Štular et al., 2012).

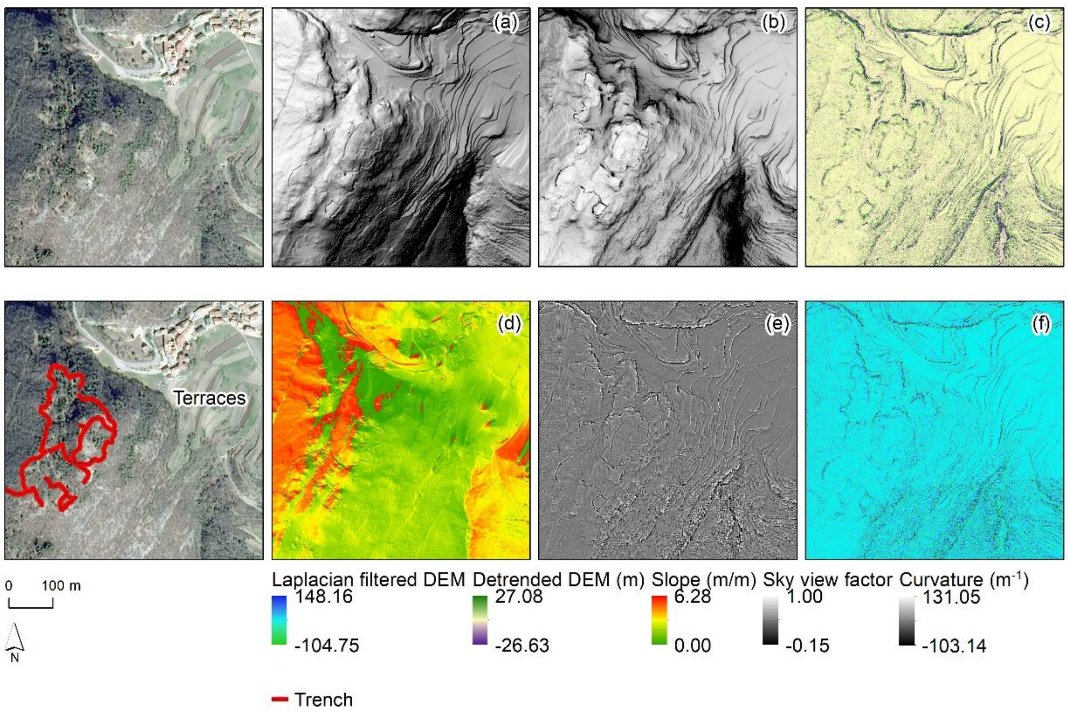

Fig. 4 WWI trenches and terraces: (a) hillshade; (b) sky-view factor; (c) detrended Digital Terrain Model (DEM); (d) slope; (e) curvature; (f) Laplacian filtered DEM.

These enhancing techniques can be applied to segment and detect anthropogenic patterns and features thanks to GEOBIA (GEOgraphic-Object-Based Image Analysis) (see (see Blaschke et al., 2014; Cerrillo-Cuenca, 2017; Diaz-Varela et al., 2014; Eckert et al., 2017; Hay and Castilla, 2008), or automatic thresholding (e.g. Fig. 5).

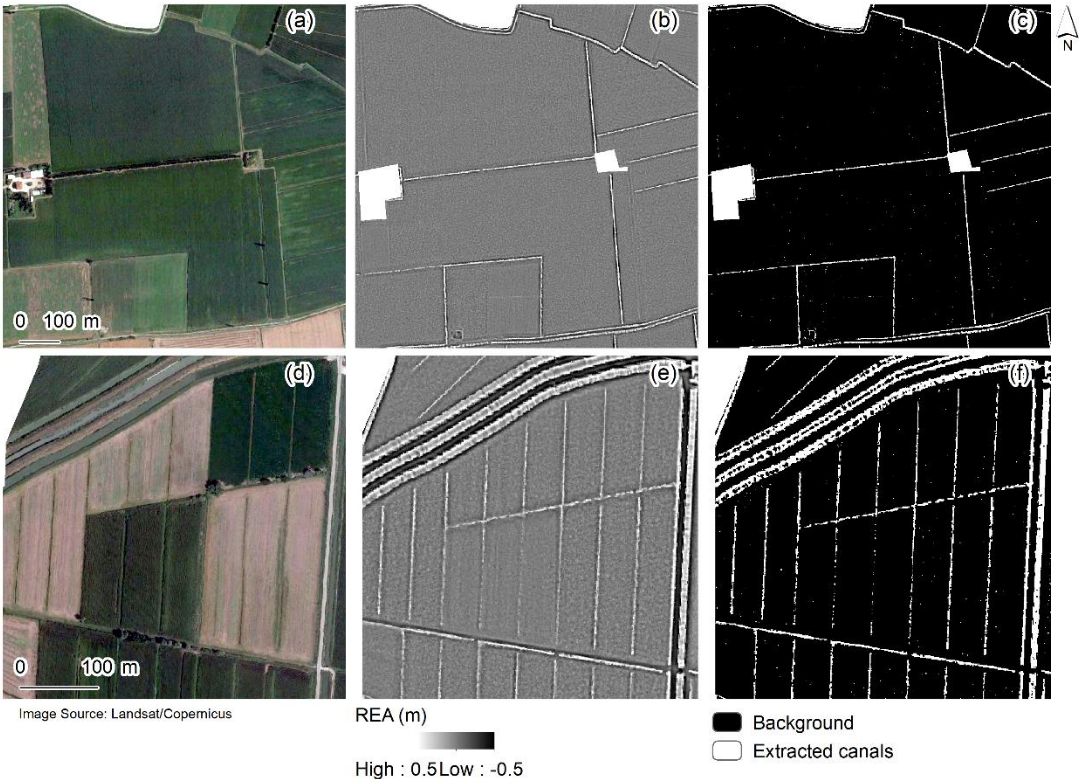

Fig. 5 Agricultural practices in northeastern Italy ((a) tobacco; (d) corn). Detrended Digital Terrain Model (REA, Cazorzi et al., 2013) (b), (e) and ditches derived automatically by applying a statistical threshold (standard deviation of Relative Elevation Attribute (REA)) (c), (f).

3.4.3 Quantitative assessment of features

Extractions carried out with thresholding or object-oriented approaches, although able to detect the two-dimensional location of anthropogenic elements, are not able to quantify whether or not they are continuous features in the landscape. Nevertheless, they can offer the basis for further evaluations of lengths, densities and volumes, for example (Sofia et al., 2014; Sofia and Tarolli, 2017), or the extent of 2D features. Additionally, high-res DEMs can offer the basis to measure the shape and sizes of anthropogenic elements directly in the digital realm (Johnson and Ouimet, 2016; Sofia et al., 2016). A further step in anthropogenic features characterization is offered by change detection techniques or time-series data analysis, that has gained significant attention due to its capability of providing volumetric and extent measures in time (see Qin et al. 2016 for a review). These techniques rely on the availability of multitemporal datasets, real or simulated, to be used to compare anthropogenic features in time (Haas et al., 2016; Prosdocimi et al., 2015; Wróżyński et al., 2017; Yucel and Turan, 2016). Fig. 6 shows an example of geomorphic change detection evaluated considering the (Wheaton et al., 2010) approach. For this area, multitemporal orthophotos (Fig.6a and Fig.6d) and Lidar DEMs (Fig.6b and Fig.6e) are freely available (Institut Cartografic De Catalunya (ICC), 2005; Institut Cartographic de Catalunya (ICC), 2008) for the year 2005 and 2008. From these maps, it is possible to compute a volumetric difference (Fig.6c) keeping into account the errors that might be present in the DEMs themselves (see Lane et al. 2003 for specification on the method).

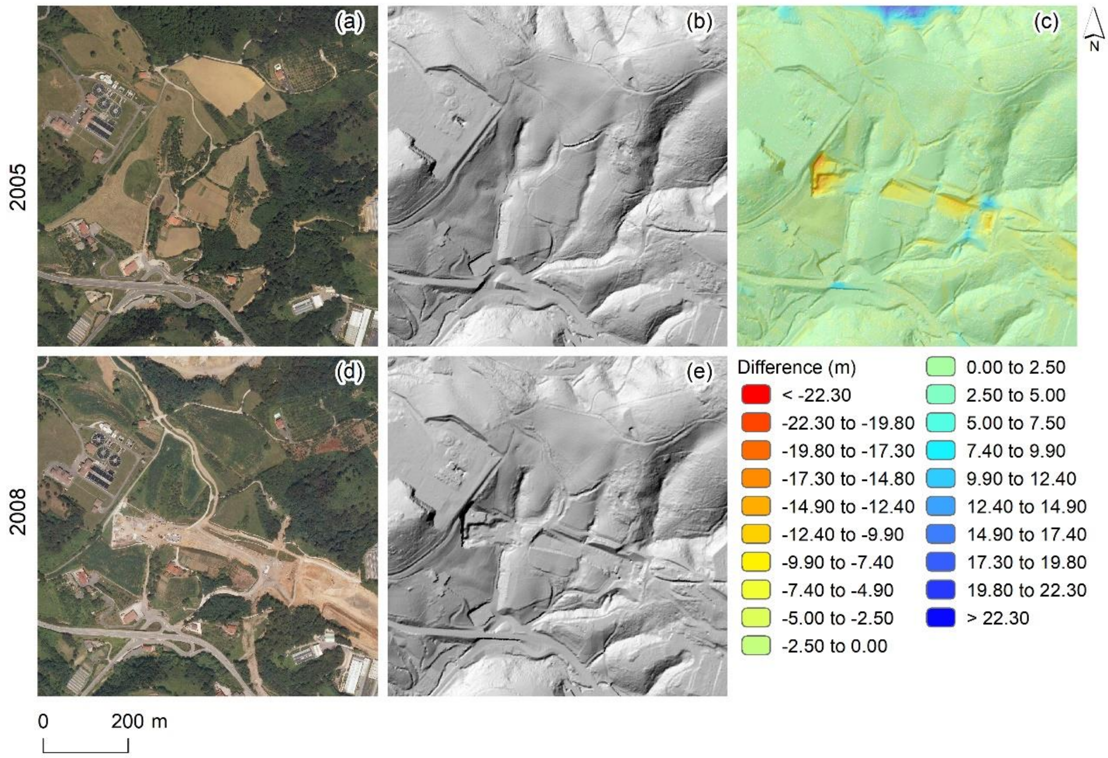

Fig. 6. Example of change of detection from LiDAR Digital Terrain Model (DEM). Orthophotos for the year 2005 (a) and 2008 (c), LiDAR DEM in 2005 (b) and 2008 (e) and derived change of detection in m (c).

3.4.4 Limits and merits

Improvements in spectral, spatial and temporal resolution are revealing more and more rich and detailed information to decipher landscape palimpsests. The synoptic view offered by compound analyses integrating satellite, airborne and photogrammetry enable integrated landscape investigations across scales in terms of resolution and coverage, from small features to entire regions, and comparisons across and within regions, and long time series allow monitoring and diachronic analysis of changes in landforms. Recent availability of wide-area, high-resolution LiDAR is revolutionizing these efforts, owing to its unique capability to penetrate vegetation canopies and identify earthwork features at high spatial resolutions even under dense vegetation cover. Challenges remain for using these data to detect anthropogenic features and their distributions across landscapes and regions. A better understanding of the representation of anthropogenic features within the data itself will be critical, combined with improvements in processing techniques that make analyses of vast quantities of data more manageable. Moreover, each study presents its own challenges. For example, traces of ancient ruins and infrastructures might lie below relatively modern roads, buildings and agricultural fields, or ancient structures might be made of the same material that underlies a whole study area. A further impediment to reliable feature identification is that long-term exposure to natural environmental processes, such as erosion and sediment deposition, can make anthropogenic features extremely difficult to distinguish from natural ones (Liu et al., 2017). A clear example of this is the effect of natural weathering processes on landfills or tells: ancient mounds nowadays might resemble natural hillslopes, and modern landfills will, over time, tend to smooth out to the same level as the surrounding land surface. Developments in computer science and statistics offer a wide range of powerful tools to augment the detection and interpretation of anthropogenic features, and potentially the sociocultural fingerprints of entire societies across large regions. These tools include advanced systems for geographic information systems (GISs), 3D modelling, predictive modelling, visualization, simulations and machine learning (e.g. Guyot et al., 2018). Ironically, however, there remains no standard ontological framework within which to classify and understand anthropogenic landscapes and the features within them, despite their coverage of the vast majority of Earth’s terrestrial surface (Ellis et al., 2013). By developing standardized frameworks for feature and fingerprint detection and interpretation, and ultimately by automating these, rapidly expanding Earth coverage by high-resolution 3D remote sensing can be utilized to examine Earth's global geomorphic transformation by human societies, together with a wide range of other useful societal applications (Tarolli et al., 2017).

3.5 Decoding palimpsests: From features to fingerprints

Few existing landforms are formed solely through natural or anthropogenic geomorphic processes operating at the current time. Mostly, landforms are palimpsests incorporating multiple layers formed by different processes at different times, written and rewritten repeatedly by various combinations of natural and anthropogenic processes (Johnson & Ouimet, 2018). In any given region therefore, complex overlapping topographic signatures can be observed. Some landform features might be very young because they are currently being shaped, but they may also bear the signature of history under specific social conditions or processes that are no longer present in that region (e.g. road networks and centuriation). Some other features may be entirely 'relictual' because they were formed at some point in the past when social conditions, processes or environments were different or operated at a different magnitude to those of the present time.

While many researchers emphasize the importance of digital landscapes to identify anthropogenic features, they rarely observe or interpret these features across the scales of time or space in which the societies that formed them operated. Here is the central challenge of anthropogenic geomorphology: to interpret anthropogenic features as diagnostic fingerprints of the societies that formed them, in relation to their social processes and their changes across the entirety of the regions where these societies have operated. To meet this challenge requires an integrated social-geophysical approach combining the theories, frameworks and methods of geomorphology, archaeology, and ecology.

3.5.1 General principles of sociocultural landscape formation

The first principle of anthropogenic geomorphology is that the sociocultural processes that form anthropogenic landforms are fundamentally different to natural processes like erosion or deposition. Even though natural and anthropogenic geomorphic features may share real similarities in form and even function (Fig. 7), the processes forming them are fundamentally different. Unlike the forces of gravity, hydrology and geophysics, which have not changed since the formation of this planet, the forces of landscape change generated by human societies can and have changed dramatically over time, together with societies themselves (Fig.s 1 and 8).

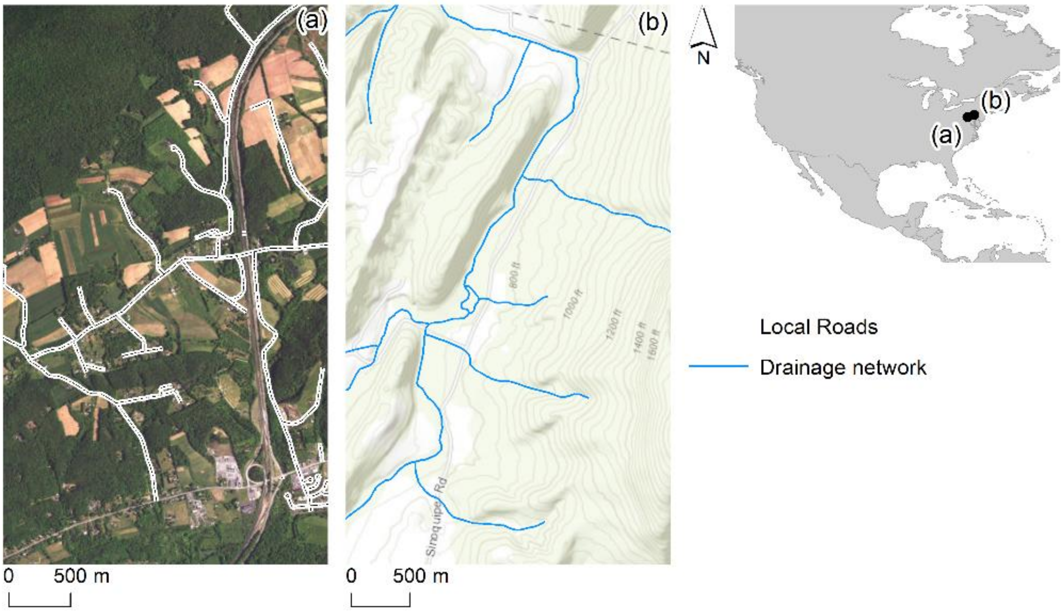

Fig. 7. Example of similarity between anthropogenic and natural features: (a) local road network; (b) flowlines in Pennsylvania (USA).

The first step towards a process-based understanding of anthropogenic geomorphology is therefore the development of a timeline of known sociocultural changes across the landscape of interest, with the aim of understanding the historical layering of anthropogenic features, together with a timeline of major natural environmental changes and events, including major changes in precipitation, floods, tectonic and volcanic activity that have interacted with anthropogenic processes in forming the landscape under observation. This basic timeline should include a catalogue of the types of anthropogenic features created by different societies, including any geometric, symbolic or other cultural identifiers that can assist in reconstructing the layers of anthropogenic features produced across landscapes during specific periods of time. By combining social geomorphologic timelines with detailed spatial data on landform structure, the spatial patterning of anthropogenic features and landforms may be understood in terms of the sociocultural and natural processes that have formed them.
While the full range of sociocultural patterns, processes and dynamics observed across

human societies (Fig. 1) is far larger than those occurring within any particular landscape, Fig. 1 illustrates that anthropogenic geomorphic practices can be completely different in different societies, and that larger, more complex societies tend to engage in a larger number of different types of anthropogenic geomorphic practices and that the size of geomorphic features is also associated with societal scales (larger scale societies are generally capable of producing larger scale features). As the features of earlier societies can be added to by societies that come later, the total number of different types of anthropogenic features should be expected generally to increase over time, although the removal, destruction and overwriting of earlier features by later societies can erase or reduce the accumulation of landform complexity, as can erosion and other natural processes.

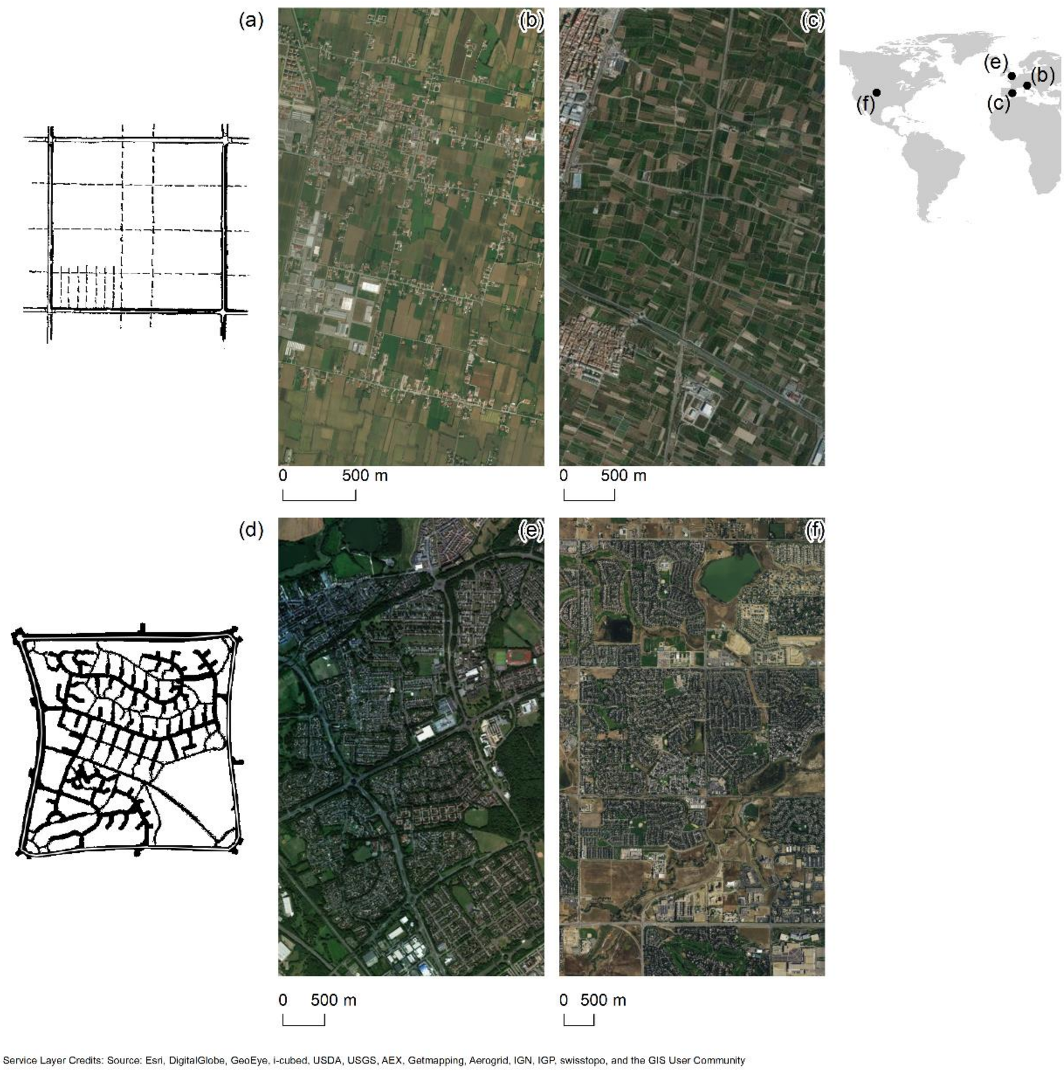

Fig. 8. Different patterns (a), (d) highlight different cultural settings. Roman

centuriation of an area near Padua (Italy (b)) and Valencia (Spain (c)), and modern residential areas in Milton Keynes (UK (e)) and Boulder (USA (f)).

A second principle of anthropogenic features and landforms is that their constituent materials may differ dramatically from those found naturally within a specific landscape or region (Zalasiewicz et al., 2017). The presence and composition of these materials, from stone, wood and other materials distinct from local materials and transported from other areas, to bricks, concrete, steel and other materials produced exclusively by human societies, and the presence and spatial organization of anthropogenic materials can be diagnostic of anthropogenic geomorphology – and detectable using remote sensing. The use of anthropogenic materials also enables the construction of anthropogenic features without natural analogues, from buildings to highway overpasses. As with feature types and sizes, the number of different types of materials utilized in feature construction also tends to increase with societal scale, with larger scale societies generally deploying a greater number of novel materials across anthropogenic landscapes.

A third principle of anthropogenic geomorphology is that within the regions influenced by a given society, the sociocultural functions that create anthropogenic features are not homogeneous, but rather differ across space in relation to both social and natural patterns. For example, within agrarian societies, there are often distinct clusters of housing, connected by paths and roads, with agricultural fields and irrigation systems in the flatter lands in between, with less used areas on hillslopes. Larger scale urban societies show similar social patterns, but these may operate at much larger scales, and even globally at the present time. These patterns are aligned with the broader model of human sociocultural niche construction (Ellis, 2015), as modified and illustrated by the state equation:

Anthropogenic landforms = f(biome, terrain, societies, centrality, time).

This model describes the anthropogenic landforms produced in a given location in terms of its general biogeophysical conditions (biome, e.g. desert, savannah, rainforest), the specific terrain (terrain, e.g. floodplain, hillslope, mountain top), the societies that have operated at the location, the social position within the societies' operating spaces (social centrality, i.e. the travel distance from social centres, such as villages, towns and cities, the opposite of remoteness) and the amount of time over which the anthropogenic processes have operated. Based on this simple conceptual model, the types of features present within a specific location are contextualized both within the social space of the societies operating across a given site or region, with anthropogenic features produced by habitation expected to occur at high frequencies in areas of high social centrality, with transport features interconnecting these, while subsistence, mining, refuse, water infrastructure and other anthropogenic features are distributed in relation to suitable terrain and distance from social centres. In smaller scale societies, these functions and features tend to be tightly clustered in space, sometimes with the exception of symbolic and mining features, while larger scale societies tend to distribute these functions and features more widely, even globally. By combining these general principles of sociocultural landscape formation in relation to underlying biogeophysical conditions, the spatial patterning of anthropogenic features and landforms can be understood as the sociocultural fingerprints of the societies that have constructed them.

3.5.2 From features to fingerprints

Although anthropogenic features can increasingly be detected through remote sensing and distinguished from natural features as a function of their shape and material composition, a separate process of anthropogenic landscape interpretation is needed to understand their sociocultural and functional identity and their relation to the sociocultural processes that formed them – the basis both for feature classification and labelling and for the interpretation of features across landscapes and regions to identify the sociocultural fingerprints of societies. Automated feature classification is now increasingly capable of identifying classes of relatively homogeneous 3D entities (Fig. 3(d)), but without further understanding of their sociocultural functions, such as habitation, symbolic culture or water infrastructure, these classifications remain purely geometric, and feature shape can at times be an unreliable indicator of function. Nevertheless, there is growing technological capacity for defining feature templates describing the geometry of specific anthropogenic feature classes, thereby enabling automated feature function identification and labelling using template matching (Schneider et al., 2015), object-oriented techniques (Blaschke et al., 2014) and/or machine learning approaches (Valentine and Kalnins, 2016). There is great promise in using these and other methods, including supervised feature classification leveraging spectral and geometric signatures developed by archaeologists and physical geographers with knowledge of the social geomorphic timeline of a given landscape and its associated anthropogenic features, to train automated procedures to identify specific functional forms of anthropogenic features, such as buildings (Fig. 3(e)). Caution is necessary, however, as natural landforms can have similar shapes to anthropogenic features: for example, a hearth-pit, a bomb crater and a karstic sinkhole might all have very similar geometry.

The confusion of natural and anthropogenic patterns across landscapes can present similar challenges to the automated analysis of sociocultural fingerprints. A wide variety of natural spatial features have been shown to be statistically self-similar over many scales, suggesting that fractal patterns are a signature of natural geomorphic patterns (Goodchild and Mark, 1987; Rodriguez-Iturbe and Rinaldo, 1997; Tarboton et al., 1988). For example, road networks can assume dendritic forms very similar to those of river networks (Fig. 7), and agricultural terraces can resemble river terraces.

Yet, built-up environments may also possess similar structures at several different scales (Batty, 2008; Batty and Longley, 1994; Frankhauser, 2008; Thomas et al., 2008). Road networks, for example, are inherently fractal (Liu et al., 2014). Nevertheless, patterns of statistical self-similarity may yet prove capable of identifying differences between natural geomorphology and sociocultural fingerprints by developing rule-based systems for the classification of spatial-scale dependence of largescale geomorphic patterns (Jiang and Brandt, 2016). The automated detection of larger scale patterns by aggregate assessment of feature composition and configuration across space through deep learning algorithms offers a clear way forward, analogous to progress with automated fingerprint detection in forensics (Schmidhuber, 2015).

3.5.3 A way forward

The future of anthropogenic geomorphology will depend on a level of integration between theory and methodology that goes far beyond what we have presented here. Nevertheless, the way forward is clear, requiring a focus on the broader sociocultural, spatial and temporal contexts of anthropogenic landscape formation, rather than the mere presence or absence of specific anthropogenic features. Analyzing the spatial structuring of features across landscapes in relation to the sociocultural and material systems that have shaped them can be essential to determine whether features have originated naturally, have anthropogenic origins or have emerged through the interplay of social and natural processes. One example of this broader focus on sociocultural fingerprints is the differential patterning of urban landscapes around the world (Fig. 8). Centuriation (Fig. 8(a)) is typical of regions historically conquered by Romans (such as

Italy (Fig. 8(b) and Spain Fig. 8(c)). In such cases, the city/agriculture follows a grid traced by extending the ancient Roman roads (Cardo Maximus and the Decumanus Maximus of the ancient cities) into the surrounding agricultural land. Parallel secondary roads were then traced on both sides of the initial axes, dividing the territory into square areas. Residential areas within modern cities present a different structure (Fig. 8(d)), where similar patterns are produced by street geometry adapted to exclude traffic at the local street level and facilitate flow at the collector and arterial levels. In such systems, major internal roads run between communities, rather than through them, and they create grid squares where the road network uses cul-de-sac streets complemented by (for example) bike and footpaths that connect the entire sector and beyond.

