From Features to Fingerprints: A General Diagnostic Framework for Anthropogenic Geomorphology

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From features to fingerprints: A general diagnostic framework for anthropogenic geomorphology

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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 plough 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 stores, to processes of soil erosion and deposition. In many of the same landscapes, archaeologists have also utilized anthropogenic geomorphic features to detect and analyse 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. Human societies are now transforming the geomorphology of landscapes at increasing rates and scales across the globe. To understand the causes and consequences of these transformations and contribute to building sustainable futures, the science of physical geography must advance towards empirical and theoretical frameworks that integrate the natural and sociocultural forces that are now the main shapers of Earth's surface processes.

1. Introduction

Before humans left their first footprints on African landscapes, Earth's terrestrial surface was shaped solely by the natural geophysical processes of climate, 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; Edgeworth, 2014; Edgeworth et al., 2015; Ellis, 2015; Ellis and Haff, 2009; Foley and Lahr, 2015; Goudie, 2018; Goudie and Viles, 2016; Guthrie, 2015; Hooke and Martin-Duque, 2012; Kirch, 2005; Lewis and Maslin, 2015; Sauer, 1925; Tarolli, 2014, 2016; Tarolli and Sofia, 2016; Tarolli et al., 2014, 2018; Waters et al., 2016; Zalasiewicz et al., 2017). As a result, a complete assessment and understanding of the formation and evolution of Earth's current landforms requires a robust theoretical understanding of the anthropogenic processes that have assisted in shaping them.

The science of physical geography and that of geomorphology, in particular, requires new tools and frameworks capable of identifying and interpreting anthropogenic geomorphic features together with the sociocultural processes that have shaped them (Ellis, 2017). The goal here is to help advance such a framework by connecting 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 et al., 2018), building on existing published work on anthropogenic geomorphology (Brown et al., 2017; Goudie and Viles, 2016; Johnson and Ouimet, 2018; Li et al., 2017; Szabo, 2010; Tarolli and Sofia, 2016; Tarolli et al., 2018).

1.1 Anthropogenic landscapes are sociocultural palimpsests

While many species alter their environments, 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 and domesticated species, and by harnessing non-human energy to accomplish these modifications, human niche construction practices have 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., 2018). Most importantly, human capacities to engineer environments are not biological, but sociocultural, and these sociocultural capacities have evolved and accumulated over time together with human capacities for cooperation and social learning (Ellis, 2015; Ellis et al., 2018) (Figure 1). Human sociocultural niche construction has diversified, scaled up and utilized increasing amounts of

energy over millennia, from the first use of fire to clear land (for greater success in hunting and foraging), to the construction and management of agricultural landscapes using animal labour, to 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 (Figure 1).

Human modification of landscapes has tended to increase in scale and complexity together with the scale and complexity of 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 and Berna, 2017), amplifying the ability of humans to transform ecosystems and the erosive and hydrologic processes accompanying land clearing 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 behaviour and material culture (Fletcher, 2009). As societies scaled up over time, into the first agricultural, urbanized and then industrial societies, their ecosystem engineering also increased in scale, complexity, durability and in the sheer amounts of material moved (Figure 1).