Other examples of sociocultural fingerprints include the spatial patterning of waste disposal sites from informal middens to the regionally planned systems of larger scale societies (Sharma, 2010), the integration of green spaces into cities, the development of "agro-urban landscapes" integrating traditional agrarian landscape patterns within contemporary urban/ industrial developments (Cavallo et al., 2016; Evans, 2016; Seto and Fragkias, 2005) and the spread of road networks (Corcoran et al., 2013; Strano et al., 2012). Even more detailed understanding of the functional roles of anthropogenic geomorphology can even enable the detection of specific cultivation practices. For example, different patterns of ditch networks (Fig.s 5(c) and (f)) support different cultivation practices (e.g. tobacco (Fig. 5(a) and corn Fig. 5(d)), and identifying these patterns requires a deeper understanding of the sociocultural practices of the societies that formed and/ or operated them. Such an understanding, formed through careful reconstructions of the material cultures of societies across sites, is at the core of much archaeological research (Butzer, 1982b; David and Thomas, 2016). As the spatial and social scale of societies has increased, so have their capacities to reshape landforms locally, regionally and globally. Evidence already supports the hypothesis that anthropogenic transformations of land surface processes now move more of Earth's surface than any pre-existing natural process (Wilkinson and McElroy, 2007; Zalasiewicz et al., 2017). Yet, these broad estimates of anthropogenic global change demand to be assessed with the greater precision and spatial context made possible by high-resolution reconstructions of anthropogenic geomorphic changes at local and regional scales. These measurement capabilities, for example the computation of volumetric changes caused by anthropogenic reshaping of landforms (e.g. Fig. 6(c)), are only increasing as a result of advances in sensor systems, computational technology and large-scale data sharing, making the prospect of quantifying processes of anthropogenic geomorphic change globally over the long term a real possibility (Tarolli et al., 2017). The prospect of global assessment of anthropogenic geomorphology is illustrated in Fig. 9, examining a suite of sites around the world in which anthropogenic geomorphology has been mapped using satellite and LiDAR data available to the public as free open-data or as samples. Given that different uses of land are expected to shape different landforms differently (e.g. Sofia et al., 2014b), stratifying these observations in relation to global patterns of land use, such as the anthropogenic biomes (Fig. 9), may offer a general sampling framework for the global mapping and quantification of anthropogenic geomorphic change.

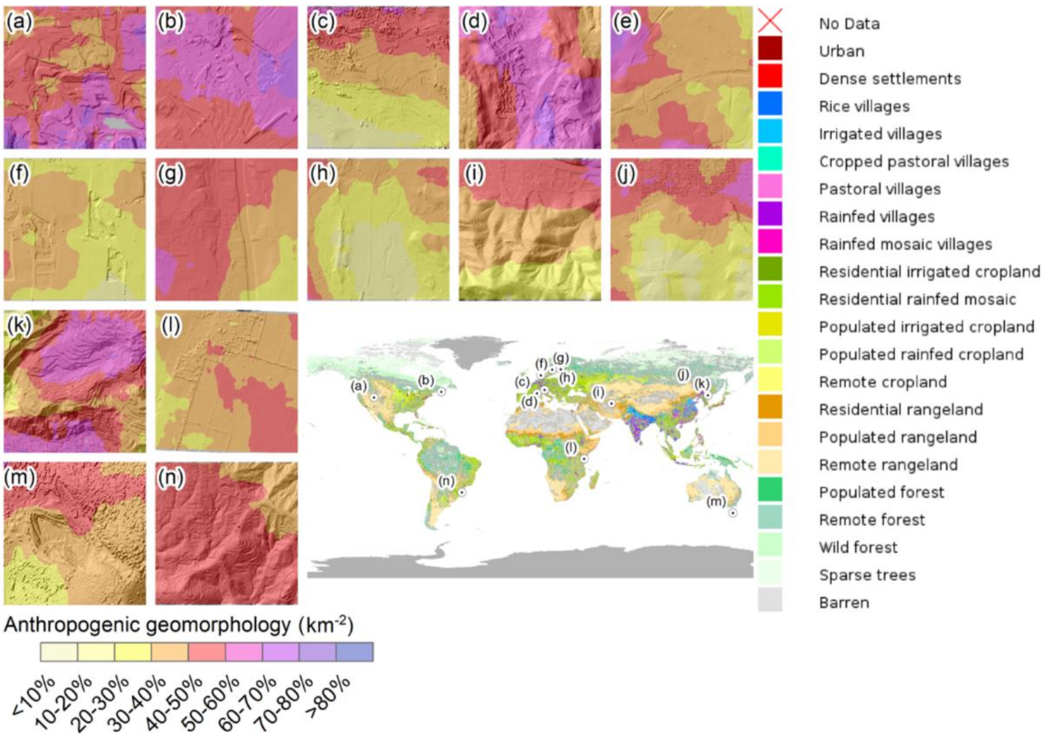

Fig. 9. Local-scale percentage of anthropogenic geomorphology, as compared to anthropogenic biomes (Ellis and Ramankutty, 2008). Dataset credit: (a) Minnesota Geospatial Information Office (MnTOPO®); (b) Halifax Regional Municipality – Canada; (d) Autonomous Province of Trento (Provincia Autonoma di Trento, Italy); (e) Department of Environment, Food and Rural Affairs, UK; (f) Sturelsen for Dataforsyning og Effektivisering; (g) National Land Survey Finland; (h) Sample data by the Lantmateriet (Sweden); (c),(i), (j), (k), (l) data from CNES© Distribution Airbus

DS; (m) TERN© AusCover; (n) Open Topography Facility with support from the National Science Foundation under NSF Award Numbers 0930731 & 0930643 FAPESP grant 2009/17675-5.

Anthropogenic geomorphology forms just one of many layers of the evolving geomorphic palimpsests that now cover most of Earth's dynamic terrestrial surface. Through a systematic assessment of anthropogenic geomorphology around the world and across time periods, it may yet be possible to develop a more general framework, perhaps even a predictive theory, on the geomorphological niche of societies, uniting the analysis of distinct geomorphic features to assess the evolving sociocultural fingerprints of societal change.

3.6 Concluding remarks

Human society, through millennia, have reshaped Earth's geomorphology to produce distinctive anthropogenic features. On the one hand, these features directly or indirectly alter Earth surface processes. On the other, they reflect the sociocultural conditions of different societies. As a result, both archeological and contemporary site assessments provide a wealth of diverse anthropogenic geomorphic features that can serve as diagnostic signatures, or 'sociocultural fingerprints' of the societies that formed them, including their interaction and communication with other societies. This paper offers a general framework aimed at integrating geophysical and archaeological approaches to observe, identify, and interpret anthropogenic geomorphic features, based on their societal structure and functioning. By introducing the concept of 'sociocultural fingerprints', we connect the novel Earth system processes introduced by the emergence and evolution of human societies with their continuous shaping and reshaping of Earth's geomorphology from the deep past into the foreseeable future. Building on this concept, we underline the opportunity to recognize the geomorphic signatures of sociocultural fingerprints across Earth's land surface using high-resolution remote sensing approaches combined with an empirical and theoretical framework that integrates the natural and sociocultural forces that have and will shape the landscapes of the Anthropocene. By engaging these frameworks together, the long-term dynamics of anthropogenic landscapes can be more effectively investigated and understood, towards more sustainable management of the Earth system, including its hydrosphere and lithosphere, into the deep future.

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CHAPTER 4

GEOMORPHOMETRIC CHARACTERISATION OF NATURAL AND ANTHROPOGENIC LAND COVERS[3]

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4.1 Abstract

The scientific community has widely discussed the role of abiotic and biotic forces in reshaping the Earth's surface. Currently, the literature is debating the topographical signatures produced by humans. Apart from the influence of humans on processes, does the resulting landscape bear an unmistakable signature of anthropogenic activities? This research analyses from a statistical point of view the morphological signature of anthropogenic and natural land covers in different topographic context, as a fundamental challenge in the emerging debate of human-environment relationships and the modelling of global environmental change. It aims to explore how intrinsically small-scale processes, related to land-use, can influence the form of entire landscapes, and to determine whether these processes create a distinctive topography. The work focusses on four study areas in floodplains, plain to hilly, hills and mountains, for which LiDAR-derived Digital Terrain Models (DTMs) are available. Surface morphology is described with different geomorphometric parameters (slope, mean curvature and surface peak curvature) and their frequency distribution. The results show that the distribution of geomorphometric indices can reveal anthropogenic land covers and landscapes. In most cases, different land covers show statistically significant differences ($p<0.05$) in their morphology. Finally, this study demonstrates the possibility to use a geomorphic analysis to quantify anthropogenic impact based on land covers in different landscape contexts. This provides useful insight into understanding the impact of human activities on the present morphology and offers a comprehensive understanding of coupling human-land interaction from a geomorphological point of view.

Keywords: Geomorphology, Geomorphometry, Anthropogenic impact, Land cover

4.2 Introduction

Landforms represent the long-term development of geologic and geomorphologic processes (Bolongaro-Crevenna et al. 2005; Oldroyd and Grapes 2008; Kleman et al. 2016). They tend to reflect the interaction of climate, tectonics, erosion and deposition (Castelltort et al. 2015; Zhang et al. 2016; Marshall et al. 2017). An increasing amount of the research (Szabó et al. 2010; Ellis et al. 2013; Goudie and Viles 2016; Tarolli and Sofia 2016; Brown et al. 2017; Migoń and Latocha 2018; Tarolli et al. 2018; Tarolli et al. 2019) has pointed out that human activity has played a pivotal role as topographic forcing. For instance, the cultivation of agriculture is susceptible to accelerated soil erosion (Tóth 2010; Curebal et al. 2015; Tarolli et al. 2015), dams and reservoirs engineering interrupt the continuity of sediment transport in rivers system (Tessler et al. 2016; Wang et al. 2016; Poeppl et al. 2017), road network construction associates with slope stability of road cuts as well as other geological risks (Csima 2010; Chen et al. 2015; Sofia et al. 2016).

With this literature, the concept of surface reshaping from both abiotic and biotic forces has emerged (Ellis 2004; Steiger and Corenblit 2012; Pietrasiak et al. 2014; Tarolli and Sofia 2016). As suggested by Dietrich and Perron (2006), small-scale biotic processes can influence the form of landscapes, and create a distinctive topography, but this has yet to be investigated for human-made landforms. Identifying natural and anthropogenic features and further distinguishing the landform signatures still poses a significant challenge for the geomorphological community (Tarolli et al. 2019). Thanks to the progress in remote sensing techniques and open-access datasets, the recognition of large-scale geomorphic signatures is now possible at various scales (Evans 1980; Hooke 2012; Nagel et al. 2014; Sofia et al. 2014a; Tarolli 2014; Byun and Seong 2015; Jordan et al. 2016; Niculiță, 2020). However, an explicit characterisation, from a morphological point of view, of natural and anthropogenic surfaces and for different landscape contexts is still missing. This study showcases how high-resolution topographic data can offer the basis to 1) characterise specific signatures with land covers on the basis of an objective geomorphometric analysis; 2) demonstrate that the anthropogenic and natural land covers show a statistically different underlining morphology, and 3) understand (where present) the degree of anthropogenic impact due to the various land covers.

Since a significant concern is how natural systems are being modified or transformed by anthropogenic land uses, one crucial issue is how the different land surface should be disaggregated for modelling and further analysis, and if any generic relationships can be identified between land uses and morphological transformations to the landscape. Geosciences must advance towards empirical and theoretical frameworks that integrate the natural and sociocultural forces that are now among the leading shapers of Earth's surface processes (Tarolli et al. 2019) to understand the causes and consequences of these transformations and contribute to building a sustainable future. This work offers an example of such an empirical framework, providing a diagnostic tool to infer objectively morphological differences within various landscapes. Processes happen in three-dimension and observing the topographic differences among land covers offer a basis to potentially infer differences in the processes happening in these landscapes (Tarolli et al. 2017).

4.3 Study area

This study investigates four study areas of 10 x 10 km in northeastern Italy, representing different landscapes, from floodplains to mountains (Fig. 1): the Veneto floodplain (floodplain, Fig. 1 a), Colli Euganei (plain to hilly, Fig. 1b), Venetian Prealps (hilly, Fig. 1c) and Trentino (alpine mountains, Fig. 1d). These sites were selected because they share close geographic locations and distributions of land covers, but they differ in landforms.

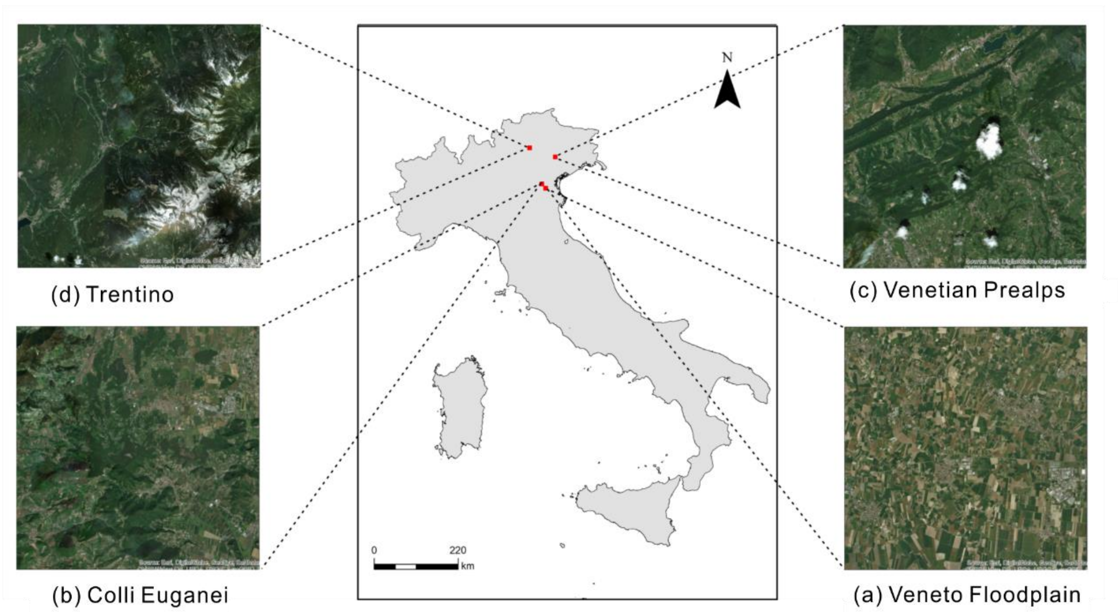

Fig.1 Considered study areas (a) floodplain (b) plain to hilly (c) hilly (d) mountain

The elevations in Veneto floodplain (Fig. 1a) range from -2 m to 10 m a.s.l., with an average of 4 m a.s.l. 75% of the area has a height lower than 5 m a.s.l. This area is characterized by a higher level of anthropogenic pressure, especially agricultural landscapes, due to urbanisation and industrialisation. The area is intensively drained for reclamation and irrigation purposes through a dense network of channels and ditches (Fig. 2a). The plain to hilly area (Fig. 1b) has an elevation ranging from 0.4 m to 601 m a.s.l. (average 112 m a.s.l.). 78% of the area has a height lower than 200m a.s.l. These hills are of volcanic origins and rise between 300 m to 600 m. Vineyard cultivation is widespread in this area (Fig. 2b). The elevation in hilly area (Fig. 1c) ranges between 88 m a.s.l to 889 m a.s.l. (average 251 m a.s.l.) 95% of the area concentrated on the height between 100 m a.s.l. and 500 m a.s.l. As in the Euganei, vineyard is also a typical characteristic of this area (Fig. 2c). The fourth area (Figs. 1d and 2d) is an alpine landscape. The elevation ranges from 541 m to 2,488 m a.s.l. with a mean value of 1,577 m a.s.l. 80% of the area has the height from 1,000 m a.s.l. to 2,000 m a.s.l.

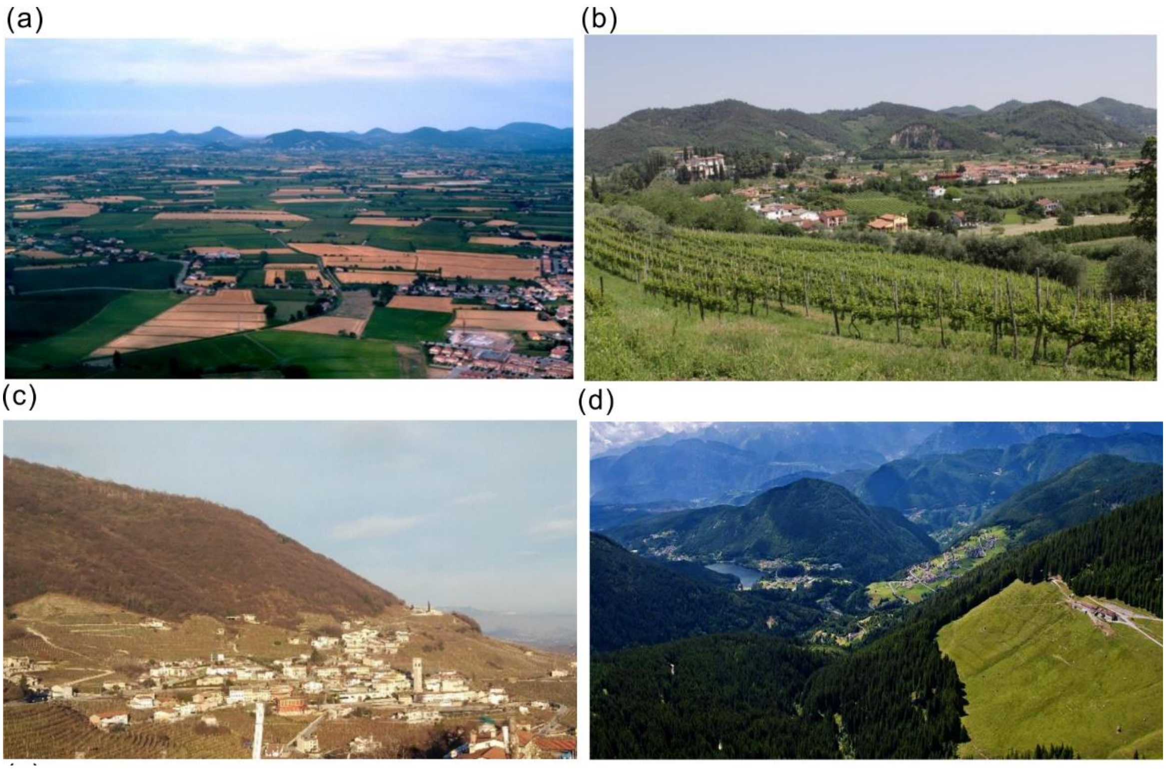

Fig. 2 The field overview of study areas (a) floodplain (b) plain to hilly (c) hilly (d) mountain (photo in 2a by P. Claudio; photo in 2b by M. Luca; photo in 2c by B. Eros, photo in 2d from www.abfotografia.it).

4.4 Method

4.4.1 Data

Light Detection and Ranging derived Digital Terrain Models (DTMs) at 2-meter resolution (Fig. 3) are available thanks to public authorities in Italy (Italian Ministry for Environment, Land and Sea; Treviso Province; Trentino Alto-Adige Autonomous Region). The datasets refer to the year's range 2010–2012.

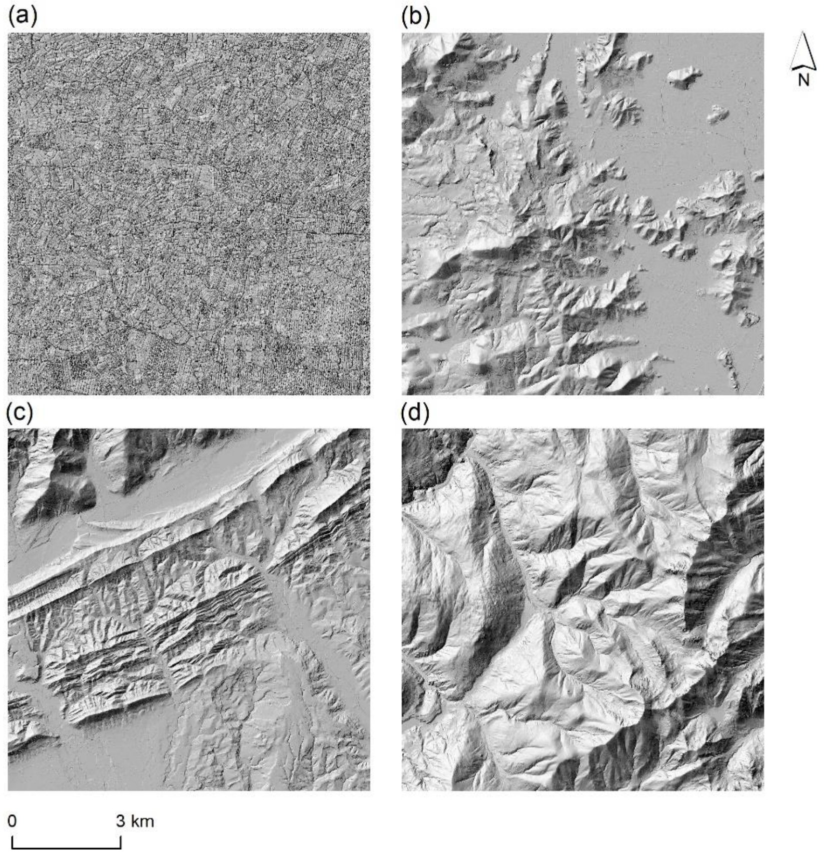

Fig.3 LiDAR DTMs of the study areas (a) floodplain (b) plain to hilly (c) hilly (d) mountain

Information about land cover is available through the Corine-Land-Cover database (CLC, Coordination of Information on the Environment Land Cover) classification, as also reported by the local authorities (Direzione Pianificazione Territoriale 2012). The considered CLC data come from an updated version of the Urban Atlas (European Environment Agency 2012) provided by the local government (Regione del Veneto, 2012). The original Urban Atlas is mainly based on the combination of statistical image classification and visual interpretation of Very High Resolution (VHR) satellite imagery. Multispectral SPOT 5 & 6 and Formosat-2 pan-sharpened imagery with a 2 to 2.5m spatial resolution is used as input data. The built-up classes are combined with density information on the level of sealed soil derived from the High-Resolution Layer imperviousness to provide more detail in the density of the urban fabric (European Environment Agency, 2012). The updated version was enriched by the local government (Regione del Veneto) with functional information (road network, services, utilities…) using ancillary data sources such as regional cartography, forest inventories, road network graphs, aerial photographs, and ground-surveys.

For the purpose of this work, we focused on artificial surfaces, agriculture and forest (level 1 of the CLC classification). However, due to the large-scale cultivation of vineyard in the plain to hilly and hilly areas, which we expect to have a significant impact on the morphology of the surfaces, we defined vineyard as an independent classification from agriculture. As well, we considered grass as an independent land cover because it may occur naturally or as the result of human activity (pastures, park and recreational sites), and this allows us to understand better the associated anthropogenic impact on land covers. The land cover classification can be seen from Fig.4.

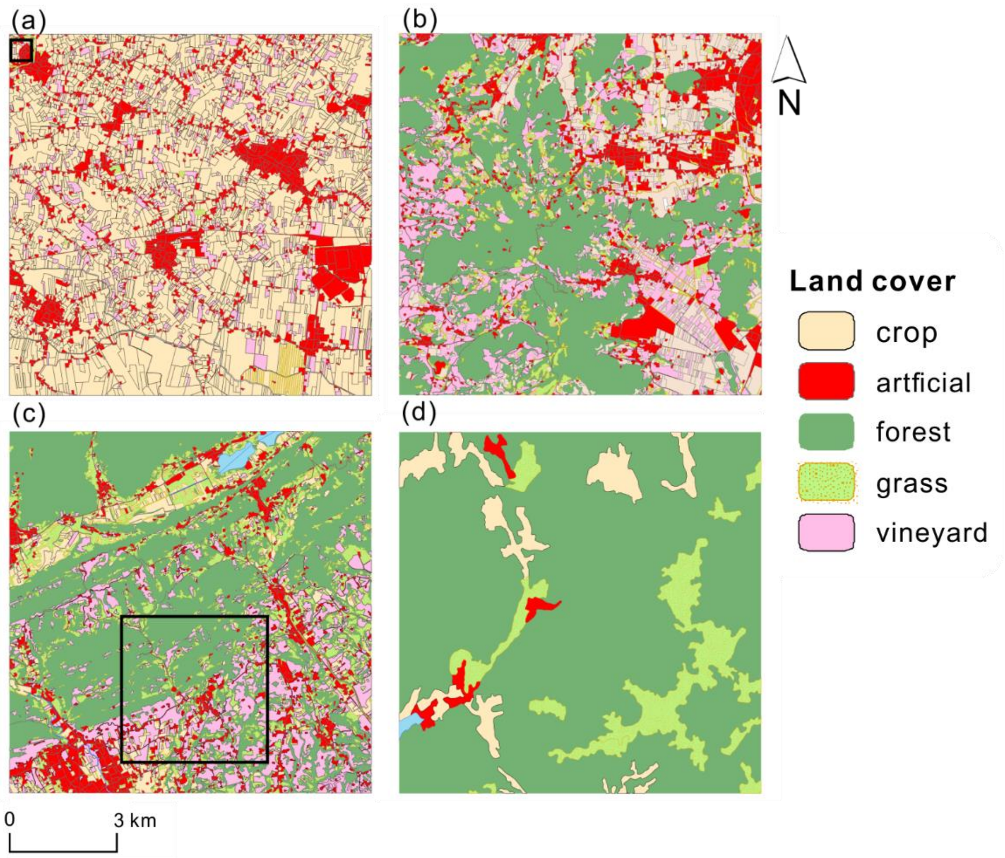

Fig.4 The land cover classification (Corine Land Cover related to 2012) in the study areas (a) floodplain (b) plain to hilly (c) hilly (d) mountain. The black rectangle areas are the case studies in Fig.12

4.4.2 Geomorphometric parameters

To make quantitative measurements of landscape properties, we considered three geomorphometric parameters: *slope* and *mean curvature* proposed by Evans (1979), and the *Spc* developed by Sofia et al. 2014a).

Slope and curvature

Evans (1979) describes the DTM surface is approximated to a bivariate quadratic function in the form of:

$$Z = ax^2 + by^2 + cxy + dx + ey + f \quad (1)$$

Where x, y and z are local coordinates, and a to f are quadratic coefficients.

From such a surface, it is possible to compute the first (*slope, Eq. 2*) and second (*curvature, Eq. 5*) derivative. Slope (Fig. 5) is calculated as:

$$Slope = \arctan\sqrt{d^2 + e^2} \quad (2)$$

where d and e are coefficients from equation (1).

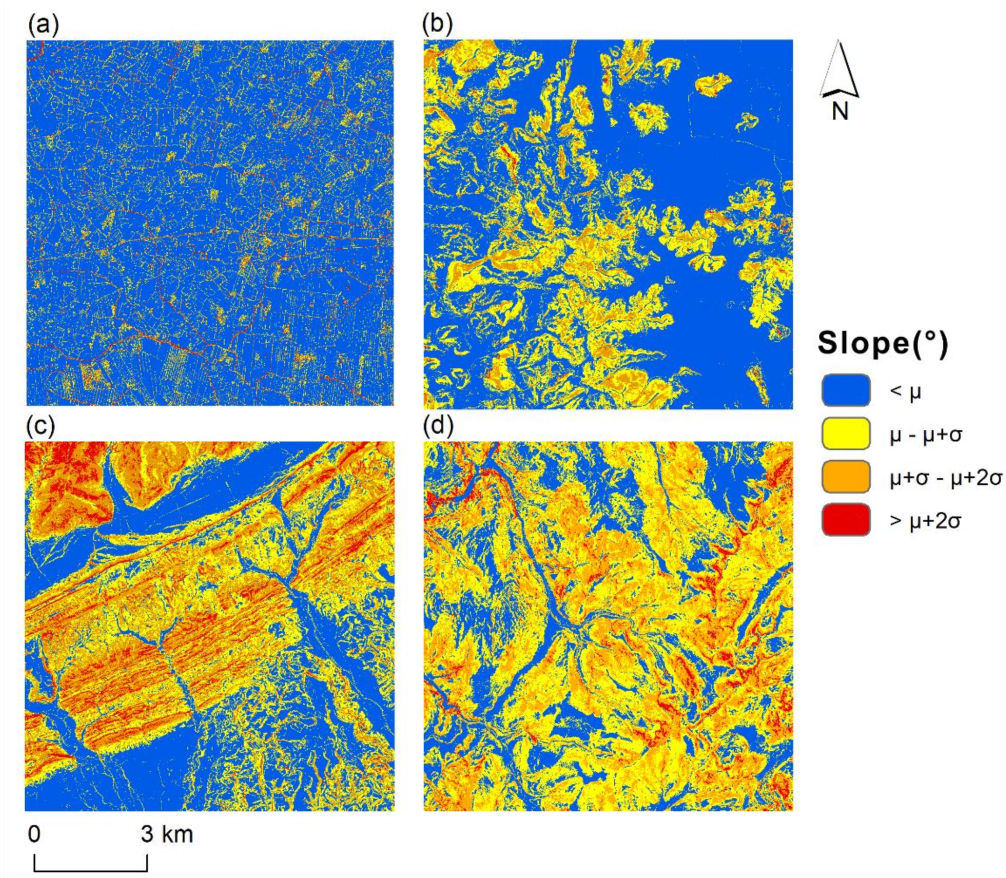

Fig.5 *Slope* maps for the four study areas (a) floodplain (b) plain to hilly (c) hilly (d) mountain. slope is colour-coded according to 1 to 2 times intervals of standard deviation σ from the mean μ

Curvature is the second derivative of the surface, also referred to the change rate of slope gradient or direction (Wilson & Gallant, 2000), and it emphasises convex and concave elements in the landscape. Evans (1979) proposes two measure of curvature, maximum and minimum, defined as

$$curvature_{max} = k \cdot g(-a - b + \sqrt{(a-b)^2 + c^2}) \quad (3)$$

$$curvature_{min} = k \cdot g(-a - b - \sqrt{(a-b)^2 + c^2}) \quad (4)$$

where a, b and c are quadratic coefficients from equation (1), and g is the grid resolution of the DTM (2m), and k is the size of the moving window.

From the equation of (3) and (4) *mean curvature* (Fig. 6) can be defined as:

$$curvature_{mean} = \frac{curvature_{max} + curvature_{min}}{2} \quad (5)$$

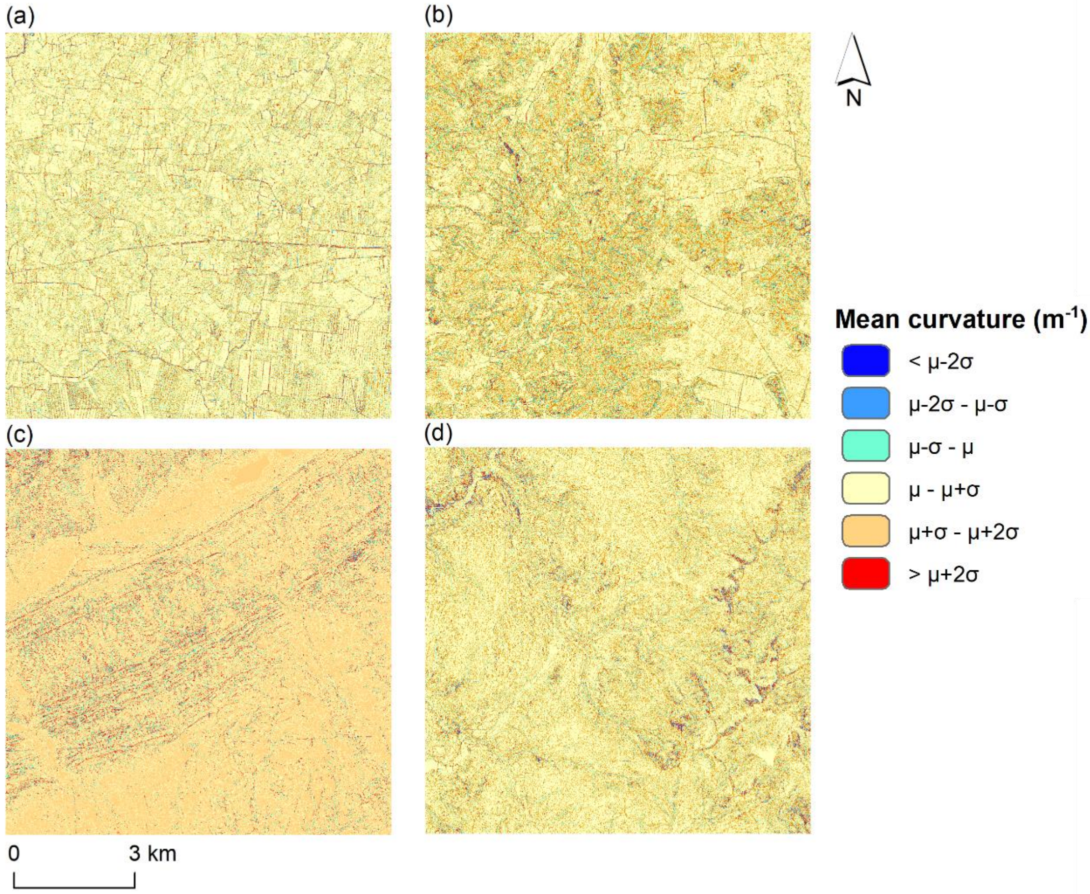

Fig.6 *Mean Curvature* maps for the four study areas (a) floodplain (b) plain to hilly (c) hilly (d) mountain. Mean curvature is colour-coded according to 1 to 2 times intervals of standard deviation σ from the mean μ

Surface Peak Curvature (Spc)

The *Spc* is inversely correlated with anthropogenic pressure (Sofia et al. 2015; Chen et al. 2015; Xiang et al. 2018). Surface morphology (*slope*) of regions presenting anthropogenic structures tends to be well organised (low *Spc*) and, in general, self-similar at a long distance. The basis for the evaluation of the Spc is the Slope Local Length of Auto-Correlation *(SLLAC*). This index quantifies the local self-similarities of slope (Sofia et al. 2014b). It is based on the (demonstrated) assumption that natural areas present low correlations within a neighbourhood because they are inherently irregular, while artificial surfaces to satisfy human needs for mobility and machine access tend to display a higher level of self-similarity with surroundings (Sofia, Marinello, et al., 2014; Xiang et al., 2019). Describing the algorithm in detail is beyond the scope of this study: the authors refer to Sofia et al. (2014b) for a complete description of the procedure, and to (Chen et al., 2015; Sofia, Marinello, et al., 2016a; Tarolli & Sofia, 2016b; Xiang, Chen, Sofia, Tian, & Tarolli, 2018; Xiang et al., 2019) for examples of applications.

Briefly, the steps to obtain the *Spc* (Fig. 7) are as follows:

1) evaluate correlation

$$Corr_{(i,j)} = \frac{\sum_{u,v}(W_{(i+u,j+v)} - \bar{W}_{i,j})(T_{u,v} - \bar{T})}{(\sum_{u.v}(W_{(i+u,j+v)} - \bar{W}_{i,j})^2 \sum_{u,v}(T_{u,v} - \bar{T})^2)^{0.5}} \quad (6)$$

between a moving window (W) and a patch (T) centred at the centre of the moving window. The implemented algorithm computes a normalized cross-correlation between a template and the patch, in the spatial frequency domain, and reports a standardized value that ranges between 0 (no correlation) to 1 (perfect correlation). The larger the absolute values, the stronger of the correlation.

2) evaluate the correlation length (L) thresholding at 37% (ISO 2013, Whitehouse 2011) the maximum correlation value (Eq. 6). The length of correlation is the length of the longest line passing through the central pixel and connecting two boundary pixels on the extracted area connected to the central pixel (*SLLAC* map in supplement 2).

3) evaluate the *Spc* (Surface Peak Curvature) of the *SLLAC* map defined as:

$$Spc = -\frac{1}{2n}\sum_{i=1}^{n}\left[\left(\frac{\partial^2 z(x,y)}{\partial^2 x}\right) + \left(\frac{\partial^2 z(x,y)}{\partial^2 y}\right)\right] \quad (7)$$

for every peak (pixel higher than its eight nearest neighbours). Where z stands for *SLLAC* value, x and y represent the cell spacing, n is the number of considered peaks.

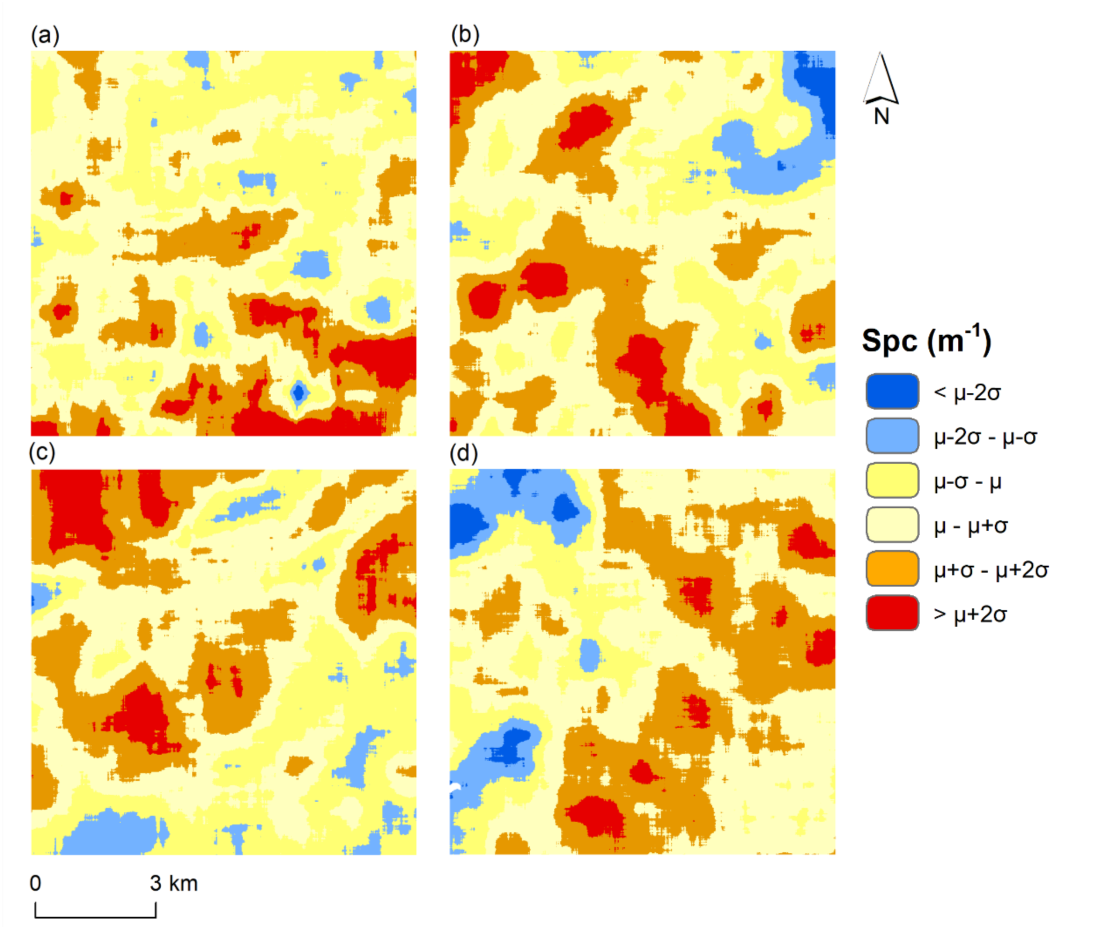

Fig.7. *Spc* maps for the four study areas (a) floodplain (b) plain to hilly (c) hilly (d) mountain. Spc is colour-coded according to 1 to 2 times intervals of standard deviation σ from the mean μ

Please refer to the supplement to infer statistic values (mean, median, STD, MAD, skewness…) of each geomorphometric parameters within each land cover.

4.4.3 Statistical analysis

We expect that the topographic signature of anthropogenic activities may be more subtle than the presence of a specific landform and that it would likely be a signature on the frequency of occurrence of the various degrees of the investigated landscape properties (slope, curvature, Spc). That is, the frequency distributions of these measurements would be very different, even though all observed landform types would be found in both natural or anthropogenically modified landscapes. Therefore, we observed the probability density function (PDF) of the considered landscape parameters to: 1) investigate statistical differences in geomorphological surfaces between land covers under different landforms contexts; 2) explore the specific topographic signatures of land-uses. For this work, the PDFs are a probability density estimate for the sampled data. The estimate is based on a normal kernel function, and is evaluated at equally-spaced points that cover the range of the sampled data. The distance between points is chosen automatically, based on the range of values. This means that it can be very narrow (<0.001) for landscape parameter with small magnitude. In these cases, the PDFs can reach values much greater than 1, but their integral over any interval is always less or equal to 1.

After statistically ensuring that the datasets did not present a normal distribution and they exhibit heteroscedasticity, we decided to consider a Kruskal-Wallis test (McKight and Najab 2010) to evaluate whether there were significant differences between landscape properties underneath a specific land-cover, across multiple landscapes, and we set a p-value threshold of 0.05 for significance. The null hypothesis for this test is that the data for each group are statistically equal.

To investigate the similarities in PDFs between land covers, we applied the two-sample Kolmogorov-Smirnov test, which specifies the equality of probability distribution between two samples (Wilcox 2005; Razali and Wah 2011). One thousand points within each land cover were randomly selected and tested ten times to ensure the robustness of the results.

4.5 Result and discussion

4.5.1 Signatures recognition with different land covers

The PDF of slope (Fig. 8) exhibits very different appearances throughout the investigated landscapes. The central tendency moves from lower value to higher value, and the PDF itself tends to be more dispersed, as we increase landscape elevation. Even though the slope PDFs are always skewed, those in steeper topography present (as expected) a much longer tail than that of more gentle landscapes (i.e. floodplain). Taking a closer view of landcover distributions, the forest distribution in hilly and mountain areas present lower skewness respect to that in the floodplain. As well, most of the land covers in the mountain site show lower asymmetry. This could be an underlining symptom that humans activities are less marked in the mountains rather than in floodplains. Sofia et al. (2017) showed, for the Veneto region, different trends in anthropogenic expansion depending on the topographic location, highlighting a significant pressure in floodplains rather than in high-mountains. Other works also highlighted how anthropogenic processes in the Alps are not fundamentally different from the processes in the floodplains, but they occur with a time lag and on a smaller scale (Perlik, Messerli, & Batzing, 2001). Consequentially, the human signature on morphology might be less marked (Sofia, Marinello, et al., 2016a). At the same time, the anthropogenic signatures on morphology in the Alpine environments reflect the fact that activities are generally shaped through valley bottoms and ridges, and by limits due to the slope and the steepness of the terrain (Forman et al., 2003).

A further interesting result is the striking similarity between the PDFs of vineyards in the plain to hilly (b) and the hilly sites (c): for these landscapes, the PDFs present a double peak.

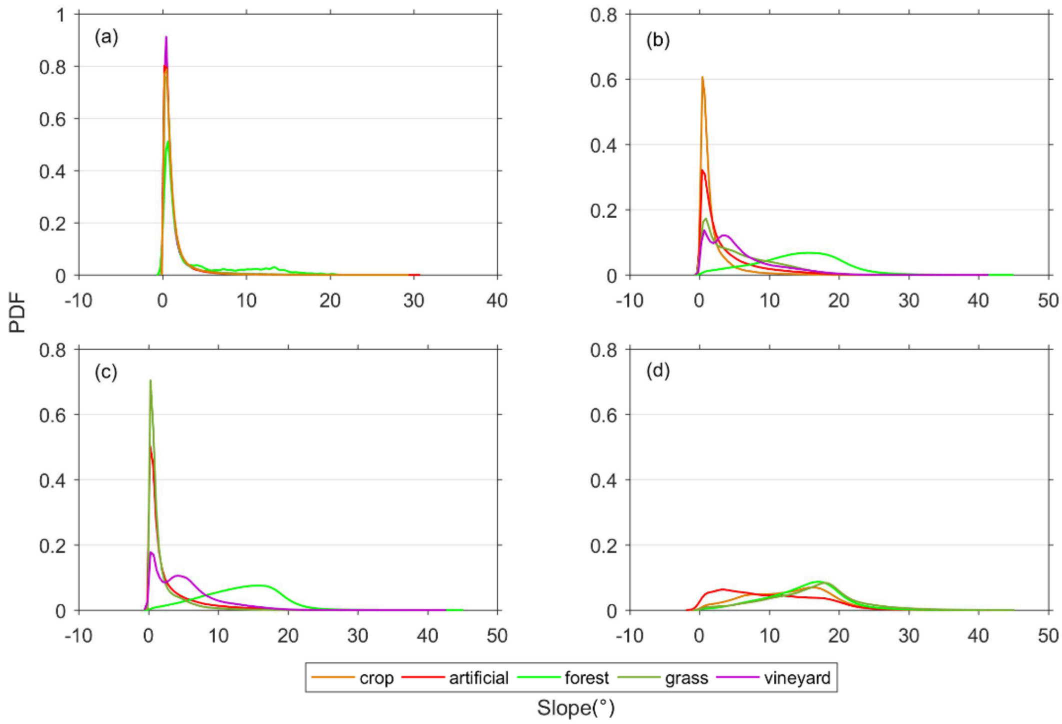

Fig.8 The PDFs of the slope with different land covers in the four study areas. (a) floodplain (b) plain to hilly (c) hilly (d) mountain. The vineyard in plain to hilly (b) and hilly (c) areas present bimodal curve

The first peak falls at a range of 0–3 °, while the second peak around 3 °–10 °. It is possible to note that in this landscape (Fig. 9), vineyards are constructed over terraces: the terrace walls present slope with the highest values (the second peak), on the other hand, the slope with lower values (the first peak) is related to the terrace benches. This peculiar double peak in terraced landscapes was also showed by (Tarolli and Sofia 2016), for terraces related to urbanization over hillslopes.

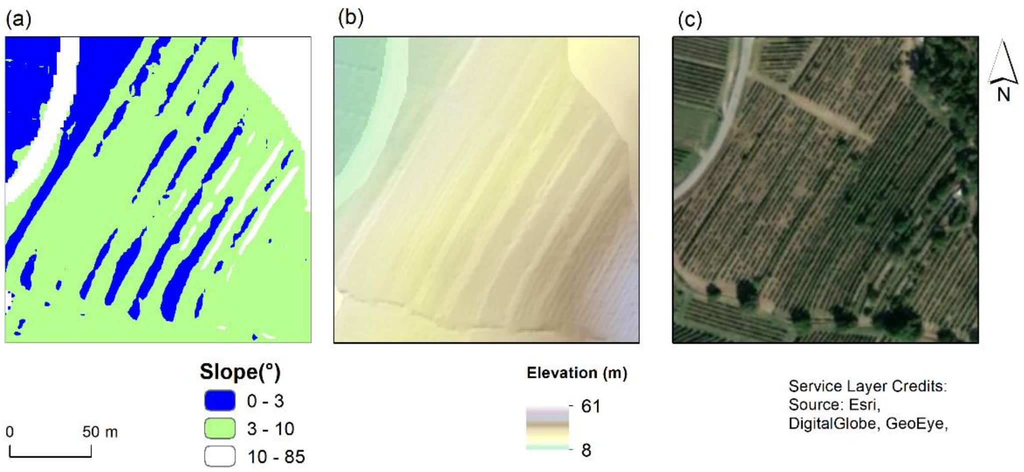

Fig.9. Overview of a typical vineyard in the plain to hilly landscape (the blue color represents the first slope peak value which is the terrace bench, and the green shows the second slope peak value which represents the terrace walls

Focusing on mean curvature (Fig. 10), all landforms present a distribution that peaks around 0. The extreme values on the positive side are related to divergent-convex landforms, and they are generally associated with the dominance of hillslopes. The presence of extreme values on the negative side is related to convergent-concave landforms associated generally with fluvial-dominated erosion (Tarolli et al. 2012; Evans 2013). As shown in Fig. 10, the long tails of extreme value are related to artificial land covers in the floodplain, and to forests in the plain to hilly and hilly areas.

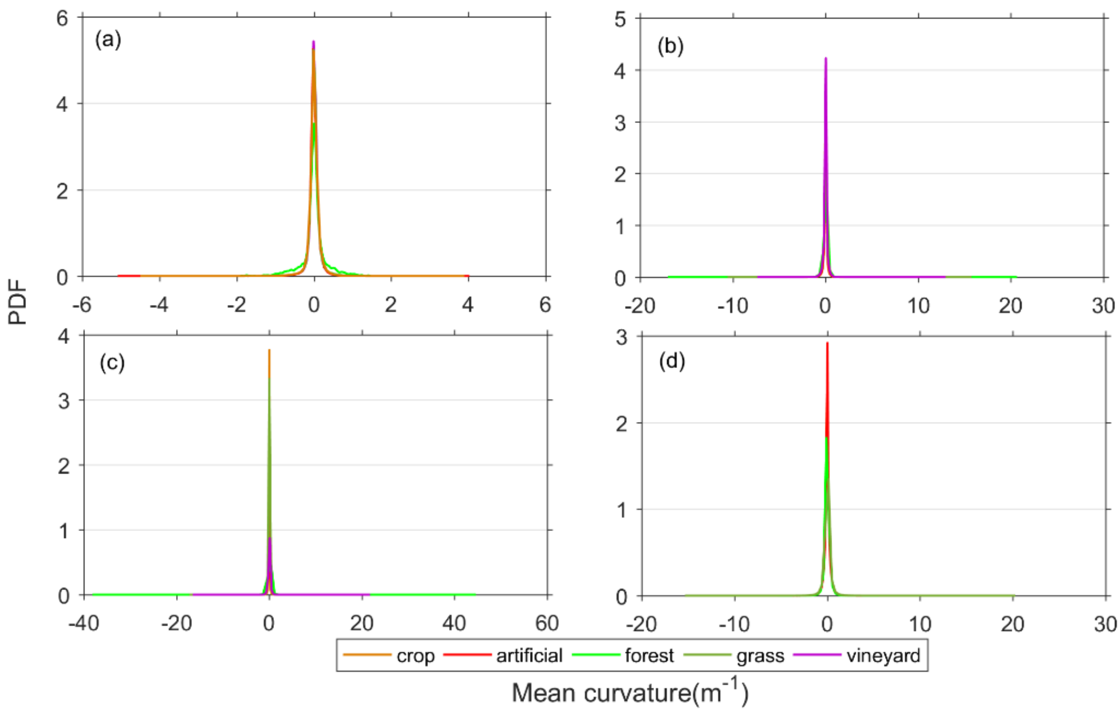

Fig.10 The PDFs of the *mean curvature* with different land covers in the four areas. (a) floodplain (b) plain to hilly (c) hilly (d) mountain.

To better identify the reason behind these long tails, we used boxplots to detect the positive and negative outliers (Fig. 11) The idea behind this is that convex features can be identified as curvature values above the upper bound, and on the contrary, concave features can be identified as value below the lower bound (Sofia et al. 2014b).

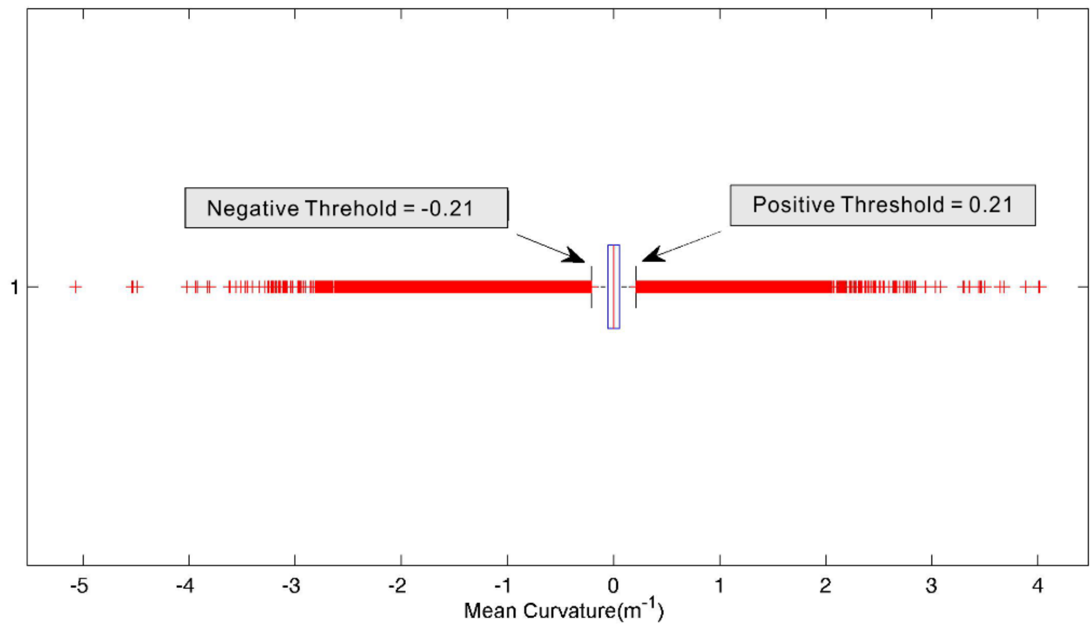

Fig.11 The boxplot of *mean curvature* and the negative/ positive threshold in the floodplain.

As we can see from the satellite image (Fig. 12), the negative outliers of curvature in the floodplain are mostly related to channel networks, while the positive outliers are related to scarps, levees and small banks around them. Some noise in the curvature map is given by the footprint of the urban area, where negative and positive outliers can be found around buildings. For the hilly area, the outliers on the positive side are related to ridges, while the negative ones are channelized valleys, where forests are mostly present.

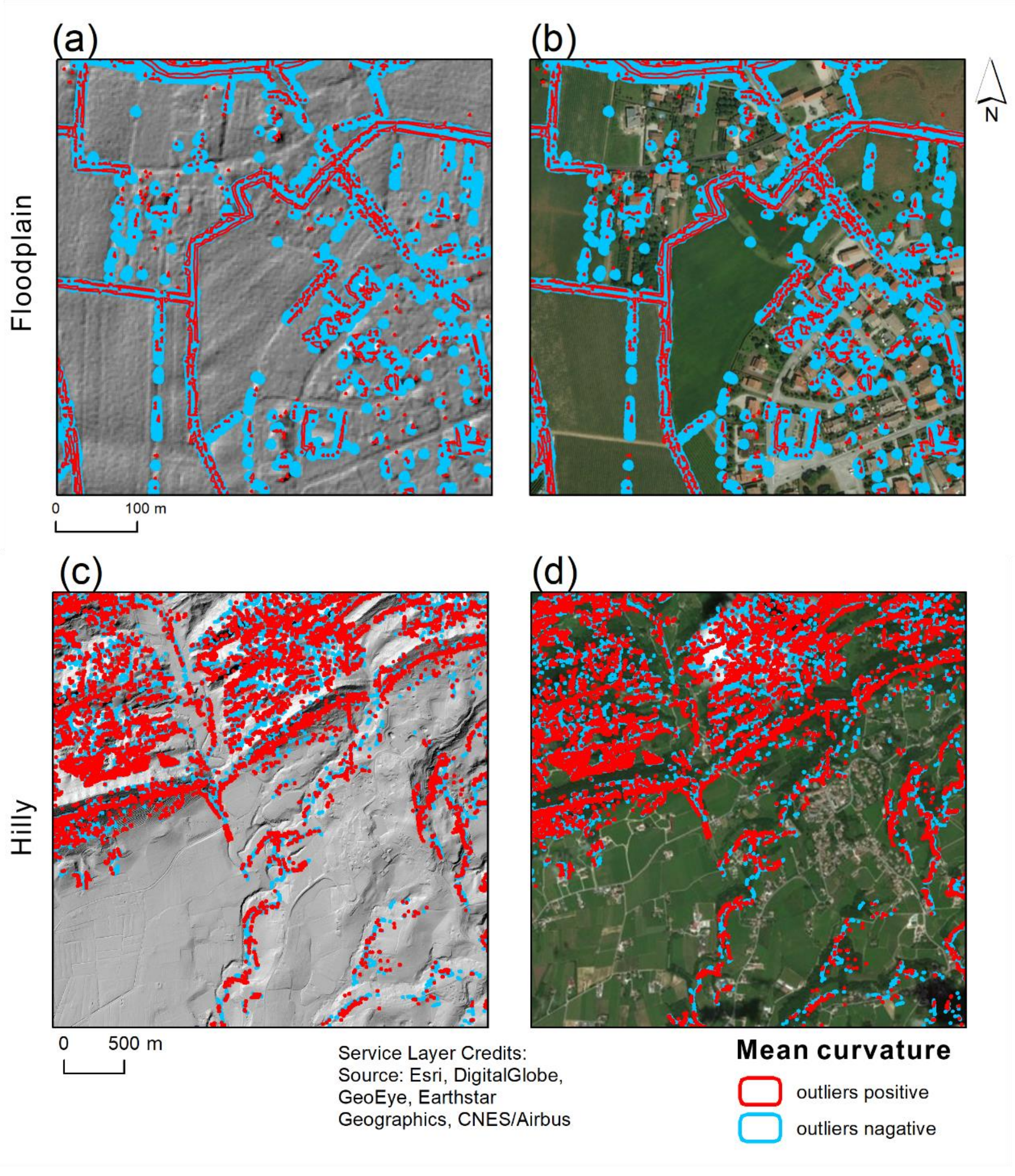

Fig. 12 The positive and negative outliers identified from *mean curvature* in the floodplain (a) and hilly area (c), the left side is the DTM, and the right side is the satellite image. The location of the study areas is marked in black rectangle in Fig.4

4.5.2 Statistic test on the morphology of different land covers under various landforms

The results of Kruskal-Wallis test (Table 1) show that significant differences ($p<0.05$) exist among land covers regarding their slope.

Tab.1 Kruskal-Wallis significance tests of difference in *slope* between different land covers in each study area

	Source	SS	MS	Chi-sq	Prob>Chi-sq
floodplain	Groups	1.22E+09	3.04E+08	583.76	5.06E-125
	Error	9.20E+09	1.84E+06		
	Total	1.04E+10			
plain to hilly	Groups	4.23E+09	1.06E+09	2031.16	0
	Error	6.18E+09	1.24E+06		
	Total	1.04E+10			
hilly	Groups	5.86E+09	1.465E+09	2813.1	0
	Error	4.55E+09	911886.3		
	Total	1.04E+10			
mountain	Groups	5.99E+08	2.0E+08	449.18	4.90E-97
	Error	4.73E+09	1.18E+06		
	Total	5.33E+09			

(Source means the origin of variance, and it includes the variance between groups (different land covers) and Error (geomorphometric value in the same land cover); SS means sum of square; MS represent standard deviation, and it could reflect the degree of dispersion of a data set; Chi-sq is the H-statistic of the Kruskal-Wallis test, which is approximately chi-square distributed. The Prob>chi-sq is the p-value)

Looking at the p-values for the Kolmogorov-Smirnov test (Table 2), it is possible to highlight that 1) there are significant differences in slope between any pair of land covers in each case study areas, except for grass and vineyard in hilly sites; 2) among all the p-value, the most remarkable difference always relates to the forest and any of the other land covers.