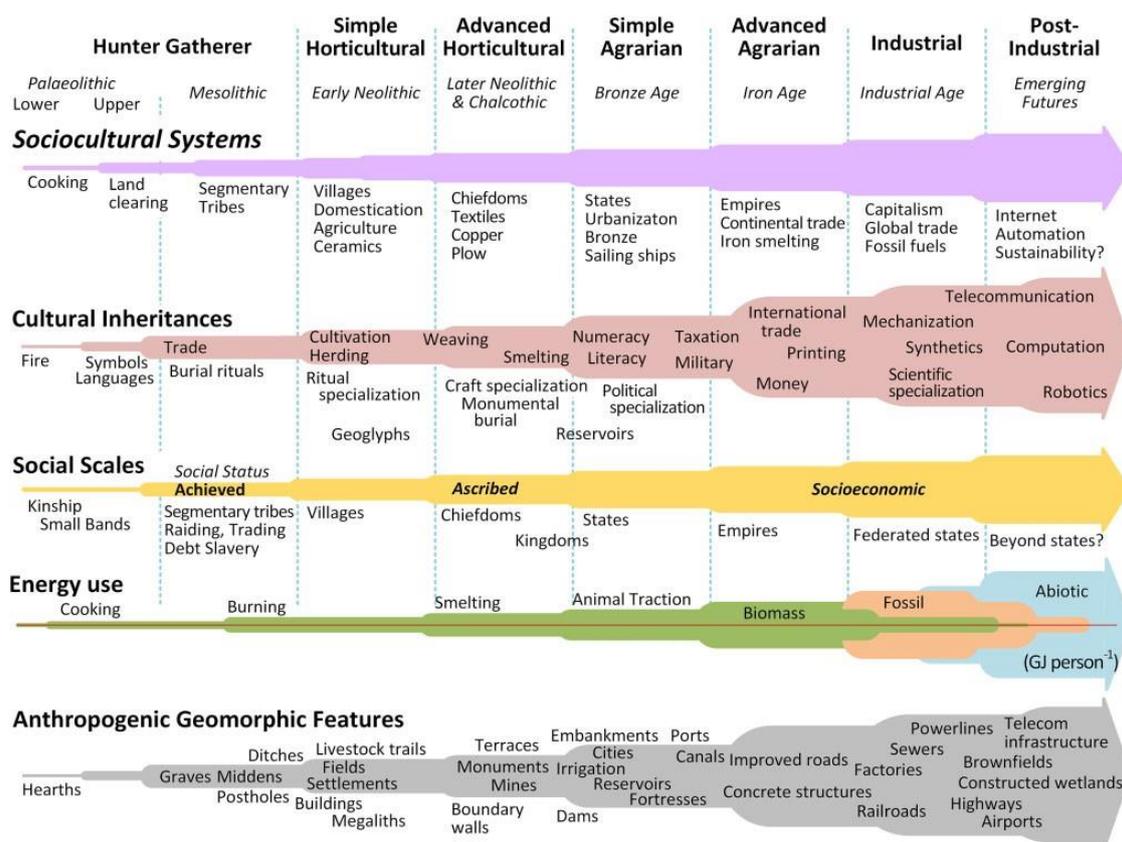Figure 1. Conceptual diagram of long-term changes in sociocultural systems, cultural inheritances, societal scale, energy use and anthropogenic geomorphic features. Different societies combine different sets of anthropogenic geomorphic features, including both pre-existing and novel, to produce their sociocultural fingerprints across landscapes (this figure expands on Ellis, 2015, Figure 3 and Ellis et al., 2018, Figure 1).
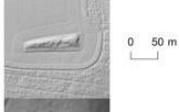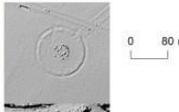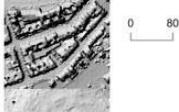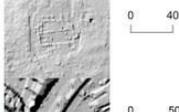
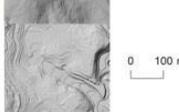| Features	Description	Function		
Hearth-pits	Bowl-shaped, ash deposits, soil discoloration, shallow (depth generally less than 0.5 m) and small (diameter less than 1 m)	Subsistence: cooking, heat, firing of ceramics, limited metallurgy		
Burial sites	Excavations, mounds, cemeteries including human remains	Symbolic: repository for human remains		0 50 m
Geoglyphs	Human rearrangement of earth, stone and other materials to create symbolic anthropogenic landforms	Symbolic: Public and ceremonial spaces, burial sites, funerary customs, animal trapping		0 12 m
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		0 80 m
Buildings	Permanent structures with roof and walls	Habitation, storage, symbolic structures, other functions requiring permanent sites with protection from weather		0 80 m
Cities	Permanent large-scale human settlement, including infrastructure	Habitation, trade; centers of human social interaction		0 40 m
Boundary walls	Linear raised features composed of earth, rock, wood, brick and other materials	Protection of settlements, fortresses, and farms from potential aggression		0 50 m
Roads	Cleared, levelled, sometimes paved, interconnected linear features	Transport: mobility for humans, livestock, vehicles, and exchange of materials among settlements		0 100 m
Middens	Mounds of domestic refuse containing shells, animal bones and other debris and remains marking sites of prehistoric settlement	Refuse disposal		0 80 m
Livestock trails	Animal-induced paths trampled into earth, often interconnecting water and shelter	Subsistence: livestock production		0 50 m
Terraces	Artificially-levelled shelves of land interrupting slopes	Subsistence: facilitating crop production on steep slopes		0 100 m
Mines	Excavations maintained for mineral extraction	Source of mineral resources, ore for metallurgy, clay for bricks, etc.		0 1000 m
Ditches	Narrow channels excavated around crop fields, buildings and road perimeters	Drainage of settlements, roads, agricultural land, and water transport for irrigation		0 50 m
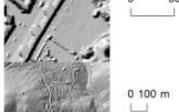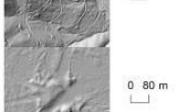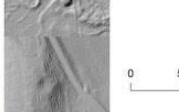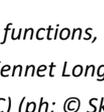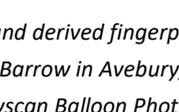
Figure 2. Examples of anthropogenic geomorphic features, their sociocultural functions, and derived fingerprint on topography. From top to bottom: hearth-pit (Shahack-Gross et al., 2014); West Kennet Long Barrow in Avebury, Wiltshire (UK), one of the largest and most impressive Neolithic graves in Britain (3650 BC) (ph: © Skyscan Balloon 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 Sánchez; LiDAR: © Centro Nacional de Información Geográfica); El Tolmo (Spain), archaeological site showing a continuous time record of ancient civilizations from 3500 yr BP onwards (ph. Laclac; LiDAR: © Centro Nacional de Información Geográfica); El Tolmo (Spain), archaeological site showing a continuous time record of ancient civilizations from 3500 yr BP onwards (ph. Laclac; LiDAR: © Centro Nacional de Información Geográfica); Roman wall of Lugo (Spain) (ph Xosema; ; LiDAR: © Centro Nacional de Información Geográfica); mountain road (ph. Chell Hill, LiDAR:
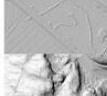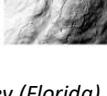
Canals	Large-scale, artificial linear excavations	Transport: of materials and people by boat, and water transport for irrigation		0 250 m
Embankments	Artificial mounds and structures of earth, stone and other materials along waterways	Supporting infrastructure for flood protection from, and access to waterways		0 80 m
Reservoirs	Artificial lakes	Water infrastructure, water storage, hydraulic power, aquaculture		0 480 m
Constructed wetlands	Flooded excavations	Drainage, water treatment		0 240 m
Trenches	Long, narrow excavations	Warfare: protection of military personnel		0 40 m