Tab.2 The significance level of two-sample Kolmogorov-Smirnov tests of pairwise differences in *slope* between land covers within topographic types

	variable	crop	forest	artificial	grass	vineyard
floodplain	crop		1.55E-45	3.59E-27	1.23E-44	3.71E-36
	forest			1.55E-45	1.23E-44	1.55E-45
	artificial				5.34E-42	1.75E-19
	grass					3.71E-36
	vineyard					
plain to hilly	crop		2.21E-08	5.96E-06	8.24E-24	9.25E-05
	forest			4.26E-13	2.69E-29	1.27E-12
	artificial				1.40E-13	5.56E-01
	grass					9.13E-18
	vineyard					
hilly	crop		5.06E-30	6.12E-07	1.34E-15	3.96E-16
	forest			3.64E-23	6.66E-19	3.28E-17
	artificial				9.25E-05	2.45E-05
	grass					0.556*
	vineyard					
mountain	crop		1.93E-39	1.68E-31	5.96E-06	
	forest			9.48E-44	2.33E-35	
	artificial				1.44E-34	
	grass					

We addressed the same analysis on *mean curvature*. However, the results (Table 3) show no significant difference among land covers (p-value >0.05).

Tab.3 Kruskal-Wallis significance tests of *mean curvature* in each study area based on different land covers

		SS	MS	Chi-sq	Prob>Chi-sq
floodplain	Groups	1.64E+07	4.11E+06	7.89	0.0958
	Error	1.04E+10	2.08E+06		
	Total	1.04E+10			
plain to hilly	Groups	9.17E+06	2.29E+06	4.4	0.35
	Error	1.04E+10	2.08E+06		
	Total	1.04E+10			
hilly	Groups	4.58E+06	1.15E+06	2.2	0.6991

	Error	1.04E+10	2.08E+06		
	Total	1.04E+10			
mountain	Groups	3.51E+06	1.17E+06	2.63	0.4516
	Error	5.33E+09	1.33E+06		
	Total	5.33E+09			

As a trial test, we randomly sampled 10.000 points from the maps: with this enlarged dataset, the results show a significant difference among various land covers as a group or pairwise (Table 4 and Table 5). Crops and vineyards give exceptions to this in the plain to the hilly area, and also crop and forest in the mountain area (p-value >0.05).

Tab.4. Kruskal-Wallis significance tests of *mean curvature* in each study area based on different land covers with 10000 sample

		SS	MS	Chi-sq	Prob>Chi-sq
plain to hilly	Groups	3.11E+09	7.77E+08	14.92	0.0049
	Error	1.04E+13	2.08E+08		
	Total	1.04E+13			
hilly	Groups	4.83E+09	1.21E+09	23.21	0.0001
	Error	1.04E+13	2.08E+08		
	Total	1.04E+13			
mountain	Groups	1.12E+09	3.73E+08	8.39	0.0386
	Error	5.33E+12	1.33E+08		
	Total	5.33E+12			

Tab.5 The significant level of two-sample Kolmogorov-Smirnov tests of pairwise differences in *mean curvature* between land covers within topographic types with 10000 sample

	variable	crop	forest	artificial	grass	vineyard
plain to hilly	crop		1.19E-129	4.60E-03	1.66E-39	0.4132*
	forest			1.03E-100	1.59E-28	4.62E-132
	artificial				1.60E-23	0.007
	grass					1.66E-39
	vineyard					
hilly	crop		1.28E-270	4.66E-58	2.77E-63	1.83E-26
	forest			4.07E-108	3.62E-91	9.59E-140
	artificial				5.95E-07	1.42E-07
	grass					3.28E-09
	vineyard					
mountain	crop		0.2791*	6.25E-08	1.70E-03	

	forest	4.64E-11	6.11E-04
	artificial		2.37E-19
	grass		

When observing the *Spc* and the result of the Kruskal-Wallis test (Table 6), it is confirmed that the different land covers present different topography signatures (p-value<0.05).

Tab.6 Kruskal-Wallis significance tests of *Spc* in each study area based on different land covers

		SS	MS	Chi-sq	Prob>Chi-sq
floodplain	Groups	8.51E+08	2.13E+08	408.41	4.23E-87
	Error	9.57E+09	1.92E+06		
	Total	1.04E+10			
plain to hilly	Groups	4.06E+09	1.01E+09	1948.22	0
	Error	6.36E+09	1.27E+06		
	Total	1.04E+10			
hilly	Groups	2.12E+09	5.30E+08	1017.81	4.92E-219
	Error	8.30E+09	1.66E+06		
	Total	1.04E+10			
mountain	Groups	2.63E+09	8.76E+08	1969.43	0
	Error	2.71E+09	677369.2		
	Total	5.33E+09			

As it is possible to infer from Table 7 : 1) pair-wise differences exist in all land covers except for grass and vineyards. 2) forest differentiates from other land covers on the *Spc*, and this is evident for all landforms' context considered.

Tab.7 The significant level of two-sample Kolmogorov-Smirnov test of pairwise differences in *Spc* between land covers within topographic types

	variable	crop	forest	artificial	grass	vineyard
floodplain	crop		1.55E-45	3.97E-25	1.23E-44	3.88E-41
	forest			1.55E-45	1.55E-45	1.55E-45
	artificial				7.19E-43	1.43E-14
	grass					5.11E-33
	vineyard					
Plain to hilly	crop		4.26E-13	2.45E-05	7.17E-28	1.80E-03
	forest			1.12E-20	8.66E-34	4.48E-20
	artificial				9.13E-18	0.677
	grass					6.67E-22

	vineyard				
hilly	crop	5.06E-30	4.81E-05	4.41E-15	1.27E-12
	forest		8.44E-26	4.48E-20	1.15E-16
	artificial			2.21E-08	2.85E-06
	grass				0.26*
	vineyard				
mountain	crop	5.77E-37	1.40E-28	1.21E-07	
	forest		1.23E-44	2.33E-35	
	artificial			5.77E-37	
	grass				

4.5.3 The distinct anthropogenic impact analysis

The Spc is mathematically related to the percentage of anthropogenic activity (Chen et al. 2015; Xiang et al. 2018; Xiang et al. 2019). As a consequence, it is a proxy to illustrate the extent of human impact on morphology for each land cover in different landforms (Fig. 13). The most recognisable topographic signature is that given by the forests in the floodplain (Fig. 13a). Besides, the peak of forest distribution (higher due to the small and uniform surface) falls within values of Spc on the range of those obtained in literature for highly anthropogenic surfaces. The forest distribution in both plain to hilly (Fig. 13b) and hilly areas (Fig. 13c) present a similar trend, but the peak in the hilly area tends to be to the right side (where Spc values are referred to be more 'natural' if compared to the mentioned literature). When moving to the mountain (Fig. 13d), the forest shape appears less skewed, which might indicate that lower human interference is present.

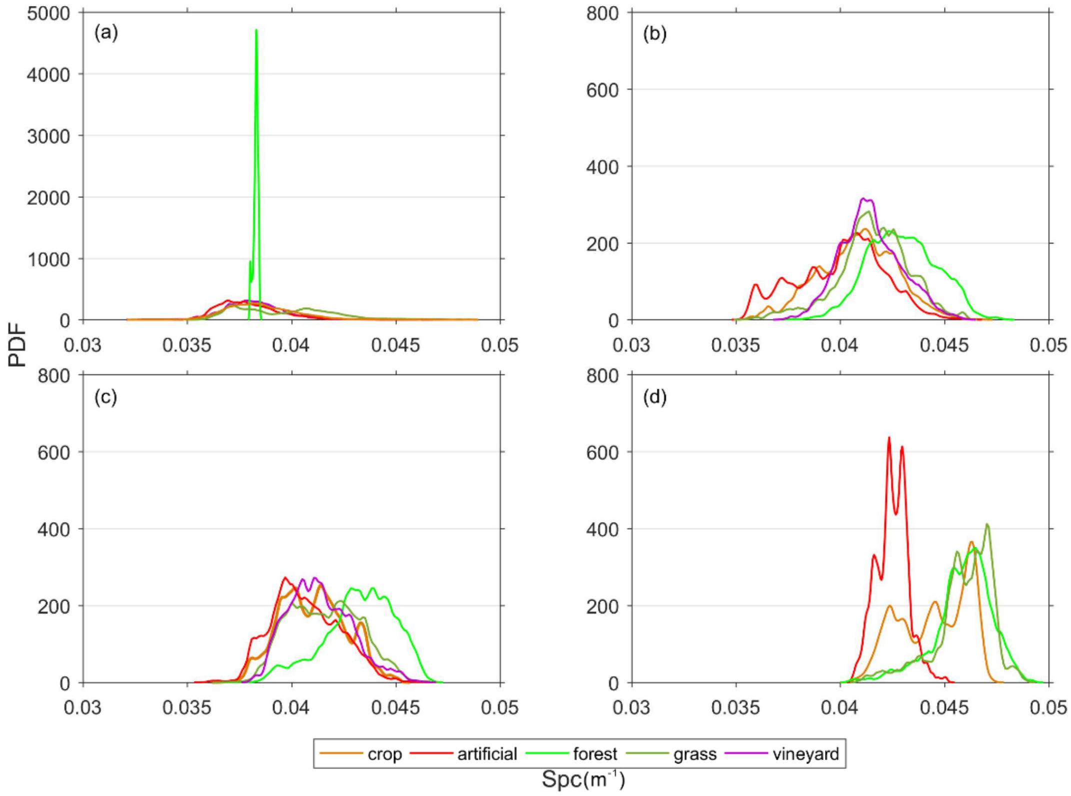

Fig. 13 The PDFs of the Spc. with different land covers in the four areas. (a) floodplain (b) plain to hilly (c) hilly (d) mountain

In Fig. 14a and 14b the map of *Spc* and forest as seen from the satellite is shown in detail. The forest here is closed to the channel and mostly on the levees. This also gives a reasonable interpretation of the lower value of Spc due to the human alteration on the forest in the floodplain. By contrast, we highlight a small area with different Spc values (Fig. 14c and 14e, marked with different colours) and the lidar-derived shaded relief map (Fig. 14d) in a different area where the transition from plain to hilly is evident. The forests with relatively lower *Spc* value are located in areas surrounded by agricultural terraces and other anthropogenic surfaces. On the other side, the forests with higher *Spc* value are distributed on the top of small hills and tend to be more natural. Forest not only presents a remarkable difference with other land covers but also shows a different morphology based on the degree of anthropogenic disturbance.

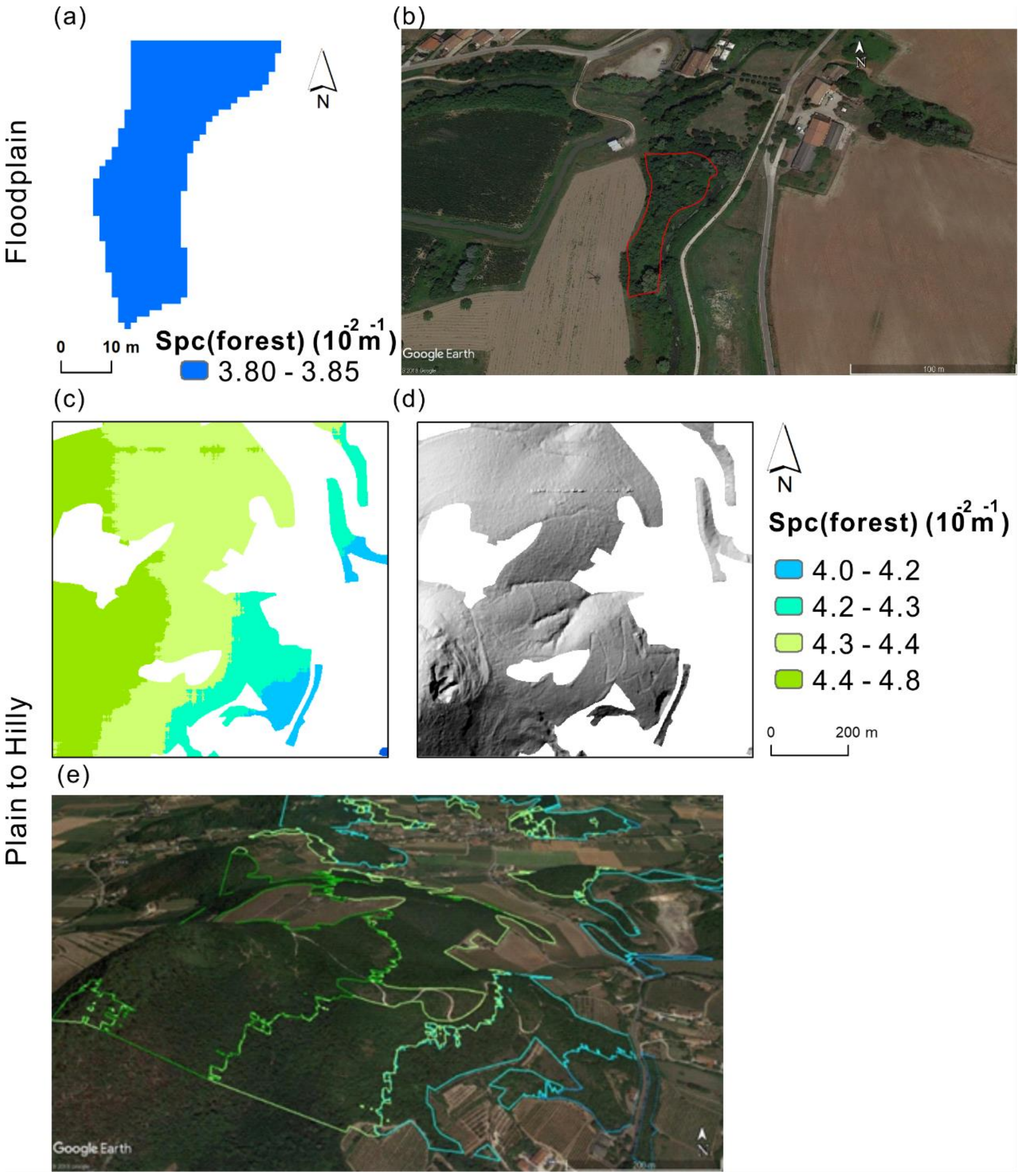

Fig.14. Forest with Spc value in floodplain (a) and 3D overview (b) of the surrounding from google earth (the red outline extracted from forest); Forest with Spc value in plan to hilly (c), LiDAR (d) and 3D overview (e), the outline with different color denote the different Spc value

Xiang et al. (2019) highlighted how morphological differences under forest cover emerged by considering natural forests or artificial plantations, with higher Spc for natural forests. In actuality, the forest (mixed of shrubs and medium trees) in the floodplain area considered in this study have been altered in their structure and distribution, thus appearing as small patches surrounded by agricultural and urban areas, in lands highly disturbed by human activities. Forests in this floodplain are also managed to adopt peculiar forestry technique to preserve and maintain the vegetation, through new plantations near the ancient wood (Bellio & Pividori, 2009). Our results confirm (from a morphological perspective) that the described forest for the floodplain is related to a surface affected by anthropogenic pressure, while a lower anthropogenic disturbance might be present on forests on hilly places, with the existence of more natural forests.

Some land covers do not exhibit apparent differences in specific landforms. For example, grass and vineyards present some similarities in hilly (Table 2). As it is shown on Fig. 15, the floodplain grass (left side) has lower values of *Spc*, which implies that anthropogenic disturbance might be relatively significant in this environment. Taking a closer view (Fig. 15d) this area is related to a sports field and a park. By contrast, the grass in the hilly area (right side) shows a relatively higher *Spc* value than that of the floodplain. This could imply that anthropogenic modifications in this grassland still exist, even though there are less marked than in floodplain, and from the satellite image (Fig. 15h) the grass in hilly can be identified as pastures.

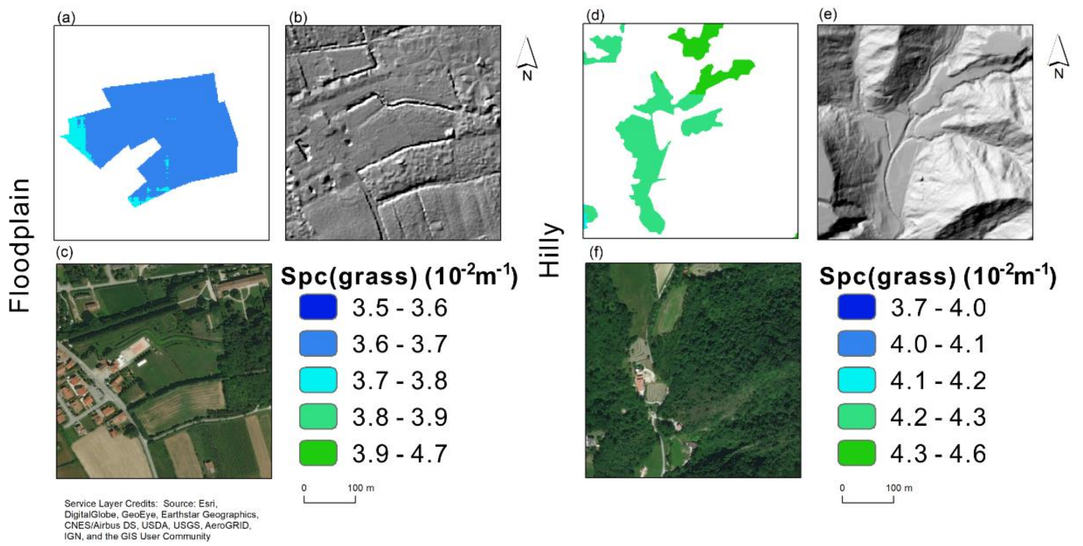

Fig.15 Grass with *Spc* value in floodplain (a) and hilly (d), LiDAR-derived shaded relief map in floodplain (b) and hilly (e), and satellite image in floodplain (c) and hilly (f)

The similarities in morphology (Spc) between grass and vineyard in hilly areas can be explained by the fact these pastures are human-modified, to maximize forage production. Some of them have been abandoned (‘*prati vegri*’), and are (in part) being converted to vineyards. Therefore, the human-morphological signature is still evident and appears in the Spc.

4.6. Conclusion

The primary goal of this work was to investigate the statistical differences of surface morphologies of anthropogenic and natural land covers, testifying that human activities alter the landforms from a statistical point of view. This work highlights how, if we were to make quantitative measurements of landscape properties on a landscape without human interference, and compare them to measurements of a landscape where humans activities are preponderant, the frequency distributions of these measurements would be very different, even though all observed landform types would be found in both realities. Possibly, if we had to model and describe a landscape without humans, it would look much different from the one we are used to, but it would not exhibit much different landforms. Rather, the subtle differences would lie in the frequency distributions of specific landform properties. This work also confirms the possibility to recognise with a pure geomorphometric analysis the signatures of anthropogenic activities within a specific landscape context, and further demonstrate how people use of the land change the earth surface in three dimensions. Different utilizations of the same land cover show a different extent of anthropogenic impacts, underlining the opportunity for future analyses of the “magnitude “and “type” of human forcing on Earth. The results provide a robust evidence of the human activity’s impact on some terrestrial surfaces, fostering therefore future studies linking the relationship between humans, land use and geomorphological alterations. Our study offers a new insight to understand the present geomorphology coupling the function of human activities, and pose a challenge for future research of the geomorphic and human systems in a world increasingly affected by anthropogenic activities.

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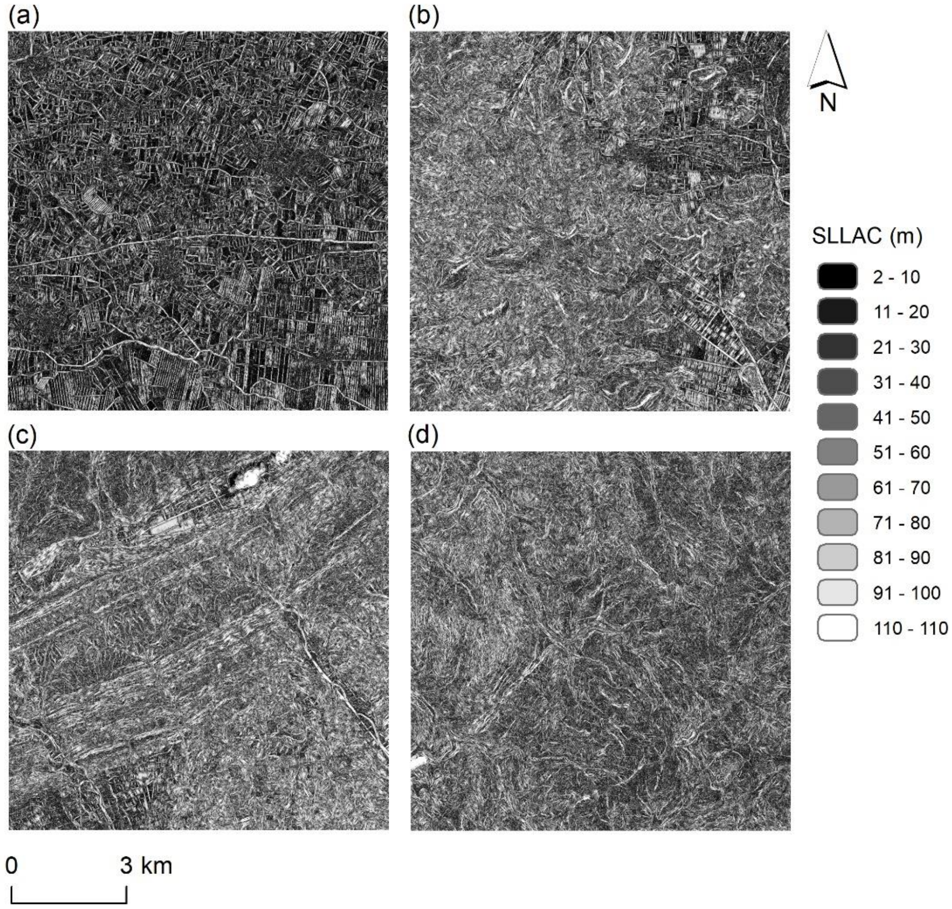
Supplement 1:

		floodplain					plain to hilly					hilly					mountain			
		crop	forest	artificial	grass	vineyard	crop	forest	artificial	grass	vineyard	crop	forest	artificial	grass	vineyard	crop	forest	artificial	grass
slope	mean	1.186	3.781	1.235	2.042	0.982	2.687	13.174	2.871	6.467	6.467	2.208	14.123	3.664	5.810	5.661	12.834	14.990	9.908	15.867
	median	0.732	1.638	0.739	1.132	0.601	1.088	13.531	1.266	5.622	5.622	1.120	14.451	2.053	4.531	4.429	13.205	15.495	9.106	16.345
	standard deviation	1.429	4.175	1.597	2.711	1.265	3.618	5.249	3.832	4.775	3.877	2.922	5.928	4.098	4.899	4.591	5.938	5.439	6.503	6.381
	interquartile(IQR)	0.955	5.408	0.955	1.671	0.714	2.826	7.383	3.031	6.800	4.922	1.820	8.093	4.051	7.139	5.463	8.762	6.921	10.547	7.715
	outliers(neg)	-1.030	-7.356	-1.098	-1.925	-0.726	-3.733	-1.550	-4.004	-7.597	-5.798	-2.132	-2.015	-5.198	-9.016	-5.896	-4.859	1.158	-11.486	0.230
	outliers(pos)	2.792	14.275	2.883	4.758	2.132	7.570	27.983	8.120	19.603	13.889	5.146	30.355	11.007	19.538	15.958	30.189	28.841	30.700	31.088
	mean absolute deviation(MAD)	0.883	3.444	0.955	1.677	0.737	2.582	4.233	2.673	3.845	2.960	1.903	4.759	3.022	3.977	3.557	4.861	4.254	5.497	4.927
	skewness	3.546	1.246	4.000	3.067	3.976	2.265	0.011	2.486	0.911	1.310	2.819	-0.018	1.946	1.089	1.267	0.161	-0.020	0.475	0.125
		crop	forest	artificial	grass	vineyard	crop	forest	artificial	grass	vineyard	crop	forest	artificial	grass	vineyard	crop	forest	artificial	grass
spc	mean	0.0386	0.0383	0.0379	0.0397	0.0382	0.0408	0.0430	0.0400	0.0416	0.0415	0.0411	0.0433	0.0407	0.0416	0.0414	0.0445	0.0459	0.0425	0.0459
	median	0.0384	0.0383	0.0377	0.0396	0.0381	0.0409	0.0429	0.0403	0.0416	0.0414	0.0410	0.0434	0.0405	0.0416	0.0412	0.0447	0.0461	0.0425	0.0462
	standard deviation	0.0018	0.0001	0.0014	0.0023	0.0015	0.0019	0.0016	0.0021	0.0017	0.0015	0.0016	0.0017	0.0016	0.0017	0.0015	0.0016	0.0014	0.0008	0.0014
	interquartile(IQR)	0.0022	0.0001	0.0019	0.0036	0.0018	0.0026	0.0024	0.0029	0.0020	0.0019	0.0023	0.0022	0.0023	0.0027	0.0021	0.0031	0.0016	0.0010	0.0016
	outliers(neg)	0.0341	0.0381	0.0340	0.0323	0.0345	0.0357	0.0382	0.0341	0.0376	0.0375	0.0364	0.0390	0.0360	0.0363	0.0370	0.0384	0.0428	0.0404	0.0429
	outliers(pos)	0.0428	0.0386	0.0416	0.0467	0.0418	0.0460	0.0477	0.0459	0.0458	0.0453	0.0457	0.0478	0.0453	0.0469	0.0456	0.0507	0.0492	0.0445	0.0494
	mean absolute deviation(MAD)	0.0013	0.0001	0.0011	0.0019	0.0011	0.0015	0.0013	0.0017	0.0013	0.0012	0.0013	0.0013	0.0013	0.0014	0.0012	0.0014	0.0011	0.0006	0.0011
	skewness	1.0799	-0.8546	0.8703	0.5530	0.4211	-0.1540	0.0646	-0.1951	-0.4008	0.2537	0.1244	-0.5151	0.2547	0.1319	0.4419	-0.3057	-0.8336	0.1044	-1.0653
		crop	forest	artificial	grass	vineyard	crop	forest	artificial	grass	vineyard	crop	forest	artificial	grass	vineyard	crop	forest	artificial	grass
mean curvature	mean	6.37E-06	-5.08E-04	1.30E-03	-0.003	4.18E-05	-9.53E-04	0.002	-0.001	-4.41E-04	-1.30E-03	-7.69E-04	-2.10E-03	0.004	0.000	0.003	-5.93E-04	-2.01E-04	2.13E-04	0.003
	median	0.003	-0.006	0.003	0.003	0.003	0.002	0.004	0.002	0.003	0.002	2.98E-04	-0.002	0.002	0.000	0.002	-0.003	4.28E-14	-0.003	9.16E-05
	standard deviation	0.150	0.314	0.154	0.229	0.132	0.154	0.272	0.201	0.235	0.166	0.113	0.349	0.220	0.195	0.179	0.316	0.306	0.303	0.440
	interquartile(IQR)	0.110	0.205	0.098	0.148	0.090	0.091	0.230	0.099	0.154	0.086	0.067	0.297	0.115	0.124	0.098	0.250	0.250	0.214	0.278
	outliers(neg)	-0.218	-0.420	-0.191	-0.291	-0.176	-0.181	-0.454	-0.195	-0.305	-0.171	-0.133	-0.594	-0.225	-0.249	-0.193	-0.500	-0.500	-0.428	-0.554
	outliers(pos)	0.223	0.400	0.199	0.299	0.182	0.185	0.466	0.201	0.312	0.174	0.134	0.592	0.236	0.248	0.198	0.499	0.501	0.426	0.556
	mean absolute deviation(MAD)	0.091	0.204	0.086	0.139	0.074	0.088	0.171	0.107	0.144	0.091	0.061	0.224	0.122	0.115	0.099	0.197	0.191	0.188	0.240
	skewness	-1.177	0.152	-1.132	-0.579	-1.826	-0.667	0.392	-0.850	-0.883	-0.081	0.774	0.433	-0.298	0.569	0.417	-0.392	0.164	-0.214	0.692

Supplement 2:



CHAPTER 5

THE GLOBAL ASSESSMENT OF ANTHROPOGENIC GEOMORPHOLOGY

5.1 Abstract

It has been acknowledged that human societies now act as a potent geomorphic agent that has already transformed landscapes across more than one-third of Earth's terrestrial surface. To interpret the intensity of human geomorphic features across Earth's land, and the driving force shaping the landscape, it would be necessary to quantify distinctive anthropogenic geomorphic features at a global scale. However, finding a proper index to measure the alteration of anthropogenic geomorphology on a large scale is still a challenge to geomorphologists.

Sofia et al. (2014) developed a methodology capable of computing percentages of human-made alterations to terrain using high-resolution DTMs (Digital Terrain Models): the SLLAC (Slope Local Length of Autocorrelation). These computations are highly dependent on the availability of fine-scale topographic data (e.g. LiDAR data) which are not yet variable at a global scale. Nevertheless, the anthropogenic geomorphic features tend to reflect the socio-economic and ecological patterns of human societies, so it may be possible to evaluate the anthropogenic geomorphology globally based on correlations with spatial data on these patterns.

The most widely used spatial indicators of socio-economic activities at a global scale are nighttime light data. Global maps such as anthropogenic biomes (Anthromes), landforms and biomes also provide a useful classification of the globally significant patterns of human transformation of ecosystems. Based on the high-resolution LiDAR data we could collect globally, we carried out a representativeness analysis to select the global pattern which gets the most covered by fine-scale topographic datasets. Then we chose sample studies from each stratification of the selected global pattern to calculate the anthropogenic modification on geomorphology and the corresponding nighttime light datasets. By combining these data, a global assessment of anthropogenic geomorphology was carried out.

5.2 Introduction

Humans have altered the landscape locally and globally. Their utilization of lands started from agriculture and settlement activities in a local scale and scaled up in the industrial age and further dramatically increased in the so-called Great Acceleration (Foley, et al., 2005; Hooke, Martín-Duque, & Pedraza, 2012; Ellis, et al. 2010). In modern society, humans' activities change the world's land in pervasive ways through deforestation, intensify farmland and expand urban areas. The scale, intensity, and rates of land-use changes that human transformed the Earth's surface have been well-acknowledged. According to Jones et, al. (2018), one-third of protected land is under intense human pressure and 55% have experienced the increase of human pressure. Smil (2010) also pointed out that humans have reduced around 45% of global terrestrial vegetations through agriculture and the conversion of grassland and wetland in the last 2000 years. Undoubtedly, the dramatic change of land use across space and time have left significant signatures on the topography and which reshape the morphology of landscapes.

The recent literature started to focus on the impacts of anthropogenic activities on geomorphology (Tarolli & Sofia, 2016; Brown et al., 2017; Lóczy & Süto, 2011; Hapke, Kratzmann, & Himmelstoss, 2013). Human activities leave distinctive geomorphic features on the topography and change the Earth surface with a direct or indirect way. For example, agriculture tillage and deforestation lead to soil erosion (Fen-Li, 2006; Anselmetti, et al. 2007; Lee et al., 2006); road network contributes to landslide in mountain areas (Tarolli & Sofia, 2016; Dyrness, et al.1970; Montgomery, 1994); engineering work of city construction may cause flooding (Sofia, et al., 2017; Huong & Pathirana, 2013; Phi, 2007). To understand the extent and intensity of human transformation across Earth's land, a quantification of the anthropogenic impact on the geomorphology at a global scale is necessary. However, a proper index to measure the human's impact on the topography is not an easy task. With the development of recent remote sensing techniques such as LiDAR, the anthropogenic features could be detected and identified at large scale. Further, some geomorphometric algorithms have been produced for the quantification of human's impact on the Earth's surface (Tarolli et al., 2015; Cavalli, et al., 2013; Panagos et al., 2015). Sofia et al. (2014) developed SLLAC (Slope Local Length of Autocorrelation) landscape metrics to delineate and quantify anthropogenic geomorphologies relying on the high-resolution DTMs (Digital Terrain Models) derived from LiDAR data. This index defines in terms of slope similarity of the surrounding morphology. The idea implies that anthropogenic surfaces tend to present less variability of slope due to the engineering construction to meet human needs. Further, the artificial alterations on the landscape could be computed based on the degree of slope similarity.

But the limited availability of high-resolution LiDAR data makes the global assessment of anthropogenic geomorphology difficult to achieve. Nevertheless, the anthropogenic geomorphic features evolve together with the human society and tend to reflect the socio-economic level and ecological patterns of societies. Therefore, it may be possible to assess the degree of human's alteration on landscape based on correlations with socio-economic spatial datasets. Considering the complexity of social evolution, so far, nighttime light could be a useful indicator for the estimation of the socio-economic activities (Mellander, et al. 2015; Román et al., 2018)

On the basis high-resolution LiDAR datasets, we selected several case studies and then computed the anthropogenic modification on geomorphology and the corresponding nighttime light luminosity. But how to select the study sites? Are the LiDAR data covered sites able to represent the global patterns?

The extent of anthropogenic landforms depends on the intensity of human intervention and the degree of perception (Szabo, et al. 2010). According to this idea, we classified the global patterns as anthromes, biomes, and landforms. Key benefits of these datasets are global coverage and high spatial resolution. We collected the LiDAR data all over the world, and then we evaluated which global pattern get the most covered by the high-resolution topographic data. Further, we chose the local scale sites according to the different classification of the selected global pattern.

5.3 Material and Method

5.3.1 Representativeness assessment

We collected anthromes (Ellis, 2010), landforms (Sayre et al. 2014) and biomes (Olson et al., 2006) and the high-resolution LiDAR datasets globally to carry out the representativeness assessment. The purpose is to select the global pattern which gets the most coverage of the high-resolution topographic data.

World Ecological Facets Landform Classes

Landforms are one of the most essential elements regarding landscape analysis and metrics (Booth, 1983). Since human activities reshaped the landforms for a long-term, such as bulldoze mountains to build cities (Li, Qian, & Wu, 2014), the landform context plays an essential role contributing to the anthropogenic assessment. Landforms tend to reflect the landscape that human activities shaped in the coevolution with the environment. The classification of landforms is significantly important for understanding the ecosystem patterns and distributions (Sayre, et al., 2014). The most well-known classification for the landform is the Hammond algorithm (1964). Hammond grouped terrain type into categories based on:

$$\text{Landform (terrain type)} = \text{slope} + \text{relief} + \text{profile} \tag{1}$$

It gives empirical definition of slope, local relief, and profile types through field experiences (Karagulle et al., 2017). In 2016, Esri produced an improved Hammond landform classification algorithm which used the Morgan and Lesh (2005) approach to the GMTED 2010 250- meter global DEM. The Morgan and Lesh (2005) algorithm offers detail information about regionalization but the general classifications keep the same as Hammond algorithm. The improved Hammond landform generated 16 regional terrain categories (Fig. 1) and provided a more balanced distribution of landform classes, reducing the overabundance of features (Karagulle, Engineer, & Frye, 2015).

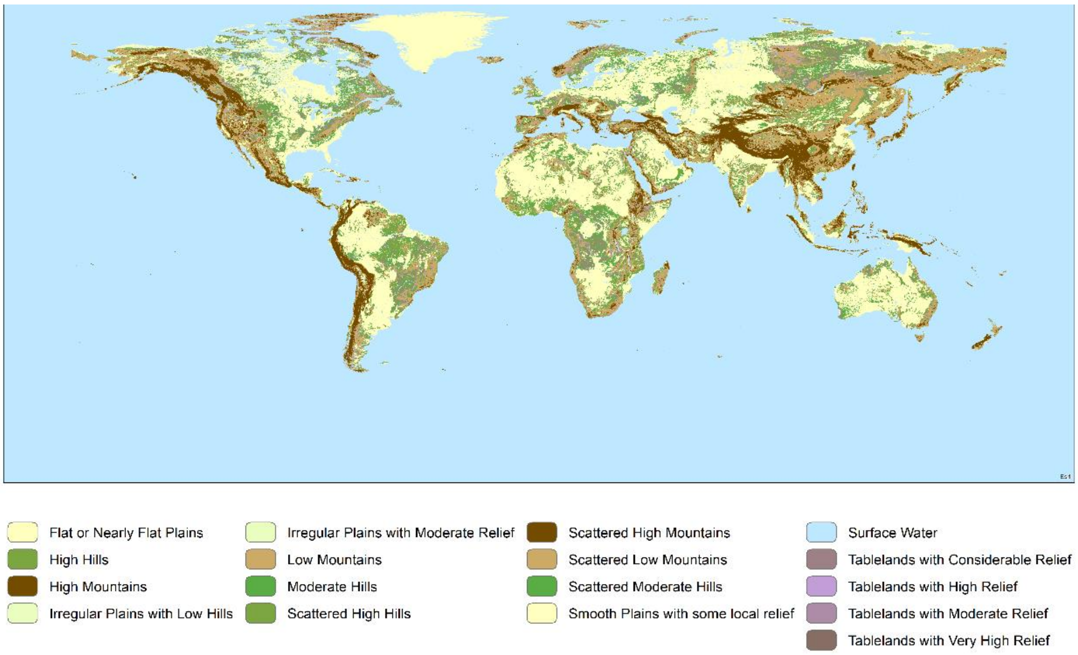


Fig.1 The global map of improved Hammond landform classification with 16 categories

Further, we aggregate the landforms into four classes: plains, hills, low mountains, and high mountains (Fig.2). These four major classes were divided according to the improved Hammond landform product and clustered the ecologically significant areas.

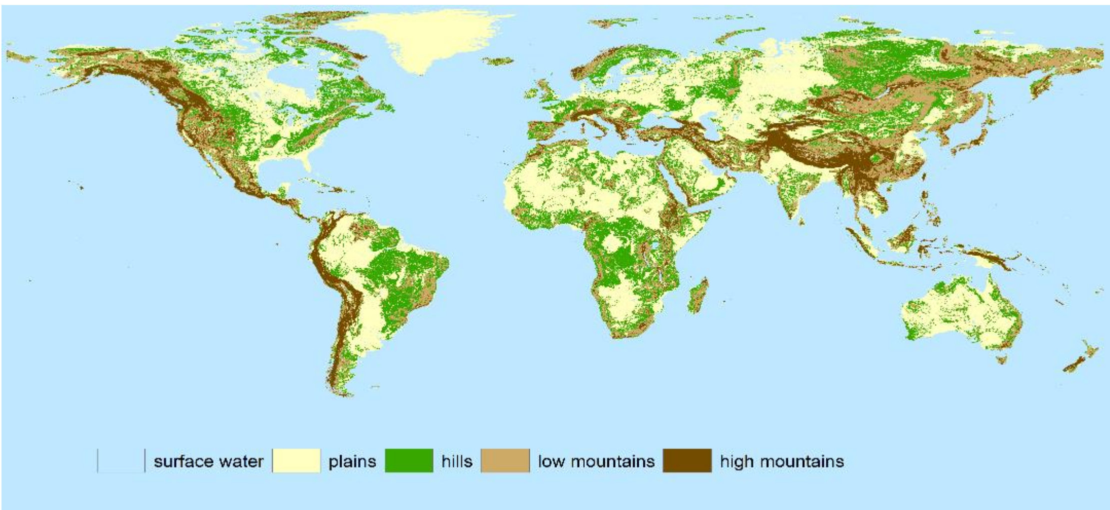


Fig. 2 The global map with 4 landform classes aggregated

Biomes

Biomes are large-scale environments that distinguished by plant and animal types and have formed in response to a shared physical climate. Each biome is mostly defined by climate and the same biome can be geographically distinct areas but with similar climate zone. Biomes tend to reflect the complexity of life patterns distribution and Earth's natural communities. It is a challenge to divide the world into a few biomes (ecological) zones, because one biome would change to the other with time. And the previous maps divide the Earth into extremely coarse biodiversity units. The latest classification is developed by Olson et al. (2001) convened by the World Wildlife Fund (WWF). It divided the terrestrial world as 14 biomes, and the resolution increased substantially compared with previous maps (Fig.3).

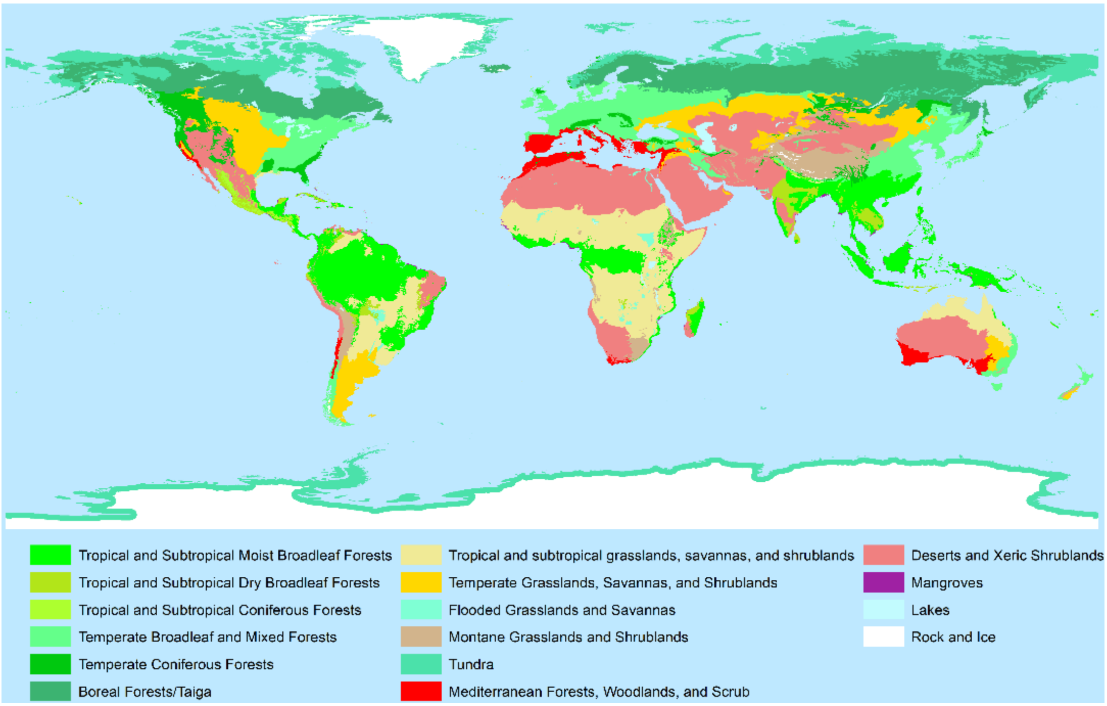


Fig.3 The global map of 14 biomes

We then grouped the biomes into three classes as forest, grassland, and desert according to the similar ecoregion (Fig.4).

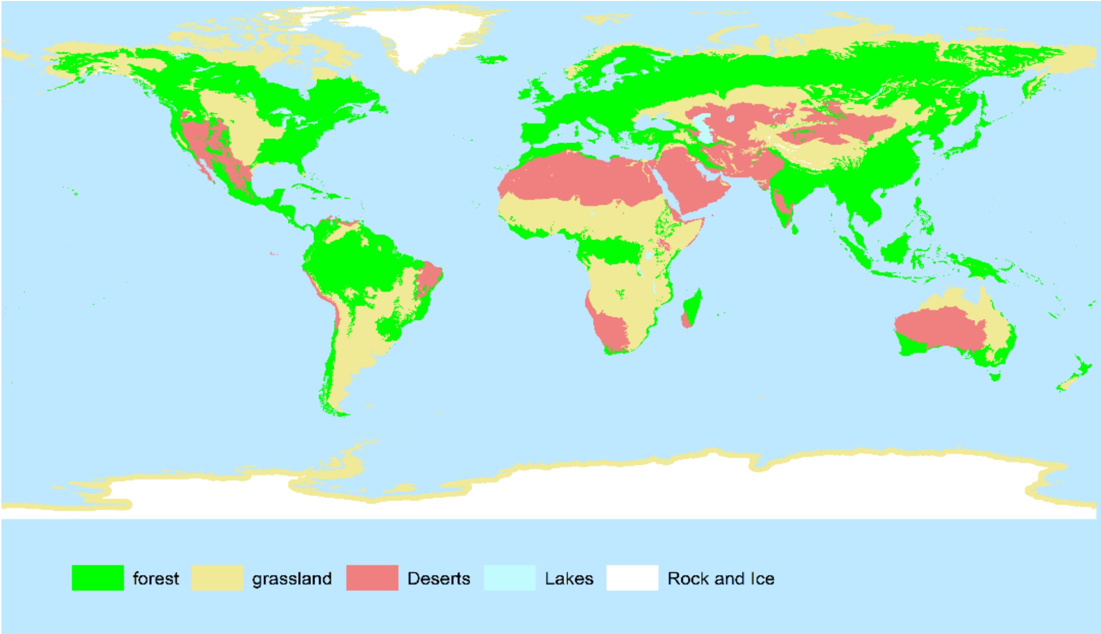


Fig.4 The global map of biomes aggregated in three classes

Anthromes (Anthropogenic biomes)

Human society has dramatically changed Earth's system and it is not accurate to classify the anthropogenic ecosystem by simply using the biomes. Therefore, anthropogenic biomes (Ellis & Ramankutty, 2008), which associate human and ecological systems, present an alternative view of the terrestrial biosphere based on an empirical analysis. The anthropogenic biomes are identified and mapped based on three databases (population, land use, and land cover) and divided into 19 anthropogenic biome classes (Fig.5).

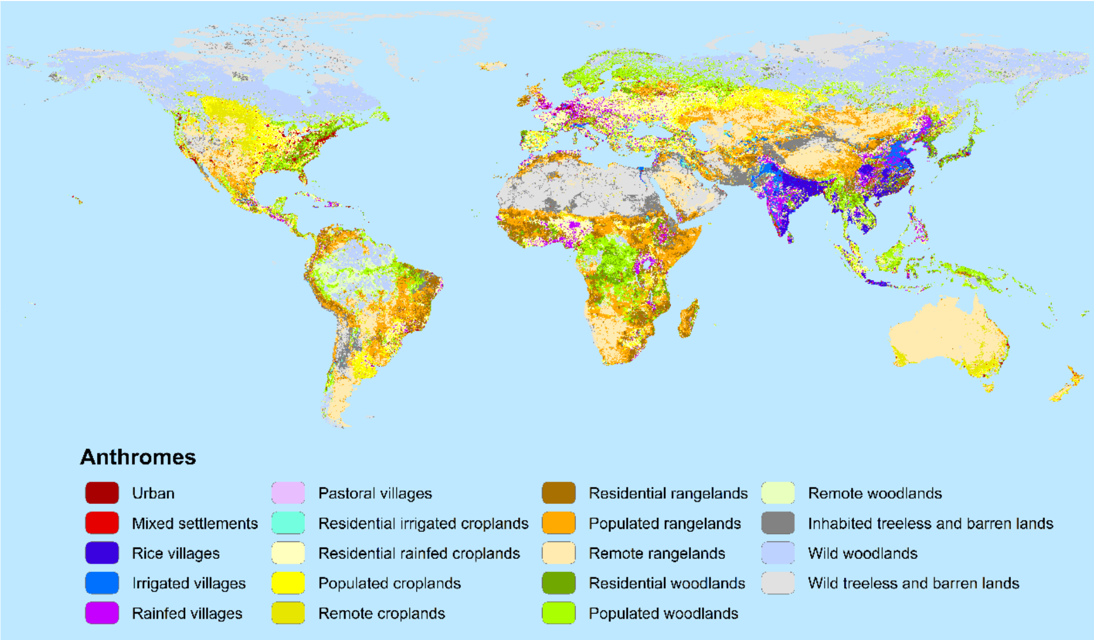


Fig.5 The global map of 19 anthromes classification

Anthromes classified human-ecosystem interaction into four classes based on the density of population: high population density (“dense” > 100 persons km^{-2}), substantial population density (“residential”, 10 to 100 persons km^{-2}), minor population density (“populated”, 1 to 10 persons km^{-2}), and inconsequential population density (“remote” < 1-person km^{-2}). According to the population density and the 19 anthromes stratifications, we further clustered the anthromes as four classes: settlements, croplands, rangelands and seminatural as well as wildlands (Fig.6).

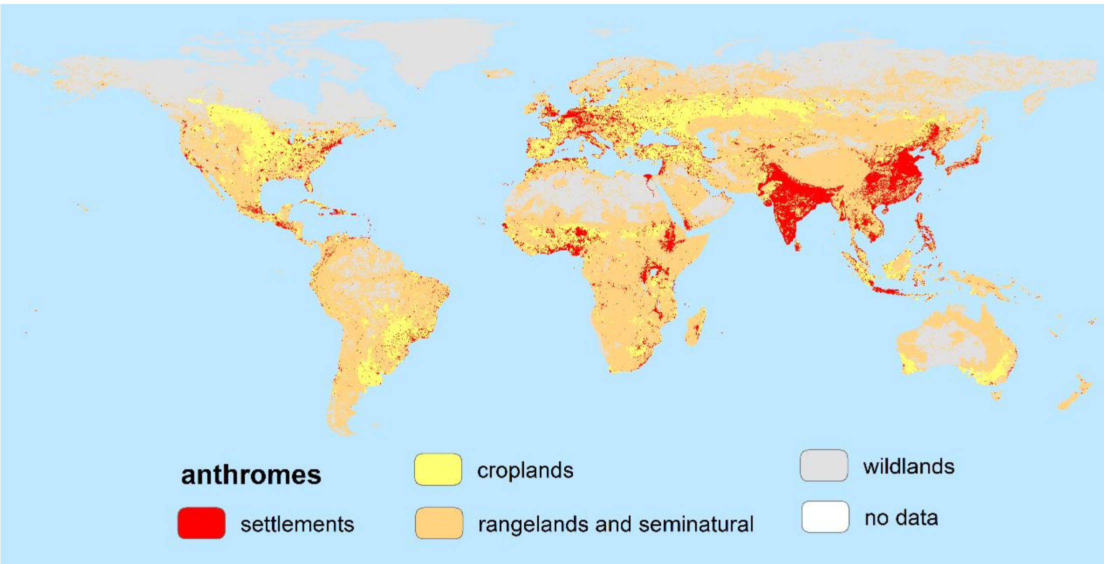


Fig. 6 The classification of aggregated anthromes

5.3.2 Data processing

The three previous described global datasets present different resolution and formats, so a unified criterion is needed for the global pattern assessment. We used the GLU (globe land units) which classified the world into 1.445 million equal-area hexagons of about approximately 100 km^2 each (Magliocca et, al. 2013). Then we stratified landforms, biomes and anthromes into GLUs and collected the high-resolution topographic datasets (point cloud, DTM) from all over the world and then categorize into GLUs. Thus, for each GLU ID, we could understand the stratification of landforms, biomes, anthromes, nighttime light and the availability of high-resolution topographic data. We finalized the global datasets according to the schematic scheme presented in Fig.7:

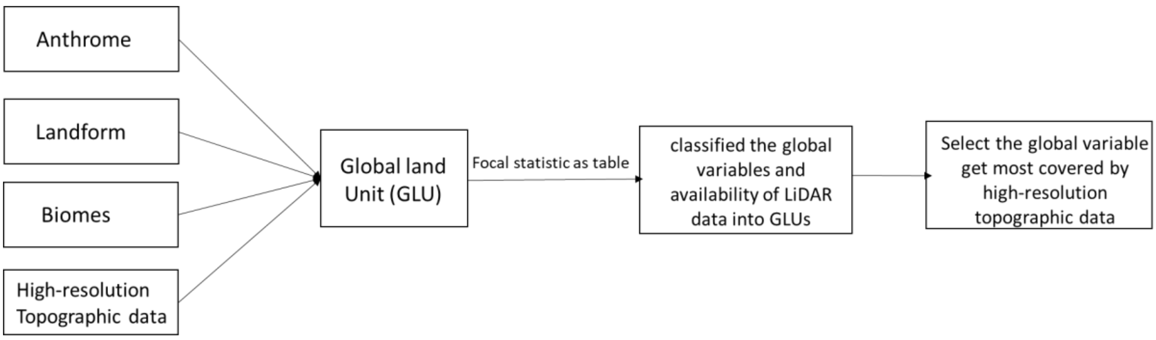


Fig.7 The workflow of the data processing

We estimated the percentage of LiDAR coverage in each classification of global variables (Tab.1) and computed that anthromes got the most covered.

Tab.1 Test of LiDAR coverage based on different stratification of global patterns (surface water is not considered)

global pattern	stratification	stratification percentage	Lidar coverage percentage
anthromes	settlement and village	10.05%	60.10%
	cropland	14.10%	16.28%
	rangeland and seminatural	47.39%	11.20%
	wildland	23.89%	3.61%

biomes	forest	43.13%	21.49%
	grassland	32.47%	24.81%
	desert	19.07%	3.14%
landforms	plains	19.89%	32.68%
	hills	12.98%	20.62%
	low mountains	8.24%	35.52%
	high mountains	5.47%	28.21%

(The sources of LiDAR data are listed in the chapter 4 supplement)

Once anthromes have been selected as the standard of global pattern stratification, we then chose sample sites where high-resolution Lidar data are available. For each classification, we selected five sites with the purpose of covering all the continents. But in some continents, such as Africa and Asia, due to the limitation of accessing to high-resolution topographic data, the sample studies cannot be evenly distributed in each continent. The selected study sites and geographic location can be seen in Fig.8.

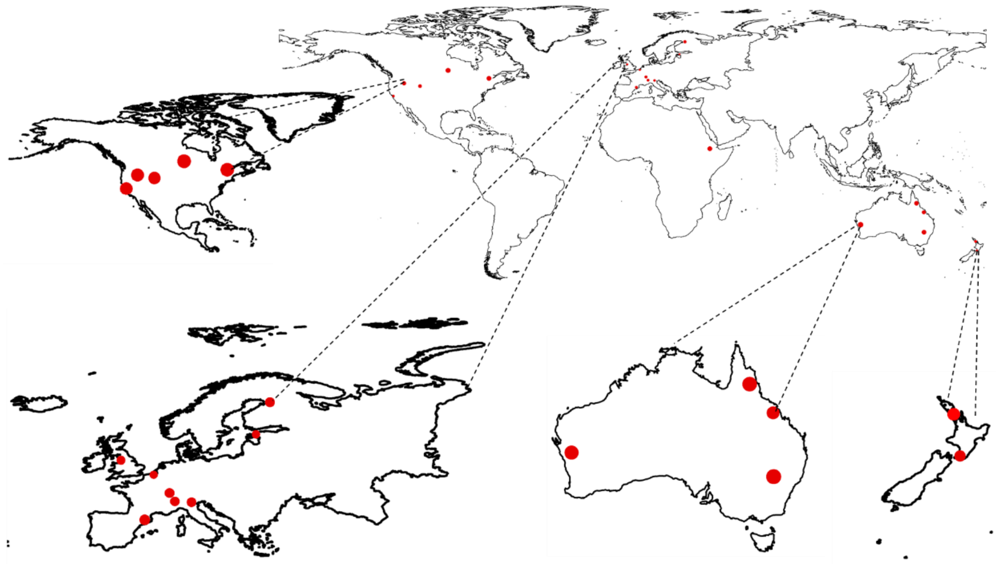


Fig. 8 The selected investigated sites across the world

5.3.3 The anthropogenic geomorphic and socio-economic parameters

Anthropogenic modification on geomorphology

We measure the percentage of human activities' alteration on morphology through the SLLAC metrics proposed by Sofia et al. (2014), which quantifies the local self-similarities of slopes. The idea based on this method is that natural areas are presenting low correlations among those neighboring since they are inherently irregular. However, artificial surfaces tend to display a higher level of self-similarity with surroundings to satisfy human needs for mobility and machine access. Therefore, the anthropogenic coverage could be computed through the degree of self-similarity of the slope. Briefly, the steps are as follows:

1) Evaluate correlation

$$Corr_{(i,j)} = \frac{\sum_{u,v}(W_{(i+u,j+v)} - \overline{W}_{i,j})(T_{u,v} - \overline{T})}{(\sum_{u.v}(W_{(i+u,j+v)} - \overline{W}_{i,j})^2 \sum_{u,v}(T_{u,v} - \overline{T})^2)^{0.5}} \quad (2)$$

To calculate the difference between a moving window (W) and a patch (T) centered at the center of the moving window. The correlation length (L) from the thresholding was defined as 37% of the maximum correlation value according to ISO standards (ISO2013). The length of correlation is the length of the longest line passing through the central pixel and connecting two boundary pixels on the extracted area connected to the central pixel. Thus, the final map of Slope Local Length of Auto-Correlation (SLLAC) could be computed accordingly.

2) The Spc (Surface Peak Curvature) of the SLLAC map defined as for every peak (pixel higher than its eight nearest neighbors):

$$Spc = -\frac{1}{2n}\sum_{i=1}^{n}\left[\left(\frac{\partial^2 z(x,y)}{\partial^2 x}\right) + \left(\frac{\partial^2 z(x,y)}{\partial^2 y}\right)\right] \quad (3)$$

Where z stands for the analyzed map value (SLLAC value) and x and y represent the corresponding cell spacing, n is the number of considered peaks. The Spc is inversely correlated with anthropogenic pressure (Sofia et al. 2015; Chen et al. 2015; Xiang et al. 2018). Surface morphology (slope) of regions presenting anthropogenic structures tends to be well organized (low Spc) and, in general, self - similar at a long distance.

3) The percentage of anthropogenic modification algorithms calculated in the form of:

$$Perc_{art} = p_1 Spc^3 + p_2 Spc^2 + p_3 Spc + p4 \quad (4)$$

Where p_1 to p_4 are empirical coefficients. This computation has been firstly presented and tested by Chen et al. (2015) through different trials.

Nighttime light data

Night-time light data have emerged as one of the most known geospatial data because of world-widely covered, easy and free access (Ghosh, 2011; Elvidge, et al. 2017;

Falchi et al., 2016; Witmer & O'Loughlin, 2011; Addison & Stewart, 2015). A lot of researches have revealed that night-time light (NTL) could be a proxy for a wide variety of human-related patterns and processes, such as socioeconomic dynamics, development level, urbanization, population density and GDP (Mellander, et al. 2015; Román et al., 2018; Wu, et al. 2018 ; Fu, et, al. 2017; Jean et al., 2016).