Figure 2. (Continued). OpenTopography Facility); shell middens at Mound Key (Florida)
(http://www.flpublicarchaeology.org/blog/crc/tag/soil-core/; LiDAR: NOAA National Oceanic Atmospheric Association
website); cow trails (ph. Herzi Pinki, LiDAR: LiDAR Laserscanning-Geodaten Kanton Zürich, Amt für 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); riverbank in Italy (Google ©2017; LiDAR: Italian
Ministry of Environment); Leech Lake Minnesota (LiDAR: MNTOPO®); constructed wetland in Northern Italy (Ph Adige
Euganeo; LiDAR: Italian Ministry of Environment); Nagià Grom war trenches in northern Italy (ph. Kevin1971; LiDAR:
Autonomous Province of Trento).

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 inherited by, overlaid by, overwritten and reconstructed by 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 rather 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 and Ouimet, 2018).

1.2 *Anthropogenic features and sociocultural fingerprints*

Individual anthropogenic features, as specific human modifications of land surfaces such as an individual graves, buildings or roads, show a wide variety of forms. In aggregate, however, the anthropogenic features produced by a given society may evince a degree of consistency within a given sociocultural milieu, as illustrated in Figure 1. Thus, as archaeologists have long recognized, the material cultures of different societies pattern the surface of Earth in specific ways that produce distinctive and recognizable sociocultural fingerprints (Butzer, 1974; 1982; David and Thomas, 2016).

Anthropogenic landforms have tended to increase in scale and complexity in parallel with the scale and complexity of the societies that produce them. Composed of individual land surface modifications, or "anthropogenic features", these are the products of socially and culturally directed efforts by individuals and social groups, increasingly assisted by animal labour, fossil-fuelled machinery and

other non-human energy, to remove, transfer, introduce and reshape elements of the physical environment to achieve the goals of these individuals, social groups and entire societies. This social production of space generates a virtually endless variety of physical forms. We must therefore acknowledge at the outset the difficulties in dividing such myriad 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, as in Figure 2: symbolic (e.g. graves and monuments), habitation (e.g. housing, villages, cities), transport and exchange (e.g. roads, canals), subsistence (e.g. plough furrows, irrigation networks), mining, refuse disposal and 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, ploughed 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 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.

1.3 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 global-scale societies are now met through processes that engage with social and environmental differences around the world at regional scales – where land, resources and labour 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.

2. The diversity of anthropogenic geomorphic features

In this work 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) mining; (vi) water infrastructure; (vii) waste disposal; (viii) 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 (Figure 2).

2.1 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 et al., 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 et al., 2013, 2017). Geoglyphs can play a role in mortuary practices 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 and 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).