The NTL accuracy improved substantially since the launch of the National Polar-orbiting Partnership (NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) Day-Night Band (DNB) sensors (Cao, et, al. 2013). Compared with the former Operational Line Scanner (OLS) on the Defense Meteorological Satellite Program (DMSP), it presents a better spatial and radiometric performance because it provides a finer spatial resolution of 500 m and it is calibrated with the onboard solar diffuser (Elvidge, et, al. 2017). The stable annual light database is developed at the National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Center (NGDC). NPP Suomi and its VIIRS instruments observe the planet in vertical strips from pole to pole and produce an image with millions of pixels by repetitive scanning. In addition, each pixel of the day-night band can reflect the amount of light emission accurately through deciding the gain mode (low, medium or high) to be used during computation. The visualization map of NASA's Black Marble nighttime light data from the VIIRS DNB sensor is shown in Fig.9.

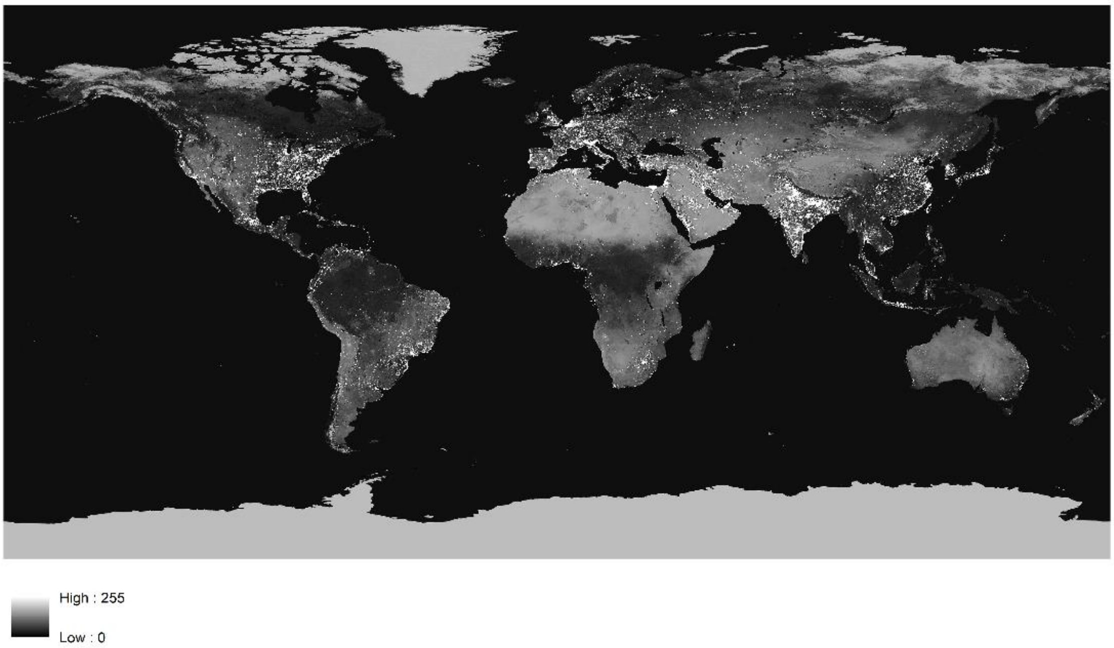


Fig.9 Global map of annual nighttime light 2016 (NASA Earth Observatory and NOAA National Geophysical Data Center)

The intensity of Visible Infrared Imaging Radiometer Suite (VIIRS) and spatial extent of anthropogenic visible emissions highly rely on the development level in urban areas. And even in a non-urban environment, the burning agricultural fields and the natural and human-made fires also generate night-time light. Studies have demonstrated that the NPP-VIIRS NTL data are useful to reflect the economic situation regionally (Wu et al., 2018; Chen & Nordhaus, 2015; Omar & Ismal, 2019; Bruederle & Hodler, 2018) and globally (Tilottama, 2011; Ghosh, et al. 2013; Proville, et al. 2017; Levin & Zhang, 2017). Therefore, it is appropriate to use NPP-VIIRS NTL data to measure the economic development level.

Since the anthropogenic geomorphic and socio-economic indicators have been chosen, the next step is to compute the correlation between these two variables based on each stratification of anthromes. We used the Pearson correlation coefficient to explore the correlations.

5.4 Results

5.4.1 Anthropogenic geomorphology assessment

We computed the anthropogenic modification on topography and the corresponding night-time light value in each study case. We selected an example of a study site in Italy, which classified as settlement in Anthromes. Fig.10 (a) presents the luminosity of night-time light, and the resolution is 500m as per the metadata. Fig. 10 (b) shows the human’s alteration of geomorphology and the pixel resolution is 2m as the same with high-resolution Lidar datasets.

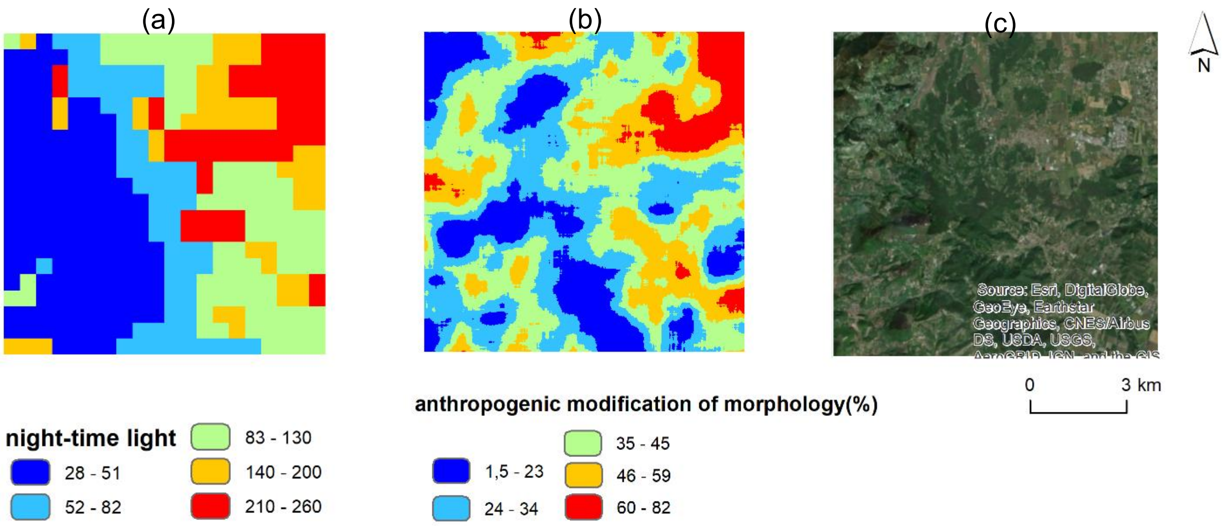


Fig.10 (a) night-time light（b）the anthropogenic modification of geomorphology (c) the satellite image (the case study is Colli Euganei, classified as settlement in anthromes)

To explore the correlation between datasets with different resolutions, we used the interpolation (Franke, 1985) to enlarge 2m resolution as 500m without losing its actual values as Fig.11 shows.

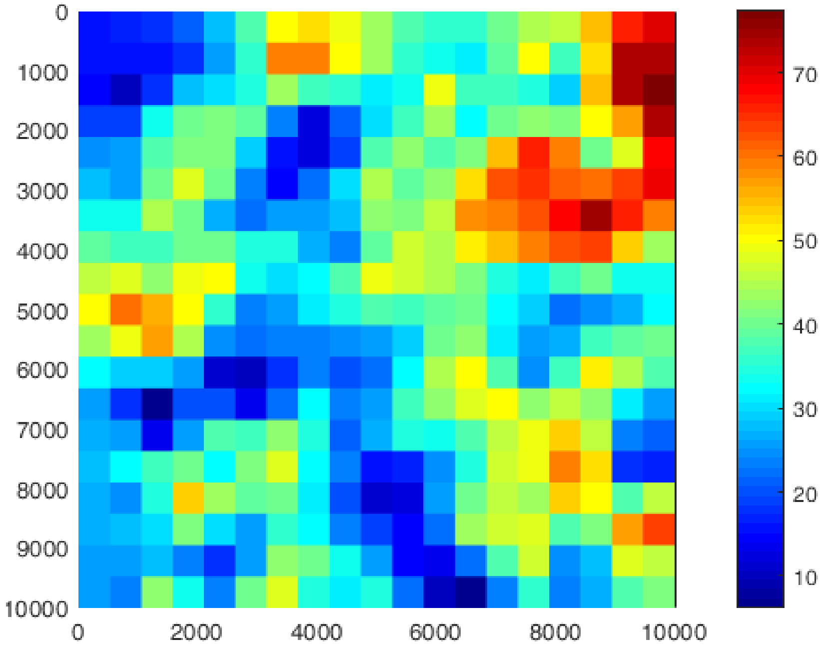


Fig.11 500m resolution of anthropogenic modification in the case study

5.4.2 The correlation between NTL and anthropogenic geomorphology

We explored the correlation between nighttime light and anthropogenic landforms in different categories. As we can see from dense settlement and village classification of anthromes (Fig.12), both the nighttime value and alteration on landforms are relatively large and the Pearson correlation coefficients are between 70%-80%.

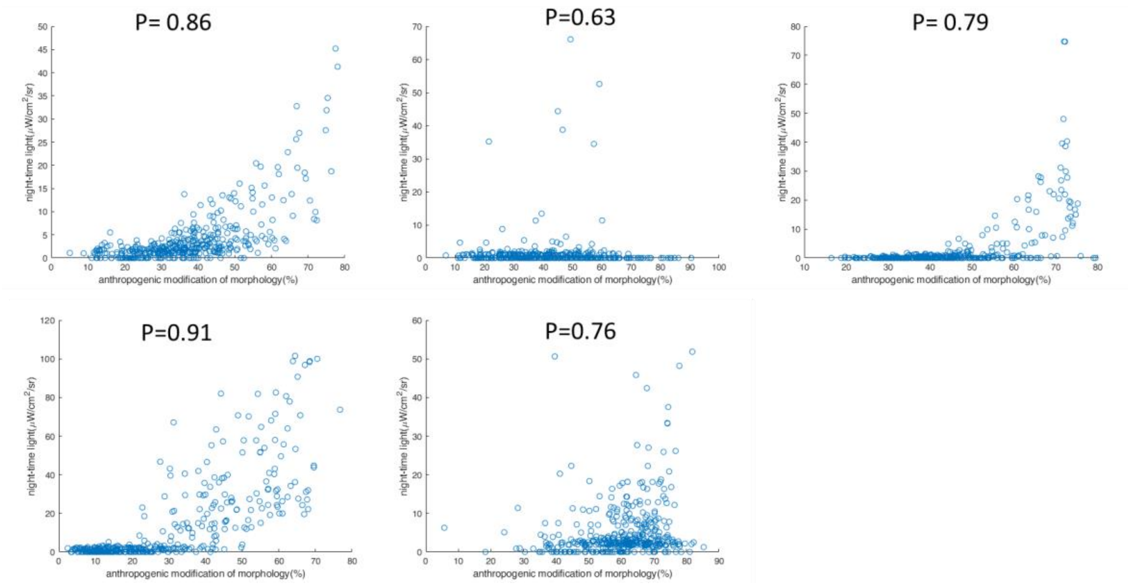


Fig. 12 The correlation between anthropogenic modification and nighttime light in dense settlement and village stratification in anthromes

From crop stratification (Fig.13) of anthromes, the Pearson correlation coefficients are around 30%- 50% percent. We can see that the anthropogenic modification is relatively high but the corresponding nighttime light value is relatively low. It is quite common in cropland because the human activities such as tillage work are intensive on the landscape, but there are less light during nighttime in farmland.

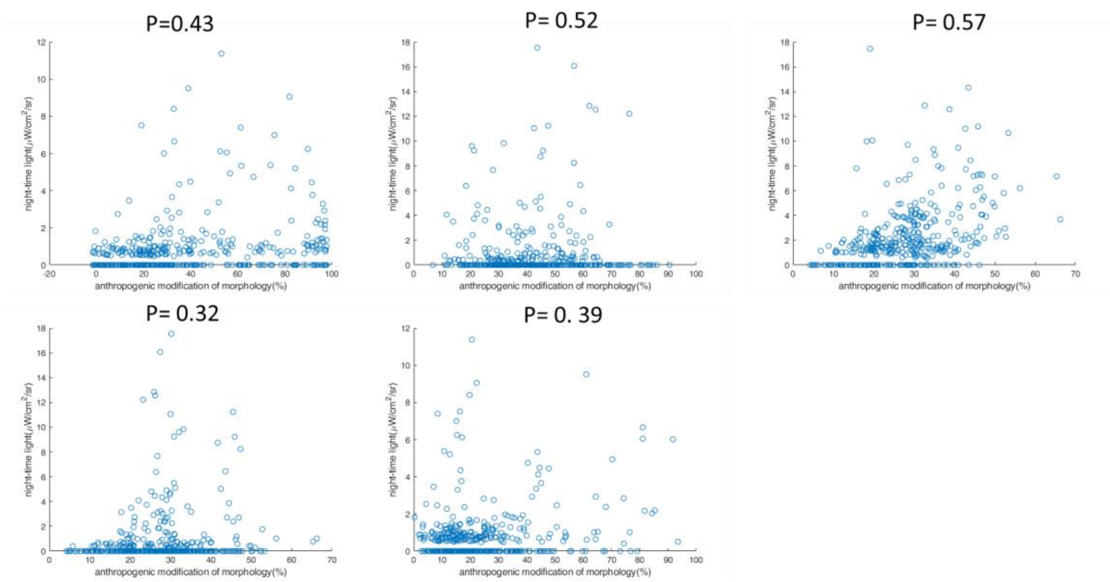


Fig. 13 The correlation between anthropogenic modification and nighttime light in crop stratification in anthromes

From the range and seminatural land of anthromes (Fig.14), the Pearson correlation coefficients are around 20% percent. Both the anthropogenic geomorphology (mostly less than 50% percent) and nighttime light (less than 15 units of luminosity) values are relatively low. The rangeland and seminatural landscape mostly affected by natural processes and less shaped from humans, so the anthropogenic impacts are little, also hard to detect the nighttime light in most of the areas.

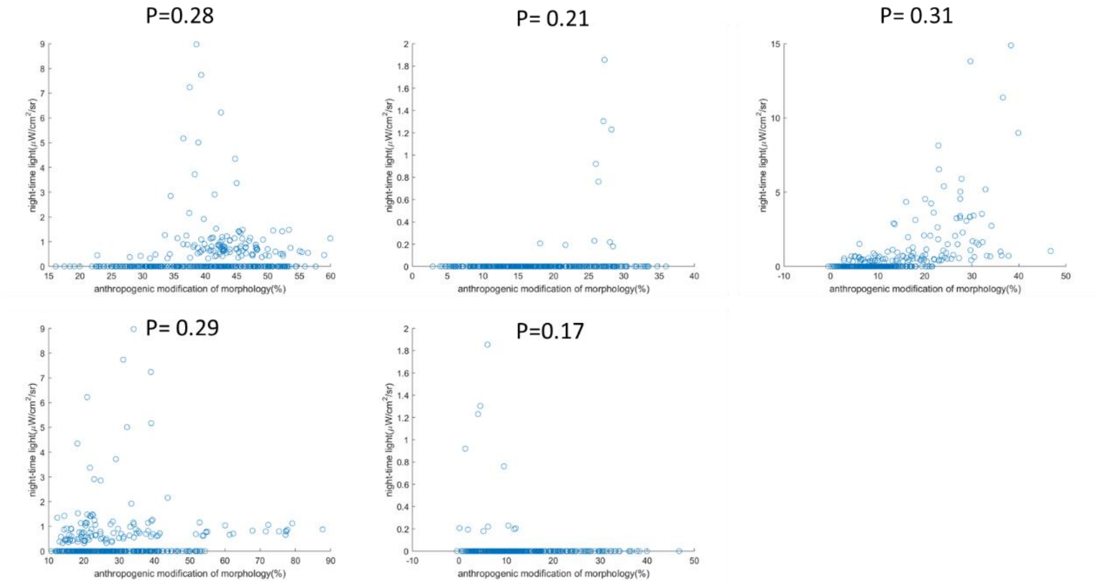


Fig. 14 The correlation between anthropogenic modification and nighttime light in range and seminatural stratification in anthromes

From the wildland of anthromes (Fig.15), the Pearson correlation coefficient are around 10%. It is hard to obtain the high-resolution datasets in wildland due to the less public attention and more resources needed to access those areas, and in some areas, the computations of anthropogenic geomorphology present big noises because almost no human's interference.

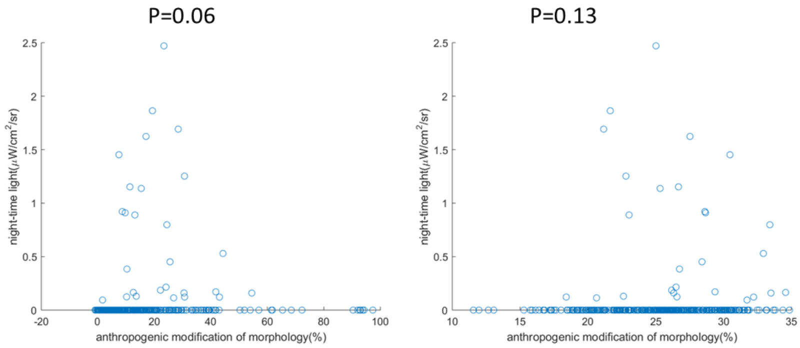


Fig. 15 The correlation between anthropogenic modification and nighttime light in wildland in anthromes

5.5 Discussion

5. 5.1 Assess the socio-economic impact on anthropogenic geomorphology

There are some scholars have made efforts to understand the human pressure on geomorphology, but the relationship between human society development and anthropogenic geomorphology modification is still unclear.

Some geomorphologists suggested to calculate the human environmental impact as a proxy to measure the anthropogenic geomorphological impact; the method is summarized by Erlich (1990):

$$I = P * A * T \qquad (5)$$

Where I is an environmental impact or the amount of pressure, P is population, and A is affluence per capita and T is technology or the power that human can make through technology. However, this equation cannot be applied to analyze the anthropogenic geomorphology impact because of several limitations. Firstly, the human's activities alteration on the landscape cannot be simply estimated through the people's functioning on the environment. The anthropogenic geomorphological impact is more related to the physical processes which haven't presented in this equation. Furthermore, the socio-economic indicators (populations, GDP, technology) have been used in the equation have no direct connection with human's capability of alteration on topography.

Nir (1983) developed an index which could be useful to quantify the potential anthropogenic geomorphological impact and formulated as

$$I = \frac{UP+DI}{2} * \frac{1}{100} * (Kc+Kr) \quad (6)$$

Where I is the index of potential anthropogenic geomorphology, UP is the percentage of urban population, DI is the percentage of illiteracy, these two parameters are related to the socio-economic conditions, and they represent the degree of development. Kc indicates the climatic condition mainly related to precipitation and Kr represent the relief categories measured by slope steepness, these two parameters tend to connect with physical processes, and the values range from 0.4 to 0.8 and from 0.2 to 0.8 respectively. The higher of Kc and Kr, the easier to be affected by climatic and the relief categories. The index has been classified into different classes between 0 to 1 based on countries and the higher value means the more harmful of the potential anthropogenic geomorphological processes. This index is the most commonly used but also has criticalities. The climatic and relief condition cannot be simply represented by precipitation and slope steepness and measured as numerical data. In addition, there is also no visible evidence to be shown that the urban population and the degree of illiteracy have direct connection with socio-economic development. And the result is exhibited with numerical data based on countries, but the physical condition varies largely from regions to regions in the same country.

Eric et al. (2002) created a map to measure the human pressure on the Earth surface and the modeling is described as follows:

Human footprint = f (population density, land transformation, accessibility, electrical power infrastructure) (7)

Such scientists provided nine datasets to represent the four indices indicated in eq. 7, and then standardized each dataset on a scale of 0 to 10 for the levels of human influence from the lowest to the highest. Then they sum up the datasets, and combined with biomes and biogeographic realms to create the percentage of human influence on the Earth surface globally. This provides a reference of indicators that relate to the socio-economic development status and the pressure on the land surface. However, these datasets highly dependent on each other and the sum of human influence scores lack of a logical justification of merely equally add up datasets. This cannot give an objective evaluation comprehensively of the human footprint on the land surface.

In our analysis, we provided a more articulated approach to assess the extent of artificial modification on the topography. We argue that the anthropogenic modification on the geomorphology relies on two key points: the intensity of human's force and the natural physical conditions of the Earth surface. We used the night time light datasets to measure the socio-economic activities which is the human's force. On the other hand, we coupled the anthromes, biomes and landforms classification to evaluate the physical condition of the landscape. After the computation based on global LiDAR availability coverage, we set anthromes to be the classification standard of anthropogenic geomorphology assessment based on topographic parameter SLLAC. In this global assessment, we considered both the anthropogenic and natural processes shaping the topography, and applied a realistic geomorphometric parameter to estimate the impact based on high-resolution topographic datasets which haven't been studied in global evaluation before.

5.5.2 The limitations of coupling the society with the geomorphology

The assessment of human's interference on the geomorphology presented this study has, of course, some limits. First, the nighttime light data cannot accurately reflect the development status of the society though it used as a proxy of socioeconomic impact. However, it is the only useable, for the purpose of this work, global spatial dataset. It is also important to acknowledge that some other socio-economic datasets (accessibility, population density, build-up environment) that reflect the human impact at a global scale could be used, but each global variable should be independent. For example, anthromes already includes the population density, so it cannot be used together with anthromes.

Most of the socioeconomic datasets correlates together and relate to population density. Another issue is that global datasets use the geographic coordination system (WGS 1984) but the geomorphometric computation indexes are often based on the projected coordination system of LiDAR data. There are some errors when transferring one coordination system to another one. But this is negligible and cannot be avoided since the projected coordination system varies from country to country. Another issue is that human's signatures on geomorphology vary from the utilizations. For example, the traditional practice of agriculture such as tillage and irrigation make a difference from the conservation practice (no-tillage, and maintaining permanent soil cover by using crop residues and cover crops). During the processing, we tried to cover different features but it's impossible to encompass all of them globally, also we couldn't find all the high-resolution data for the detailed inventory of features. Lastly, the global pattern we used is also based on general classification, and we didn't go further in this study. In a future research, we could stratify the classification in a more detailed way, covering the regional features, cultural and ecological diversities. The complexities of human society and the dynamic of people's functioning on the landscape make this study challenge; we couldn't accurately estimate human's impact on the geomorphology through data of a short time period. For example, humanity reshapes the landscape and thus influence geomorphology for thousands of years but the remote sensing data we obtain can only reflect the present status. We selected the most recent LiDAR datasets and present the correlation of the latest years without reflecting the changes of some regional areas. For example, the Loess Plateau in China has been under centuries of intensive human's interferences such as deforestation and over-grazing thus result in severe densification and soil erosion. After the grain for green project with afforestation and grazing restriction, the conservation and restoration have improved the ecosystem in the latest decades, and it may exhibit the less anthropogenic covered. Furthermore, the recent satellite data (2000-2017) reported that China and India made a prominent improvement in a greening pattern (Chen et al., 2019), and which could mitigate the human's footprint on the Earth surface.

5.5.3 The way to go forward

Humans, have been interfered the natural processes dramatically, and with the civilization transition, influenced the biota on Earth more actively and effectively (Stephens et al. 2019). The anthropogenic geomorphic impact has become a key factor of environmental management, including the appropriate distribution of environmental resources and the countermeasures of environmental values preservation. The correlation between socio-economic development and anthropogenic geomorphology provides the evidence of human's interferences over the terrestrial system with spatial scales, and identifies which areas are altered substantially with the stratification of anthromes. The results of correlation also offer the opportunity of land stewardship in a scientific and sustainable way. The countermeasures of sustainable development should be diverse with the extent of anthropogenic impacts on geomorphology. For example, if the correlation between socio-economic development and anthropogenic geomorphology index is high, the conservation practice is needed and the priority may focus on ecosystem restoration. For those places with relatively low correlation, the strategies should focus both on societal development and conservation of land together. In addition, for some developed countries or regions, the human alteration rate on the landscapes is less than some developing countries which are under intense construction. This implies that human may have less imprint on the topography in the future through scientific management and conservation awareness. Chen (2019) reveled a greening pattern that is strikingly prominent in China and India to achieve the goal of expanding forests and mitigating land degradation through a recent satellite image. Ellis (2019) also demonstrated the successful achievement of Natura 2000 network of the European Union (EU) in expanding and strengthening conservation on Earth – nearly 30,000 sites covering nearly 800,000 km^2. Taking control of our negative impact on the Earth's natural processes and maintaining the conditions for civilization to flourish maybe is the way forward. With the technology development and the perception of people (environmentalists, sensitivity versus humans related damages on the environment), humankind can take control of the negative impact and move forward to the positive way and eventually put less pressure on the landscape.

Considering the global scale impact that human have been exerted on the landscape, and the tendency of the influence is accelerating, geomorphologists need to undertake the responsibilities to raise people's awareness and be involved in the decisions for landscape conservation and restorations. In the past, geomorphologists mostly worked in the field and regional case studies, involved in a few multidisciplinary studies relate to the landscape. Mostly they focus on the geomorphometric analysis, rarely take the real responsibilities or hardly have the chance to work with land-use decisions. Nowadays, confronting with the critical situation, scientists should integrate the physical and social approaches, reinforce the multidiscipline communication, and explore a new way to capture the ongoing coactive relationships between socioeconomic development and the landscape. Especially geomorphologists are encouraged to embrace a broader view and access to wider public audiences, strengthen collaboration with ecologists, biologists, socialists, and humanists, explore the linkage of cause and effects from different perspectives. For the policymaker, it is necessary to promote a more sustainable strategy for landscape management and help the public to understand better regarding the relationship between human and the Earth. Citizens should well-understand how much pressure we exert on the Earth and put efforts together to moderate our imprints on the earth surface and build a healthier planet.

5.6 Conclusion

This paper has reviewed the potential of nighttime light data as the proxy of socioeconomic indicator, applied a geomorphometric index to compute the human's modification on topography to achieve the goal of the global assessment of anthropogenic geomorphology. Due to the limitation of global accessibility of high-resolution topographic datasets, we evaluate the human's impacts on geomorphology through the correlation of sample studies. Based on the available collection of high-resolution LiDAR datasets world widely, we selected (anthromes) as the standard of stratification of a global pattern as it got the most high-resolution topographic data coverage. We then computed the correlation between socioeconomic activities and the anthropogenic modification on the Earth surface of case studies from each classification of anthromes. Results revealed that average correlation reached up to 70%-80% for settlements, and was about 30%-50% across most croplands. The correlation was relatively lower in rangelands and seminatural (less than 20%) also in wildland (around 10%). From the results of correlation, we can understand how social development impact on the geomorphology for different ecosystem patterns.

Therefore, a wide range of countermeasures would be needed targeting different geomorphological alterations on the topography, and further goal could be achieved by exploring the relationship between human societal needs and the conservation of natural lands. The global assessment of anthropogenic geomorphology would help the public to understand that we shaped the Earth significantly, and further to find out the pathway to steward the landscape we highly dependent on. Human being already stepped into Anthropocene – in an era that human activities stewards of nature, whether in a positive or negative way. Stewardship the land facing the dilemma between human development and unavoidable geomorphic alteration in a long run. The ultimate goal for transforming the land is acquiring natural resources to meet the human's development, and which in adversely would have an impact on the landscape. Humankind needs to seek a way for moving forward with respecting the natural world but also developing society. A suitable strategy that integrate ecology, geomorphology, sociology and anthropology is needed for sustainable development.

5.7 Reference

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Supplement: LiDAR data avalibility across the world

Europe:

Country	Region	Source
Austria	Upper Austria	Land OBEROSTERREICH
	Wien	Open Data Portal Osterreich
Belgium	Flanders	Vlaanderen
	Wallonia	Géoportail de la Wallonie
Denmark		Styrelsen for Dataforsynng og Effektivisering
England	South West	Center for ecology & hydrology
Estonia		Estonia Land Board Geoportal
Finland		National land survey of Finland
France	Auvergne-Rhône-Alpes	centre regional Auvergne-Rhône-Alpes de L'information geographique
Germany	Hamburg	Transparenzportal Humburg
Germany	Hanover	Das offizielle Portal der Region und der Landeshauptstadt Hannover
Germany	North Rhine-Westphalia	OpenGeodata.NRW
Germany	Thuringia	Geoportal-Th.de
Ireland		DATA.GOV.IE
Italy	Basilicata	Regione Basilicata
	Bolzano, South Tyrol	Rete Civica dell'Alto Adige
	Calabria	Prodotti LiDAR- regione Calabria
	Friuli-Venezia	Regione Autonoma Friuli Venezia Giulia
	Lombardia	Regione Lombardia
	Sardinia	Prodotti LiDAR- regione Sardinia
	Toscana	Regione Toscana - SITA: Cartoteca
	Trentino	LiDAR Provincia Trentino
	Vale d'Aostae	Regione Autonoma Valle d'Aostae
	Veneto	OpenDataHub Italy
Lithuania		Geoportal.it
Luxemburg		The Luxembourgish data platform
Malta		Planning Authority

Netherland		Publieke Dienstverlening op de Kaart
Northern Ireland		Open data NI
Norway		HOYDEDATA
Scotland		data.gov.uk
Slovenia		ACENCIJA RS ZA OKOLJE
Spain	Gipuzkoa	Infraestructura de Datos Espaciales de Gipuzkoa
	Basque	GEO. Euskadi
	Catalonia	Institut Cartografic i Geologic de Catalunya
	La Rioja	GeoVisor IDErioja
Sweden		LANTMATERIET
Switzerland	Schaffhausen canton	Kanton Schaffhausen
	Solothurn canton	Kanton Solothurn
	Zurich canton	Kanton Zürich, Baudirektion, Amt für Raumentwicklung
Wales		Geo-Portal for Wales

North America:

Country	States	Source
USA	Alaska	Division of Geological & Geophysical surveys
	Minnesota	LiDAR Elevation Data for Minnesota
	New York City	LiDAR NYC DEM
	Idaho	IDAHO LiDAR Consortium
	Pennsylvania	PAMAP Lidar Elevation Data
	Washington	Puget Sound LiDAR Consortium
	Indiana	Indiana Spatial Data Portal
	Illinois	Illinois Geospatial Data Clearing house
	Kentucky	Kentuck's Elevation Data & Aerial Photography Program
	Louisiana	Atlas LiDAR
	Ohio	Ohio Geographically Referenced Information Program

	Vermont	Vermont Center for Geographic Information
		Interagency Elevation Inventory
		Nationwide LiDAR Dataset Wikipedia
		NOAA Digital Coast
		USGS The National Map
Canada		Government of Canada

Oceania:

Country	States	Source
New Zealand		Land Information New Zealand
Australia		Elevation and Depth – Foundation Spatial Data

Other sources :

University of Minnesota – Arctic DEM

(https://www.pgc.umn.edu/data/arcticdem/)

Earth Online – ESA (https://earth.esa.int/web/guest/home)

OpenTopography (https://opentopography.org/)

GitHub Elevation-data (https://github.com/topics/elevation-data)

6. FINAL REMARKS

Human society, together with natural forces, have reshaped the landforms through different processes, produced a variety of distinctive topographic signatures, and covered the large extent of Earth's surface. At present, at least one-third of the landscape is shaped by anthropogenic activities directly or indirectly.

To have a comprehensive understanding of anthropogenic geomorphology, this thesis first offered the interpretation of a full range of anthropogenic features as the sociocultural fingerprints of the societies. The integrated approaches combing geophysical, ecological and archeological methods are also provided. Recent remote sensing techniques helped in the feature's identification and labeling. Therefore, it is essential to understand that human modifies the landscape across multiple scales of time and space according to the socio-cultural evolution.

Then the thesis highlighted the fact that the geomorphology formed through anthropogenic forcing is statistically different if compared with surfaces affected by natural processes. The landscape has changed substantially over time with the socio-cultural changes.

Further, this thesis explored the driving force of anthropogenic modification on geomorphology and the magnitude of the impact. The result of correlation between socio-economic activities and anthropogenic geomorphology helped us to understand the extent of society's development on landscape in different stratification. Through the coupling relationship, the influence of socioeconomic development on the landforms in the past and at the present can be better explained; also the prediction of future landform and geomorphological processes produced by increasingly intensified human activities could be achieved. This offered the opportunity of suitable strategies for sustainable development in different regions.

Given the shortage of topographic datasets and the limitations of socioeconomic datasets that could offer, some uncertainties of the geomorphologic changes under human pressure exist. There are several follow-up problems to be solved to draw the correlations accurately. A statistical bias assessment is needed regarding different spatial grid units between topographic data and socioeconomic datasets. Furthermore, the correlation based on a more detailed stratification of global patterns could surely be carried out in the near future. To demonstrate the accuracy and robustness of the results, more case studies can be also conducted. In-depth explorations should move toward a global anthropogenic geomorphology map, which could further testify if the anthropogenic force exceeds the natural force and become the dominant factor influencing Earth surface. This can also be applied in urban planning and socioeconomic construction management.

The alteration of landforms by humans will probably become more evident with the ongoing socioeconomic development, especially in emerging national economies. The future research lines should also focus more on how to change people's mode of actions for a better utilization of landscape resources. The general suggestion is to balance the economic development, land use and ecological restoration for better land management in the future with multidisciplinary approaches integrating sociology, economy, ecology and geomorphology.

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Appendix: The codes for the Chapter 3 (Matlab)

The calculation of slope and mean curvature (The corresponding computation of raster load and raster write also being attached, but the Parallel slope/smooth/curvature and the method of compute slope/curvature coding haven't been put in this project because they have been tested and used)

```
%1. To calculate slope or curvature, load the input DTM (ArcGis *FLT file) [it will prompt a window to locate and load the input DTM]
%the input DTM
[dem,header] = rasterload();
cellsize=header.cellsize;

%smoothed DTM
SlopeKernel= 3; % kernel for slope evaluation;
UseParallel=1 ;% if you have the parallel toolbox active, set the parameters and then set UseParallel to 1
SmoothDTM=ParallelSmooth(dem,cellsize,SlopeKernel,UseParallel);

% for slope
SlopeKernel= 3; % kernel for slope evaluation;
UseParallel=1 ;% if you have the parallel toolbox active, set the parameters and then set UseParallel to 1
Slope=ParallelSlope(dem,cellsize,SlopeKernel,UseParallel);


% for   Curvature (see ComputeCurvature for full description)
CurvatureKernel= 3; % kernel for slope evaluation;
UseParallel=1 ;% if you have the parallel toolbox active, set the parameters and then set UseParallel to 1
Kmin=ParallelCurvature(dem,cellsize,CurvatureKernel,'min',UseParallel);         %min
```

```
curvature
Kmax=ParallelCurvature(dem,cellsize,CurvatureKernel,'max',UseParallel);        %max
curvature

% to save the file
rasterwrite(Slope,header)
rasterwrite(Kmin,header)
rasterwrite(Kmax,header)
%%Please note that the file saved from matlab, needs to be CONVERTED into a
%%raster in arcgis (conversion tool> flt to raster)
```

The rasterload coding corresponding to the loading of float value of DTM

```
function [dem,header]=rasterload(filename)
%%%load an arcGIS float raster%%%%%
% % Author: G.Sofia (giulia.sofiaATunipd.it) %%%%%
%%%%%%%latest update: 19th Feb. 2015

% Syntax
%         [dem,header]=demload(filename);
%
% Description
%
%         demload loads a matrix from an ESRI ArcGIS FLOAT file.
%         filename must be a string indicating the relative or absolute
%         file path, without the file extention. demload opens a dialog box for retrieving
the file, if no
%         filename is supplied.
%
% Output
%
%       dem -> raster map
%       header -> structure containing
%       header.nrows -> number of rows
```

```
%       header.ncols -> number of columns
%       header.cellsize -> size of cell
%       header.nodata -> nodata value
%       header.xllcorner -> x coordinates of the lower left corner
%       header.yllcorner -> y coordinate of the lower left corner

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% if the input file is not insert, the code prompt a window to search the
% file
if nargin<1
     [FileName,PathName] = uigetfile({'*.flt'});
    if FileName == 0
        disp(' no input file ')
        return
    end
    filename = [PathName FileName];
    filename=filename(1:end-4);
end
%open the header file
fid=fopen([filename,'.hdr'],'r');
% loop through header to find the information
header = struct('ncols',[],...
                'nrows',[],...
                'xllcorner',[],...
                'yllcorner',[],...
                'cellsize',[],...
                'nodata',[]);
names    = fieldnames(header);
nrnames = numel(names);
%creates the header structure
try
fseek(fid,0,'bof');
for r = 1:nrnames ;
```

```
        headertext = fgetl(fid);
        [headertext, headernum] = strtok(headertext,' ');
        I = cellfun(@(x,y) strcmpi(x(1:4),y(1:4)),names,repmat({headertext},nrnames,1));
        header.(names{I}) = str2double(headernum);
end
catch ME1
        error('header can not be read')
end

%load the raster map
dem = readmtx([filename,'.flt'],header.nrows,header.ncols,'float32',[1 header.nrows],[1
header.ncols],'ieee-le');
dem(dem==-9999)=NaN;
```

The raster write coding corresponding to the slope and curvature algorithm

```
function rasterwrite(Z,header,filename)
%%%save an arcGIS float raster%%%%%
% % Author: G.Sofia (giulia.sofiaATunipd.it) %%%%%
% % Latest Update 10.Feb.2015

% Syntax
%        rasterwrite(Z,header,filename)
%        rasterwrite(Z,header)
% Description
%        rasterwrite writes a matrix Z to an ESRI ArcGIS FLOAT file.
%        filename must be a string indicating the relative or absolute
%        file path. rasterwrite opens a dialog box for saving files, if no
%        filename is supplied.
%        header comes from the use of 'rasterload.m'
%        if the file name is not supplied, the code prompt a window to choose
%        the output file path
if nargin==2
```

```
    [FileName,PathName] = uiputfile({'*.flt'});
    if FileName == 0
        disp(' no output saved')
        return
    end
    filename = [PathName FileName];
    filename=filename(1:end-4);
end

siz = size(Z);
cellsize = header.cellsize;
nodata      = header.nodata;

% write header file
fid = fopen([filename,'.hdr'],'w');
fprintf(fid,'ncols%g\n',siz(2));
fprintf(fid,'nrows %g\n',siz(1));
fprintf(fid,'xllcorner %f\n',header.xllcorner);
fprintf(fid,'yllcorner %f\n',header.yllcorner);
fprintf(fid,'cellsize %g\n',abs(cellsize));
fprintf(fid,'NODATA_value %g\n',nodata);
fclose(fid);

Z(isnan(Z)) = nodata;

if cellsize<0;
    Z               = flipud(Z);
end
%save('filename','Z','-ascii','-append');
fileID = fopen([filename,'.flt'],'W');
fwrite(fileID,Z','float32','ieee-le');
fclose(fileID);
```

The statistical test in the four study areas (take an example of slope in floodplain, the other geomorphometric parameters and landforms keep the same)

```
%% crops
[dem_crop,header]=rasterload();
cellsize=header.cellsize;
nodata=-9999;
%Mean
mn=mean(dem_crop(isfinite(dem_crop)))
%Median
mdn=median(dem_crop(isfinite(dem_crop)))
%Standard deviation
dev_stdem_crop=-nanstd(dem_crop(isfinite(dem_crop))); %calcola la STD della xxx
%interquartile IQR
Interquantiledem_crop=iqr(dem_crop(isfinite(dem_crop)));
%outliers positive e negative
outliers_negdem_crop=quantile((dem_crop(isfinite(dem_crop))),.25)-
1.5*iqr((dem_crop(isfinite(dem_crop))));

outliers_posdem_crop=quantile((dem_crop(isfinite(dem_crop))),.75)+1.5*iqr((dem_c
rop(isfinite(dem_crop))));
%MAD (mean absolute deviation)
 madsdem_crop=mad((dem_crop(isfinite(dem_crop))));
%SKEWNESS
 sks=skewness((dem_crop(isfinite(dem_crop))));
%BOXPLOT
 figure(1)
 boxplot(dem_crop(isfinite(dem_crop)))
%PDF (probability density function)
figure
hist(dem_crop(isfinite(dem_crop)))   %this is just histogram
figure
[f,xi] = ksdensity(dem_crop(isfinite(dem_crop)));     %this is the PDF
plot(xi,f);
```

```
%% forests
[dem_fore,header]=rasterload();
cellsize=header.cellsize;
nodata=-9999;
%Mean
mn=mean(dem_fore(isfinite(dem_fore)))
%Median
mdn=median(dem_fore(isfinite(dem_fore)))
%Standard deviation
dev_stdem_fore=-nanstd(dem_fore(isfinite(dem_fore))); %calcola la STD della xxx
%interquartile IQR
Interquantiledem_fore=iqr(dem_fore(isfinite(dem_fore)));
%outliers positive e negative
  outliers_negdem_fore=quantile((dem_fore(isfinite(dem_fore))),.25)-
1.5*iqr((dem_fore(isfinite(dem_fore))));
outliers_posdem_fore=quantile((dem_fore(isfinite(dem_fore))),.75)+1.5*iqr((dem_for
e(isfinite(dem_fore))));
%MAD (mean absolute deviation)
  madsdem_fore=mad((dem_fore(isfinite(dem_fore))));
%SKEWNESS
  sks=skewness((dem_fore(isfinite(dem_fore))));
%BOXPLOT
  figure(1)
  boxplot(dem_fore(isfinite(dem_fore)))
%PDF (probability density function)
figure
hist(dem_fore(isfinite(dem_fore)))    %this is just histogram
figure
[f,xi] = ksdensity(dem_fore(isfinite(dem_fore)));     %this is the PDF
plot(xi,f);

%% Artificial
[dem_art,header]=rasterload();
cellsize=header.cellsize;
```

```
nodata=-9999;
%Mean
mn=mean(dem_art(isfinite(dem_art)))
%Median
mdn=median(dem_art(isfinite(dem_art)))
%Standard deviation
dev_stdem_art=-nanstd(dem_art(isfinite(dem_art))); %calcola la STD della xxx
%interquartile IQR
Interquantiledem_art=iqr(dem_art(isfinite(dem_art)));
%outliers positive e negative
  outliers_negdem_art=quantile((dem_art(isfinite(dem_art))),.25)-
1.5*iqr((dem_art(isfinite(dem_art))));
outliers_posdem_art=quantile((dem_art(isfinite(dem_art))),.75)+1.5*iqr((dem_art(isfi
nite(dem_art))));
%MAD (mean absolute deviation)
  madsdem_art=mad((dem_art(isfinite(dem_art))));
%SKEWNESS
  sks=skewness((dem_art(isfinite(dem_art))));
%BOXPLOT
  figure(1)
  boxplot(dem_art(isfinite(dem_art)))
%PDF (probability density function)
figure
hist(dem_art(isfinite(dem_art)))    %this is just histogram
figure
[f,xi] = ksdensity(dem_art(isfinite(dem_art)));      %this is the PDF
plot(xi,f);

%% grass
[dem_gras,header]=rasterload();
cellsize=header.cellsize;
nodata=-9999;
%Mean
mn=mean(dem_gras(isfinite(dem_gras)))
```

```
%Median
mdn=median(dem_gras(isfinite(dem_gras)))
%Standard deviation
dev_stdem_gras=-nanstd(dem_gras(isfinite(dem_gras))); %calcola la STD della xxx
%interquartile IQR
Interquantiledem_gras=iqr(dem_gras(isfinite(dem_gras)));
%outliers positive e negative
outliers_negdem_gras=quantile((dem_gras(isfinite(dem_gras))),.25)-
1.5*iqr((dem_gras(isfinite(dem_gras))));
outliers_posdem_gras=quantile((dem_gras(isfinite(dem_gras))),.75)+1.5*iqr((dem_gr
as(isfinite(dem_gras))));
%MAD (mean absolute deviation)
  madsdem_gras=mad((dem_gras(isfinite(dem_gras))));
%SKEWNESS
  sks=skewness((dem_gras(isfinite(dem_gras))));
%BOXPLOT
  figure(1)
  boxplot(dem_gras(isfinite(dem_gras)))
%PDF (probability density function)
figure
hist(dem_gras(isfinite(dem_gras)))    %this is just histogram
figure
[f,xi] = ksdensity(dem_gras(isfinite(dem_gras)));      %this is the PDF
plot(xi,f);

%% vineyards
[dem_viny,header]=rasterload();
cellsize=header.cellsize;
nodata=-9999;
%Mean
mn=mean(dem_viny(isfinite(dem_viny)))
%Median
mdn=median(dem_viny(isfinite(dem_viny)))
%Standard deviation
```

```
dev_stdem_viny=-nanstd(dem_viny(isfinite(dem_viny))); %calcola la STD della xxx
%interquartile IQR
Interquantiledem_viny=iqr(dem_viny(isfinite(dem_viny)));
%outliers positive e negative
outliers_negdem_viny=quantile((dem_viny(isfinite(dem_viny))),.25)-
1.5*iqr((dem_viny(isfinite(dem_viny))));
outliers_posdem_viny=quantile((dem_viny(isfinite(dem_viny))),.75)+1.5*iqr((dem_v
iny(isfinite(dem_viny))));
%MAD (mean absolute deviation)
  madsdem_viny=mad((dem_viny(isfinite(dem_viny))));
%SKEWNESS
  sks=skewness((dem_viny(isfinite(dem_viny))));
%BOXPLOT
  figure(1)
  boxplot(dem_viny(isfinite(dem_viny)))
%PDF (probability density function)
figure
hist(dem_viny(isfinite(dem_viny)))    %this is just histogram
figure
[f,xi] = ksdensity(dem_viny(isfinite(dem_viny)));      %this is the PDF
plot(xi,f);


%% Plot 5 PDF
figure
[f_crop,xi_crop] = ksdensity(dem_crop(isfinite(dem_crop)));
plot(xi_crop,f_crop,'c','LineWidth',2); %special for crop
hold on
[f_art,xi_art] = ksdensity(dem_art(isfinite(dem_art)));
plot(xi_art,f_art,'r','LineWidth',2);
hold on
[f_fore,xi_fore] = ksdensity(dem_fore(isfinite(dem_fore)));
plot(xi_fore,f_fore,'g','LineWidth',2);
hold on
```

```
[f_gras,xi_gras] = ksdensity(dem_gras(isfinite(dem_gras)));
plot(xi_gras,f_gras,'b','LineWidth',2);
hold on
[f_viny,xi_viny] = ksdensity(dem_viny(isfinite(dem_viny)));
plot(xi_viny,f_viny,'m','LineWidth',2);
hold off
legend('crops','Artificial','forest','grass','vineyard');
xlabel('slope(°)')
ylabel('PDFs')

%% the Kruskalwallis test
K_crop=dem_crop(isfinite(dem_crop));
K_fore=dem_fore(isfinite(dem_fore));
K_art=dem_art(isfinite(dem_art));
K_gras=dem_gras(isfinite(dem_gras));
K_viny=dem_viny(isfinite(dem_viny));
group=[repmat({'crop'},5074364,1);repmat({'forest'},9998537,1);repmat({'artificial'},
3694383,1);repmat({'grass'},1452574,1);repmat({'vineyard'},3995614,1)];
rng('default');
X=[K_crop;K_fore;K_art;K_gras;K_viny];
p = kruskalwallis(X,group);

%% the sample of kruskalwaills test
r1=randi(numel(dem_crop),1,1000);
r2=randi(numel(dem_fore),1,1000);
r3=randi(numel(dem_art),1,1000);
r4=randi(numel(dem_gras),1,1000);
r5=randi(numel(dem_viny),1,1000);
K_crop=dem_crop(r1');
K_fore=dem_fore(r2');
K_art=dem_art(r3');
K_gras=dem_gras(r4');
K_viny=dem_viny(r5');
group=[repmat({'crop'},1000,1);repmat({'forest'},1000,1);repmat({'artificial'},1000,1)
```

```
;repmat({'grass'},1000,1);repmat({'vineyard'},1000,1)];
rng('default');
X=[K_crop;K_fore;K_art;K_gras;K_viny];
p = kruskalwallis(X,group);

%% boxplot distribution
f_crop=dem_crop(isfinite(dem_crop));
f_fore=dem_fore(isfinite(dem_fore));
f_art=dem_art(isfinite(dem_art));
f_gras=dem_gras(isfinite(dem_gras));
f_viny=dem_viny(isfinite(dem_viny));
F=[f_crop;f_fore;f_art;f_gras;f_viny];
V1=repmat('crop',5074364,1);
V2=repmat('forest',9998537,1);
V3=repmat('artificial',3694383,1);
V4=repmat('grass',1452574,1);
V5=repmat('vineyard', 3995614,1);
V_LABEL=char(V1,V2,V3,V4,V5);
figure
boxplot(F,V_LABEL);
```

To keep the matrix size the same (take an example of land covers in floodplain)

```
%% change the dem_fore matrix size
b = zeros(4963,4990);
b(b == 0) = NaN;
b(1374:3588,2024:2966) = dem_fore;

%% change the dem_grass matrix size
d = zeros(4963,4990);
d(d == 0) = NaN;
d(1:4963,62:4927) = dem_gras;

%% stack and combine all data
```

```
a = dem_crop(:);
b = dem_fore(:);
c = dem_art(:);
d = dem_gras(:);
e = dem_viny(:);
%% stack and combine all data
a = dem_crop(:);
b = dem_fore(:);
c = dem_art(:);
d = dem_gras(:);
e = dem_viny(:);
rng('default');
x = [a b c d e];
x(isnan(x)) = 1000;
p = kruskalwallis(x);
```

To get the valid data and the outliers of land covers (take an example of crop in floodplain)

```
function
[NaNDataNum_crop,ValidData_crop,ValidDataUsing_crop,OutliersData_crop]=Calc
ulate(dem_crop)

% define the negative and postive limit
outliers_negdem_crop=quantile((dem_crop(isfinite(dem_crop))),.25)-
1.5*iqr((dem_crop(isfinite(dem_crop))));
outliers_posdem_crop=quantile((dem_crop(isfinite(dem_crop))),.75)+1.5*iqr((dem_c
rop(isfinite(dem_crop))));

    rc=size(dem_crop);
    row=rc(1);
    clo=rc(2);

    numNaN=0;
    numOutliers=0;
```

```
    numValidNum=0;
    numValidUsingNum=0;
    dem_crop_Outliers=[];
    dem_crop_Valid=[];
    dem_crop_ValidUsing=[];

    for i=1:row
        for j=1:clo
            if (isnan(dem_crop(i,j)))
%                   Get the number of NaN data
                numNaN=numNaN+1;
            else
%
                numValidNum=numValidNum+1;
                dem_crop_Valid(numValidNum)=dem_crop(i,j);
%
                if(dem_crop(i,j)>outliers_posdem_crop                    ||
dem_crop(i,j)<outliers_negdem_crop)
%
                    numOutliers=numOutliers+1;
                    dem_crop_Outliers(numOutliers)=dem_crop(i,j);
                else
%
                    numValidUsingNum=numValidUsingNum+1;
                    dem_crop_ValidUsing(numValidUsingNum)=dem_crop(i,j);
                end
            end
        end
    end
    NaNDataNum_crop=numNaN;
    ValidData_crop=dem_crop_Valid;
    ValidDataUsing_crop=dem_crop_ValidUsing;
    OutliersData_crop=dem_crop_Outliers;
    length(ValidData_crop)
```

```
    length(OutliersData_crop)
end
```

The codes for chapter 4

To classify the anthromes, biomes and landforms accordingly with the global land ID (Matlab)

```
clear;
profile on
%% load data
% load glu data (it was seperated into two parts now merge into one)
tmp                =    percentland11;
tmp2               =    percentland12;
id                 =    [tmp(:,1); tmp2(:,1)]; % id of glu
landarea               =    [tmp(:,2); tmp2(:,2)]; % land area percentage of glu
clear tmp tmp2
% initialize the data for saving
glu_id             =    zeros(size(id));
glu_mean           =    zeros(size(id));
glu_median         =    zeros(size(id));
%% read data anthrome seperated by continent names
% 1) Africa
anth_id            =    Africabiomes(:,1);
anth_mean          =    Africabiomes(:,7);
anth_median        =    Africabiomes(:,13);

[ind1,ind2]     =    ismember(anth_id,id);
ind1               =    find(ind1); % fitted index for anth_id
ind                =    find(ind2==0);
ind2(ind)          =    [   ]; % get the index of id

% set the value to the glu
glu_id(ind2)      =    anth_id(ind1); % redundantly reset the id, could be deleted
glu_mean(ind2)    =    anth_mean(ind1); % set mean val
```

```
glu_median(ind2)=     anth_median(ind1); % set median value

%% 2) Asia
anth_id             =     Asiabiomes(:,1);
anth_mean           =     Asiabiomes(:,7);
anth_median         =     Asiabiomes(:,13);

[ind1,ind2]         =     ismember(anth_id,id);
ind1                =     find(ind1); % fitted index for id
ind                 =     find(ind2==0);
ind2(ind)           =     [   ]; % get the index of anth_id

% set the value to the glu
glu_id(ind2)        =     anth_id(ind1); % redundantly reset the id, could be deleted
glu_mean(ind2)      =     anth_mean(ind1); % set mean val
glu_median(ind2)=     anth_median(ind1); % set median value

%% 3) Australia
anth_id             =     Australiabiomes(:,1);
anth_mean           =     Australiabiomes(:,7);
anth_median         =     Australiabiomes(:,13);

[ind1,ind2]         =     ismember(anth_id,id);
ind1                =     find(ind1); % fitted index for id
ind                 =     find(ind2==0);
ind2(ind)           =     [   ]; % get the index of anth_id

% set the value to the glu
glu_id(ind2)        =     anth_id(ind1); % redundantly reset the id, could be deleted
glu_mean(ind2)      =     anth_mean(ind1); % set mean val
glu_median(ind2)=     anth_median(ind1); % set median value(:,1);

%% 4) Europe
anth_id             =     Europebiomes(:,1);
```

```
anth_mean          =    Europebiomes(:,7);
anth_median        =    Europebiomes(:,13);

[ind1,ind2]        =    ismember(anth_id,id);
ind1               =    find(ind1); % fitted index for id
ind                =    find(ind2==0);
ind2(ind)          =    [   ]; % get the index of anth_id

% set the value to the glu
glu_id(ind2)       =    anth_id(ind1); % redundantly reset the id, could be deleted
glu_mean(ind2)     =    anth_mean(ind1); % set mean val
glu_median(ind2)=       anth_median(ind1); % set median value



%% 5) NorthAmerica
anth_id            =    northamericabiomes(:,1);
anth_mean          =    northamericabiomes(:,7);
anth_median        =    northamericabiomes(:,13);

[ind1,ind2]        =    ismember(anth_id,id);
ind1               =    find(ind1); % fitted index for id
ind                =    find(ind2==0);
ind2(ind)          =    [     ]; % get the index of anth_id

% set the value to the glu
glu_id(ind2)       =    anth_id(ind1); % redundantly reset the id, could be deleted
glu_mean(ind2)     =    anth_mean(ind1); % set mean val
glu_median(ind2)=       anth_median(ind1); % set median value
%% 6) Oceania
anth_id            =    oceaniabiomes(:,1);
anth_mean          =    oceaniabiomes(:,7);
anth_median        =    oceaniabiomes(:,13);

[ind1,ind2]        =    ismember(anth_id,id);
```

```
ind1               =    find(ind1); % fitted index for id
ind                =    find(ind2==0);
ind2(ind)          =    [   ]; % get the index of anth_id
% set the value to the glu
glu_id(ind2)       =    anth_id(ind1); % redundantly reset the id, could be deleted
glu_mean(ind2)     =    anth_mean(ind1); % set mean val
glu_median(ind2)=       anth_median(ind1); % set median value
%% 7) South America
anth_id            =    southamericabiomes(:,1);
anth_mean          =    southamericabiomes(:,7);
anth_median        =    southamericabiomes(:,13);

[ind1,ind2]        =    ismember(anth_id,id);
ind1               =    find(ind1); % fitted index for id
ind                =    find(ind2==0);
ind2(ind)          =    [   ]; % get the index of anth_id
% set the value to the glu
glu_id(ind2)       =    anth_id(ind1); % redundantly reset the id, could be deleted
glu_mean(ind2)     =    anth_mean(ind1); % set mean val
glu_median(ind2)=       anth_median(ind1); % set median value
%% save the data to excel
dlmwrite('glu_biomes.csv',[glu_id(:) glu_mean(:) glu_median(:)]);

glu_total=[id landarea gluanthrome(:,2:3) glulandform(:,2:3) glubiomes(:,2:3)];
a = table(glu_total);
writetable(a, 'G:\anthro_geo\glu_totaldata.csv')

profile viewer
```

To find out the matching ID for the local area which accessible for the high-resolution free LiDAR/point cloud data

```
clear;
profile on
%% find the corresponding global id in the local file
```

```
% Global data: glu_total.xlsx
% local data: northAmerica_topo.xlsx
gfname          =     'glu_total.xlsx';
glob            =     xlsread(gfname,'A:A'); % global data

%% import the global data
tmp                   =     glutotal1;
tmp2                  =     glutotal2;
glob_id             =     [tmp(:,1); tmp2(:,1)];
lidar           =     zeros(size(glob_id)); % initialize lidar accessbility
loc             =     xlsread('northAmerica_topo.xlsx','A:A'); % local data

% find the corresponding global id in the local data
ind             =     find(ismember(glob_id,loc));
lidar(ind)    =     1; % those have corresponding id

a=lidar(1:length(glutotal1));
b=lidar(length(glutotal1)+1:length(glutotal1)+length(glutotal2));



%% local data for Europe
% UK Lidarglu
loc_Wales = walesglu;
loc_Eng = Englandglu;
loc_UK = [loc_Wales(:,1); loc_Eng(:,1)];

% Germany Lidarglu
loc_Berlin = Berlinglu;
loc_Hum = Humberglu;
loc_NRW = NRWglu;
loc_Germ = [loc_Berlin(:,1); loc_Hum(:,1);loc_NRW(:,1)];

% Italy Lidarglu
loc_Sis = Sisilyglu;
```

```
loc_Merge = mergeglu;
loc_Italy = [loc_Sis(:,1); loc_Merge(:,1)];

loc_Austria = Wienglu;
loc_Bel = Flandersglu;
loc_Den = Denmarkglu;
loc_Est = Estoniaglu;
loc_Fin = Finlandglu;
loc_Fra = Franceglu;
loc_Mal = MLTglu;
loc_Neth = Netherlandglu;
loc_Slo = Sloveniaglu;
loc_spa = Cataloniaglu;
loc_Swiss = Swissglu;

loc_Europe = [loc_Austria(:,1);
loc_Bel(:,1);loc_Den(:,1);loc_Est(:,1);loc_Fin(:,1);loc_Fra(:,1);loc_Mal(:,1);loc_Neth
(:,1);loc_Slo(:,1);loc_spa(:,1);loc_Swiss(:,1);loc_Italy(:,1);loc_Germ(:,1);loc_UK(:,1)
];
ind_Europe = find(ismember(glob_id,loc_Europe));
lidar = zeros(size(glob_id));
lidar(ind_Europe) = 1;

a_Europe=lidar(1:length(glutotal1));

b_Europe=lidar(length(glutotal1)+1:length(glutotal1)+length(glutotal2));

%% the Australia and New Zealand and Asia global ID
loc_NS = NewSouthglu;
loc_QS = Queenslandglu;
loc_Tas = Tasmaniaglu;
loc_Australia = [loc_NS(:,1); loc_QS(:,1);loc_Tas(:,1)];

% New Zealand global ID from the web crawler
```

```
loc_NZ = NZglu;

% Asia global ID
loc_Asia = Angkorglu;

%% the north America global ID
loc_America   = Americaglu;
loc_Canada   = Canadaglu;
loc_NA = [loc_America(:,1); loc_Canada(:,1)];

%% the Arctic of the world global ID
Russia_Asia = RAglu;
Russia_Europe = REglu;
loc_Russia =   [Russia_Asia(:,1); Russia_Europe(:,1)];



loc_Arctic_Canada = ArcticCanadaglu;
loc_Arctic_Norway = ArcticNorwayglu;
loc_Arctic_Iceland = ArcticIcelandglu;
loc_Arctic_Greenland = ArcticGreenlandglu;
loc_Arctic = [loc_Russia(:,1);
loc_Arctic_Canada(:,1);loc_Arctic_Norway(:,1);loc_Arctic_Iceland(:,1);loc_Arctic_
Greenland(:,1)];

%% the local data combination
loc_total = [loc_NA(:,1); loc_Europe(:,1);loc_Arctic(:,1);
loc_Australia(:,1);loc_NZ(:,1);loc_Asia(:,1)];

ind_total      =   find(ismember(glob_id,loc_total));
lidar          =   zeros(size(glob_id));
lidar(ind_total ) =   1;

a_total=lidar(1:length(glutotal1));
```

b_total=lidar(length(glutotal1)+1:length(glutotal1)+length(glutotal2));

The Web crawler python code for downloading the high-resolution Lidar datasets (take an example of New Zealand elevation website, The Web crawler coding is different accordingly to the different website, I just show an example)

```
#login the elevation website
def login(driver):
    # access https://data.linz.govt.nz/data/category/elevation
    driver.get('https://data.linz.govt.nz/data/category/elevation')

    # find the sign in button
    signinlinkpath='//*[@id="userMenus"]/div[2]/a'
    #click the sign in button
    driver.find_element_by_xpath(signinlinkpath).click()

    # input username,the username is my username
    usernameinputpath='//*[@id="id_username"]'
    driver.find_element_by_xpath(usernameinputpath).send_keys("my username")

nextButtonpath='/html/body/div[1]/div[2]/div/div[2]/div/div[2]/form/div[2]/input'
    driver.find_element_by_xpath(nextButtonpath).click()

    # //input the password,the password is Echo_password
    passwordInputPath='//*[@id="id_password"]'

driver.find_element_by_xpath(passwordInputPath).send_keys("Echo_password")

    # click the login button to login

loginbtnpath='/html/body/div[1]/div[2]/div/div[2]/div/div[2]/form/div[2]/input'
    driver.find_element_by_xpath(loginbtnpath).click()
```

```
# get all the url of the index tiles
def getIndexTileLink():
    fullspanpath = '//*[@id="leftpaneContent"]/div[1]'
    fullspan = driver.find_element_by_xpath(fullspanpath).find_elements_by_tag_name("p")
    for paragraph in fullspan:
        paracontent = paragraph.text
        if "The index tiles are available as layer" in paracontent:
            links = paragraph.find_elements_by_tag_name("a")
            link = links[1].get_attribute("href")
            return link

#main function
if __name__=="__main__":
    # initial the chrome browser setting
    chrome_options = webdriver.ChromeOptions()
    chrome_options.add_argument('--headless')
    # driver = webdriver.Chrome(r"C:\Users\Administrator\PycharmProjects\AllCase\tool\chromedriver.exe",
    #                           options=chrome_options)
    # load the driver of chrome
    driver = webdriver.Chrome(r"../tool/chromedriver.exe")
    url = 'https://data.linz.govt.nz/data/category/elevation/?page='
    driver.implicitly_wait(20)
    page=1
    links = [ ]
    #login
    login(driver)

    # there are 65 items and every page has 10 items
    for i in range(7):
        pageNum = i+1
        # construct the url of every page
```

```
            currentURL = url+str(pageNum)
            try:
                # access the url
                driver.get(currentURL)
                contentpath='//*[@id="ResultContainer"]/div'
                contentTable=driver.find_element_by_xpath(contentpath)
                rows=contentTable.find_elements_by_tag_name("h4")
                for item in rows:
                    # get the url from the content
                    link = item.find_element_by_tag_name("a").get_attribute("href")
                    print(link)
                    # add the link to the array and store it in memory
                    links.append(link)
                driver.get_cookies()
                driver.delete_all_cookies()
            except:
                # print the exception
                print(Exception)
        # after we get all the links,just access the URL and download the shape file
        for linkitem in links:
            driver.get(linkitem)
            indextilelink=getIndexTileLink()
            driver.get(indextilelink)
            panelPath='//*[@id="leftpaneHeader"]'

menu=driver.find_element_by_xpath(panelPath).find_element_by_class_name("item
Menu")
            menu.click()
            downloaddiv=menu.find_element_by_class_name("trigger-download-
dialog")
            # get the url
            downloadlink=downloaddiv.get_attribute("href")
            driver.get(downloadlink)
```

```
downloadbuttonpath = '//*[@id="form_submit"]'
downbutton = driver.find_element_by_xpath(downloadbuttonpath)
downbutton.click()

#download
exportclasspath='downloadDialogZipLink'
driver.find_element_by_class_name(exportclasspath).click()
print("get the shape file "+linkitem)
```

To calculate the percentage of Lidar accessibility with corresponding nighttime light datasets (take an example of dense settlement in category 2)

```
function [x] = identify(data,lidar,nt)            % x is the sample data
% input data
% 1. data = matrix that has land categories inside
% 2. lidar = matrix of lidar (ex. lidar = 1 is there is lidar)
% 3. nt = matrix of nighttime (ex. nt = 0 is no nighttime VALUE)


x = zeros(size(data));

for i = 1:length(x)
    if data(i,:) ==2 && lidar(i,:) == 1
        x(i,:) = nt(i,:);
    else
        x(i,:)= NaN;
    end
end

end

function [T] = identify(data,nt)               % T is the totality
% input data
% 1. data = matrix that has land categories inside
% 2. nt = matrix of nighttime (ex. nt = 0 is no nighttime VALUE)

T = zeros(size(data));

for i = 1:length(T)
    if data(i,:) == 1
        T(i,:) = nt(i,:);
    else
        T(i,:)= NaN;
    end
end
```

```
end
```

The interpolation of anthropogenic geomorphology (the resolution of anthropogenic geomorphology is 2m and need to keep in line with the resolution of night time light data, I didn't put the computation coding of anthropogenic geomorphology in the attachment because those coding are already being tested and verified)

```
% define data geometry
xmin = 0; xmax = 10e3; % x
ymin = 0; ymax = 10e3; % y
nx=20; ny = 20; % no. of nodes
% generate grid @ night
[xnt,ynt] = meshgrid(linspace(xmin,xmax,nx),linspace(ymin,ymax,ny));

% original data
nxat= 5001;nyat=5001;
[xant,yant] = meshgrid(linspace(xmin,xmax,nxat),linspace(ymin,ymax,nyat));

figure(1),clf;pcolor(xant,yant,dem_ant);shading interp;colorbar;colormap(jet)
axis ij image

% help interp2
% interpolate original data to low resolution 20*20
data_low = interp2(xant,yant,dem_ant,xnt,ynt);
data_low = inpaint_nans(data_low,4);
% % just in case data <0
% ind          =     find(data_low<0);
% if ~isempty(ind)
%        [i,j]     =     sub2ind(size(data_low),ind);
%
% end
```

```
figure(2),clf;pcolor(xnt,ynt,data_low);shading interp;colorbar;colormap(jet)
axis ij image;
shading flat

data_low(:);
```

The way of interpolating

```
function B=inpaint_nans(A,method)
% INPAINT_NANS: in-paints over nans in an array
% usage: B=INPAINT_NANS(A)              % default method
% usage: B=INPAINT_NANS(A,method)     % specify method used
%
% Solves approximation to one of several pdes to
% interpolate and extrapolate holes in an array
%
% arguments (input):
%     A - nxm array with some NaNs to be filled in
%
%     method - (OPTIONAL) scalar numeric flag - specifies
%          which approach (or physical metaphor to use
%          for the interpolation.) All methods are capable
%          of extrapolation, some are better than others.
%          There are also speed differences, as well as
%          accuracy differences for smooth surfaces.
%
%          methods {0,1,2} use a simple plate metaphor.
%          method   3 uses a better plate equation,
%                     but may be much slower and uses
%                     more memory.
%          method   4 uses a spring metaphor.
%          method   5 is an 8 neighbor average, with no
%                     rationale behind it compared to the
```

```
%                         other methods. I do not recommend
%                         its use.
%
%            method == 0 --> (DEFAULT) see method 1, but
%              this method does not build as large of a
%              linear system in the case of only a few
%              NaNs in a large array.
%              Extrapolation behavior is linear.
%
%            method == 1 --> simple approach, applies del^2
%              over the entire array, then drops those parts
%              of the array which do not have any contact with
%              NaNs. Uses a least squares approach, but it
%              does not modify known values.
%              In the case of small arrays, this method is
%              quite fast as it does very little extra work.
%              Extrapolation behavior is linear.
%
%            method == 2 --> uses del^2, but solving a direct
%              linear system of equations for nan elements.
%              This method will be the fastest possible for
%              large systems since it uses the sparsest
%              possible system of equations. Not a least
%              squares approach, so it may be least robust
%              to noise on the boundaries of any holes.
%              This method will also be least able to
%              interpolate accurately for smooth surfaces.
%              Extrapolation behavior is linear.
%
%              Note: method 2 has problems in 1-d, so this
%              method is disabled for vector inputs.
%
%            method == 3 --+ See method 0, but uses del^4 for
%              the interpolating operator. This may result
```

```
%               in more accurate interpolations, at some cost
%               in speed.
%
%            method == 4 --+ Uses a spring metaphor. Assumes
%               springs (with a nominal length of zero)
%               connect each node with every neighbor
%               (horizontally, vertically and diagonally)
%               Since each node tries to be like its neighbors,
%               extrapolation is as a constant function where
%               this is consistent with the neighboring nodes.
%
%            method == 5 --+ See method 2, but use an average
%               of the 8 nearest neighbors to any element.
%               This method is NOT recommended for use.
%
% arguments (output):
%      B - nxm array with NaNs replaced
%
%
% Example:
%    [x,y] = meshgrid(0:.01:1);
%    z0 = exp(x+y);
%    znan = z0;
%    znan(20:50,40:70) = NaN;
%    znan(30:90,5:10) = NaN;
%    znan(70:75,40:90) = NaN;
%
%    z = inpaint_nans(znan);
%
%
% See also: griddata, interp1
%
% Author: John D'Errico
% e-mail address: woodchips@rochester.rr.com
```

```
% Release: 2
% Release date: 4/15/06


% I always need to know which elements are NaN,
% and what size the array is for any method
[n,m]=size(A);
A=A(:);
nm=n*m;
k=isnan(A(:));

% list the nodes which are known, and which will
% be interpolated
nan_list=find(k);
known_list=find(~k);

% how many nans overall
nan_count=length(nan_list);

% convert NaN indices to (r,c) form
% nan_list==find(k) are the unrolled (linear) indices
% (row,column) form
[nr,nc]=ind2sub([n,m],nan_list);

% both forms of index in one array:
% column 1 == unrolled index
% column 2 == row index
% column 3 == column index
nan_list=[nan_list,nr,nc];

% supply default method
if (nargin<2) || isempty(method)
   method = 0;
elseif ~ismember(method,0:5)
```

```
    error 'If supplied, method must be one of: {0,1,2,3,4,5}.'
end

% for different methods
switch method
  case 0
    % The same as method == 1, except only work on those
    % elements which are NaN, or at least touch a NaN.

    % is it 1-d or 2-d?
    if (m == 1) || (n == 1)
        % really a 1-d case
        work_list = nan_list(:,1);
        work_list = unique([work_list;work_list - 1;work_list + 1]);
        work_list(work_list <= 1) = [];
        work_list(work_list >= nm) = [];
        nw = numel(work_list);

        u = (1: nw)';
        fda = sparse(repmat(u,1,3),bsxfun(@plus,work_list,-1:1), ...
            repmat([1 -2 1],nw,1),nw,nm);
    else
        % a 2-d case

        % horizontal and vertical neighbors only
        talks_to = [-1 0;0 -1;1 0;0 1];
        neighbors_list=identify_neighbors(n,m,nan_list,talks_to);

        % list of all nodes we have identified
        all_list=[nan_list;neighbors_list];

        % generate sparse array with second partials on row
        % variable for each element in either list, but only
        % for those nodes which have a row index > 1 or < n
```

```
    L = find ((all_list(:,2) > 1) & (all_list(:,2) < n));
    nl =length(L);
    if nl>0
      fda=sparse(repmat(all_list(L,1),1,3), ...
        repmat(all_list(L,1),1,3)+repmat([-1 0 1],nl,1), ...
        repmat([1 -2 1],nl,1),nm,nm);
    else
      fda=spalloc(n*m,n*m,size(all_list,1)*5);
    end

    % 2nd partials on column index
    L = find((all_list(:,3) > 1) & (all_list(:,3) < m));
    nl=length(L);
    if nl>0
      fda=fda+sparse(repmat(all_list(L,1),1,3), ...
        repmat(all_list(L,1),1,3)+repmat([-n 0 n],nl,1), ...
        repmat([1 -2 1],nl,1),nm,nm);
    end
  end

  % eliminate knowns
  rhs=-fda(:,known_list)*A(known_list);
  k=find(any(fda(:,nan_list(:,1)),2));

  % and solve...
  B=A;
  B(nan_list(:,1))=fda(k,nan_list(:,1))\rhs(k);

 case 1
  % least squares approach with del^2. Build system
  % for every array element as an unknown, and then
  % eliminate those which are knowns.

  % Build sparse matrix approximating del^2 for
```

```
% every element in A.

% is it 1-d or 2-d?
if (m == 1) || (n == 1)
   % a 1-d case
   u = (1:(nm-2))';
   fda = sparse(repmat(u,1,3),bsxfun(@plus,u,0:2), ...
      repmat([1 -2 1],nm-2,1),nm-2,nm);
else
   % a 2-d case

   % Compute finite difference for second partials
   % on row variable first
   [i,j]=ndgrid(2:(n-1),1:m);
   ind=i(:)+(j(:)-1)*n;
   np=(n-2)*m;
   fda=sparse(repmat(ind,1,3),[ind-1,ind,ind+1], ...
      repmat([1 -2 1],np,1),n*m,n*m);

   % now second partials on column variable
   [i,j]=ndgrid(1:n,2:(m-1));
   ind=i(:)+(j(:)-1)*n;
   np=n*(m-2);
   fda=fda+sparse(repmat(ind,1,3),[ind-n,ind,ind+n], ...
      repmat([1 -2 1],np,1),nm,nm);
end

% eliminate knowns
rhs=-fda(:,known_list)*A(known_list);
k=find(any(fda(:,nan_list),2));

% and solve...
B=A;
B(nan_list(:,1))=fda(k,nan_list(:,1))\rhs(k);
```

```
case 2
 % Direct solve for del^2 BVP across holes

 % generate sparse array with second partials on row
 % variable for each nan element, only for those nodes
 % which have a row index > 1 or < n

 % is it 1-d or 2-d?
 if (m == 1) || (n == 1)
   % really just a 1-d case
   error('Method 2 has problems for vector input. Please use another method.')

 else
   % a 2-d case
   L = find((nan_list(:,2) > 1) & (nan_list(:,2) < n));
   nl=length(L);
   if nl>0
     fda=sparse(repmat(nan_list(L,1),1,3), ...
       repmat(nan_list(L,1),1,3)+repmat([-1 0 1],nl,1), ...
       repmat([1 -2 1],nl,1),n*m,n*m);
   else
     fda=spalloc(n*m,n*m,size(nan_list,1)*5);
   end

   % 2nd partials on column index
   L = find((nan_list(:,3) > 1) & (nan_list(:,3) < m));
   nl=length(L);
   if nl>0
     fda=fda+sparse(repmat(nan_list(L,1),1,3), ...
       repmat(nan_list(L,1),1,3)+repmat([-n 0 n],nl,1), ...
       repmat([1 -2 1],nl,1),n*m,n*m);
   end
```

```
    % fix boundary conditions at extreme corners
    % of the array in case there were nans there
    if ismember(1,nan_list(:,1))
      fda(1,[1 2 n+1])=[-2 1 1];
    end
    if ismember(n,nan_list(:,1))
      fda(n,[n, n-1,n+n])=[-2 1 1];
    end
    if ismember(nm-n+1,nan_list(:,1))
      fda(nm-n+1,[nm-n+1,nm-n+2,nm-n])=[-2 1 1];
    end
    if ismember(nm,nan_list(:,1))
      fda(nm,[nm,nm-1,nm-n])=[-2 1 1];
    end

    % eliminate knowns
    rhs=-fda(:,known_list)*A(known_list);

    % and solve...
    B=A;
    k=nan_list(:,1);
    B(k)=fda(k,k)\rhs(k);

  end

 case 3
  % The same as method == 0, except uses del^4 as the
  % interpolating operator.

  % del^4 template of neighbors
  talks_to = [-2 0;-1 -1;-1 0;-1 1;0 -2;0 -1; ...
      0 1;0 2;1 -1;1 0;1 1;2 0];
  neighbors_list=identify_neighbors(n,m,nan_list,talks_to);
```

```
% list of all nodes we have identified
all_list=[nan_list;neighbors_list];

% generate sparse array with del^4, but only
% for those nodes which have a row & column index
% >= 3 or <= n-2
L = find( (all_list(:,2) >= 3) & ...
          (all_list(:,2) <= (n-2)) & ...
          (all_list(:,3) >= 3) & ...
          (all_list(:,3) <= (m-2)));
nl=length(L);
if nl>0
  % do the entire template at once
  fda=sparse(repmat(all_list(L,1),1,13), ...
      repmat(all_list(L,1),1,13) + ...
      repmat([-2*n,-n-1,-n,-n+1,-2,-1,0,1,2,n-1,n,n+1,2*n],nl,1), ...
      repmat([1 2 -8 2 1 -8 20 -8 1 2 -8 2 1],nl,1),nm,nm);
else
  fda=spalloc(n*m,n*m,size(all_list,1)*5);
end

% on the boundaries, reduce the order around the edges
L = find((((all_list(:,2) == 2) | ...
           (all_list(:,2) == (n-1))) & ...
          (all_list(:,3) >= 2) & ...
          (all_list(:,3) <= (m-1))) | ...
         (((all_list(:,3) == 2) | ...
           (all_list(:,3) == (m-1))) & ...
          (all_list(:,2) >= 2) & ...
          (all_list(:,2) <= (n-1))));
nl=length(L);
if nl>0
  fda=fda+sparse(repmat(all_list(L,1),1,5), ...
    repmat(all_list(L,1),1,5) + ...
```

```
          repmat([-n,-1,0,+1,n],nl,1), ...
        repmat([1 1 -4 1 1],nl,1),nm,nm);
end

L = find( ((all_list(:,2) == 1) | ...
                  (all_list(:,2) == n)) & ...
                (all_list(:,3) >= 2) & ...
                (all_list(:,3) <= (m-1)));
nl=length(L);
if nl>0
    fda=fda+sparse(repmat(all_list(L,1),1,3), ...
        repmat(all_list(L,1),1,3) + ...
          repmat([-n,0,n],nl,1), ...
        repmat([1 -2 1],nl,1),nm,nm);
end

L = find( ((all_list (:,3) == 1) | ...
                  (all_list(:,3) == m)) & ...
                (all_list(:,2) >= 2) & ...
                (all_list(:,2) <= (n-1)));
nl=length(L);
if nl>0
    fda=fda+sparse(repmat(all_list(L,1),1,3), ...
        repmat(all_list(L,1),1,3) + ...
          repmat([-1,0,1],nl,1), ...
        repmat([1 -2 1],nl,1),nm,nm);
end

% eliminate knowns
rhs=-fda(:,known_list)*A(known_list);
k=find(any(fda(:,nan_list(:,1)),2));

% and solve...
B=A;
```

```
  B(nan_list(:,1))=fda(k,nan_list(:,1))\rhs(k);

case 4
  % Spring analogy
  % interpolating operator.

  % list of all springs between a node and a horizontal
  % or vertical neighbor
  hv_list=[-1 -1 0;1 1 0;-n 0 -1;n 0 1];
  hv_springs=[];
  for i=1:4
     hvs=nan_list+repmat(hv_list(i,:),nan_count,1);
     k=(hvs(:,2)>=1) & (hvs(:,2)<=n) & (hvs(:,3)>=1) & (hvs(:,3)<=m);
     hv_springs=[hv_springs;[nan_list(k,1),hvs(k,1)]];
  end

  % delete replicate springs
  hv_springs=unique(sort(hv_springs,2),'rows');

  % build sparse matrix of connections, springs
  % connecting diagonal neighbors are weaker than
  % the horizontal and vertical springs
  nhv=size(hv_springs,1);
  springs=sparse(repmat((1:nhv)',1,2),hv_springs, ...
       repmat([1 -1],nhv,1),nhv,nm);

  % eliminate knowns
  rhs=-springs(:,known_list)*A(known_list);

  % and solve...
  B=A;
  B(nan_list(:,1))=springs(:,nan_list(:,1))\rhs;

case 5
```

```
% Average of 8 nearest neighbors

% generate sparse array to average 8 nearest neighbors
% for each nan element, be careful around edges
fda=spalloc(n*m,n*m,size(nan_list,1)*9);

% -1,-1
L = find((nan_list(:,2) > 1) & (nan_list(:,3) > 1));
nl=length(L);
if nl>0
   fda=fda+sparse(repmat(nan_list(L,1),1,2), ...
      repmat(nan_list(L,1),1,2)+repmat([-n-1, 0],nl,1), ...
      repmat([1 -1],nl,1),n*m,n*m);
end

% 0,-1
L = find(nan_list(:,3) > 1);
nl=length(L);
if nl>0
   fda=fda+sparse(repmat(nan_list(L,1),1,2), ...
      repmat(nan_list(L,1),1,2)+repmat([-n, 0],nl,1), ...
      repmat([1 -1],nl,1),n*m,n*m);
end

% +1,-1
L = find((nan_list(:,2) < n) & (nan_list(:,3) > 1));
nl=length(L);
if nl>0
   fda=fda+sparse(repmat(nan_list(L,1),1,2), ...
      repmat(nan_list(L,1),1,2)+repmat([-n+1, 0],nl,1), ...
      repmat([1 -1],nl,1),n*m,n*m);
end

% -1,0
```

```
L = find(nan_list(:,2) > 1);
nl=length(L);
if nl>0
   fda=fda+sparse(repmat(nan_list(L,1),1,2), ...
      repmat(nan_list(L,1),1,2)+repmat([-1, 0],nl,1), ...
      repmat([1 -1],nl,1),n*m,n*m);
end

% +1,0
L = find(nan_list(:,2) < n);
nl=length(L);
if nl>0
   fda=fda+sparse(repmat(nan_list(L,1),1,2), ...
      repmat(nan_list(L,1),1,2)+repmat([1, 0],nl,1), ...
      repmat([1 -1],nl,1),n*m,n*m);
end

% -1,+1
L = find((nan_list(:,2) > 1) & (nan_list(:,3) < m));
nl=length(L);
if nl>0
   fda=fda+sparse(repmat(nan_list(L,1),1,2), ...
      repmat(nan_list(L,1),1,2)+repmat([n-1, 0],nl,1), ...
      repmat([1 -1],nl,1),n*m,n*m);
end

% 0,+1
L = find(nan_list(:,3) < m);
nl=length(L);
if nl>0
   fda=fda+sparse(repmat(nan_list(L,1),1,2), ...
      repmat(nan_list(L,1),1,2)+repmat([n, 0],nl,1), ...
      repmat([1 -1],nl,1),n*m,n*m);
end
```

```
  % +1,+1
  L = find((nan_list(:,2) < n) & (nan_list(:,3) < m));
  nl=length(L);
  if nl>0
    fda=fda+sparse(repmat(nan_list(L,1),1,2), ...
      repmat(nan_list(L,1),1,2)+repmat([n+1, 0],nl,1), ...
      repmat ([1 -1],nl,1),n*m,n*m);
  end

  % eliminate knowns
  rhs=-fda(:,known_list)*A(known_list);

  % and solve...
  B=A;
  k=nan_list(:,1);
  B(k)=fda(k,k)\rhs(k);

end

% all done, make sure that B is the same shape as
% A was when we came in.
B= reshape (B,n,m);

% ====================================================
%           end of main function
% ====================================================
% ====================================================
%           begin subfunctions
% ====================================================
function neighbors_list=identify_neighbors(n,m,nan_list,talks_to)
% identify_neighbors: identifies all the neighbors of
%      those nodes in nan_list, not including the nans
%      themselves
```

```
%
% arguments (input):
%   n,m - scalar - [n,m]=size(A), where A is the
%         array to be interpolated
%   nan_list - array - list of every nan element in A
%         nan_list(i,1) == linear index of i'th nan element
%         nan_list(i,2) == row index of i'th nan element
%         nan_list(i,3) == column index of i'th nan element
%   talks_to - px2 array - defines which nodes communicate
%         with each other, i.e., which nodes are neighbors.
%
%         talks_to(i,1) - defines the offset in the row
%                        dimension of a neighbor
%         talks_to(i,2) - defines the offset in the column
%                        dimension of a neighbor
%
%         For example, talks_to = [-1 0;0 -1;1 0;0 1]
%         means that each node talks only to its immediate
%         neighbors horizontally and vertically.
%
% arguments(output):
%   neighbors_list - array - list of all neighbors of
%         all the nodes in nan_list

if ~isempty(nan_list)
  % use the definition of a neighbor in talks_to
  nan_count=size(nan_list,1);
  talk_count=size(talks_to,1);

  nn= zeros(nan_count*talk_count,2);
  j=[1,nan_count];
  for i=1:talk_count
    nn(j(1):j(2),:)=nan_list(:,2:3) + ...
        repmat(talks_to(i,:),nan_count,1);
```

```
    j=j+nan_count;
  end

  % drop those nodes which fall outside the bounds of the
  % original array
  L = (nn(:,1)<1)|(nn(:,1)>n)|(nn(:,2)<1)|(nn(:,2)>m);
  nn(L,:)=[];

  % form the same format 3 column array as nan_list
  neighbors_list=[sub2ind([n,m],nn(:,1),nn(:,2)),nn];

  % delete replicates in the neighbors list
  neighbors_list=unique(neighbors_list,'rows');

  % and delete those which are also in the list of NaNs.
  neighbors_list=setdiff(neighbors_list,nan_list,'rows');

else
  neighbors_list=[];
end
```

The coefficient of nighttime light data and anthropogenic geomorphology datasets (this is a showcase of one study area)

```
%% import the data of nightitme
[dem_night,header]=rasterload();
cellsize=header.cellsize;
nodata=-9999;

%% import data of anthropogenic geomorphology
[dem_ant,header]=rasterload();
cellsize=header.cellsize;
nodata=-9999;

%% the coefficient
```

```
dem_night2=dem_night(1:20,1:20);
dem_ant2=data_low(1:20,1:20);
a=dem_night2(:);
b=dem_ant2(:);
c=corrcoef(a,b);

%% scatter plot
scatter(a,b)
xlabel('night-time light')
ylabel('anthropogenic modification of morphology(%)')
```