2.2. Habitation

Early human encampments relied on rock shelters formed by natural processes, such as caves (Farrand, 2001; Judson et al., 2005; Simms and Russell, 1997), whose natural and anthropogenic deposits offer details on human activities, natural environments inside such caves and their dynamic interactions over time (Courty and 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 recognizable components of the archaeological record (Boyce et al., 2015; Cassel, 2012; Rojas, 2010). Other urban forms include the largescale urban complexes and hydraulic systems that evolved in densely forested landscapes in Asia and Amazonia (Evans et al., 2013; Liu et al., 2017; Roberts et al., 2017). The production of built structures, from walls to housing and those for other specialized purposes, induces 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 and Vallverdu, 2001; Farrand, 2001).

2.3 Transport/exchange networks

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 centres (Bell and Iida, 1997; Kara and Verter, 2004; Morriss, 2003, 2005; Ruiz, 2016; Snead et al., 2009). Roads are ubiquitous features of landscapes and different shapes of road network represent the different evolution of civilization at different times (Strano et al., 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. In addition, since the Industrial Revolution, railroads have been an important form of transportation (Li, 2017; Morriss, 2003), shaping not only cities and economic growth (Hanedar, 2017; Nerlove, 1966), but also landscape processes (Bell and Iida, 1997; Blanton and Marcus, 2009, 2013; Kumar et al., 2014; Martinović et al., 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 centres 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 et al., 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 and Jones, 1980; Day, 1995; Pratesi et al., 2016; Watson et al.,

2001). More recently, the development of underground tunnels for transport has created extensive subterranean networks in many large cities (Zalasiewicz et al., 2014).

2.4 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 and 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 et al., 2015; Pearson and 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 and Zeder, 2013). Soil tillage leaves especially clear and widespread geomorphic signatures across landscapes in terms of anthropogenic soils and erosive deposits (Certini and Scalenghe, 2011; Ellis, 2011; Tarolli et al. 2019). The need to exploit steep lands for agriculture also introduced the construction of terraces (Chase et al., 2014; Tarolli et al., 2014; 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 the 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).

2.5 Mining

Although mining is as old as the manufacture of stone tools and leaves clear geomorphic signatures, it occupies a relatively small surface area worldwide (Tarolli and Sofia, 2016). Mining activity has been driven by a wide variety of objectives, including obtaining materials for making items such as tools, utensils, weapons, ornaments, decoration and currency (Timberlake, 2017). Mining of clay for bricks is also widespread and continues globally (Shakir and Mohammed, 2013). Further mining drivers have been the need for structures, and machinery, and obtaining resources for energy, electronics, nuclear fission (Hartman and Mutmansky, 2002; Herrington, 2013) and for low-carbon energy production (Vidal et al., 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 and James, 2013). The main characteristic is the persistence in time of the landform itself (Chen et al., 2015; Hooke and Martin-Duque, 2012; Xiang et al., 2018) and of the related effects on the environment (Kircher et al., 2003; Mossa and James, 2013; Rivas et al., 2006; Toy and Hadley, 1987).

2.6 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 and Andreas, 2012; Kollyropoulos et al., 2017; Tegel et al., 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 this would be Qanat, which are gently sloping underground channels designed to transport water from an aquifer or water well to the 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 et al., 2017; Harandi and 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 and drainage alongside roadways or fields (Terry and Hughes, 1978). As well, canals provide water conveyance, navigation and water storage (Swamee and Chahar, 2015). Along water infrastructures, especially in floodplains, humans built embankments, levees and scarps. These infrastructures not only offer protection from floods, but they also change the flood frequency and create disconnectivity between the river landscape and its floodplain (Chin et al., 2013; Gregory, 2006; Overeem et al., 2013; Thoms et al., 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), 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., 2003, 2004).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 et al., 2008; FAO, 2001; Gordon and Meentemeyer, 2006; Hall and Shelby, 2000; Le et al., 2007). These functions are, however, accompanied by environmental changes, including subsequent impacts on lowland rivers and coastal systems, climate-changing greenhouse gases emissions, changes in the temperature regime, sedimentation, water pollution and destruction of ecosystems due to the reservoir effect on downstream environmental flows and sediment supply (Dević, 2015). 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 and for land reclamation after mining, refineries or other ecological disturbances (ElZein et al., 2016; Vymazal and Kröpfelová, 2008; Zhang et al., 2009). Some of the most dramatic anthropogenic transformations of 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 and Viles, 2016; Martín-Antón et al., 2016).

2.7 Refuse disposal

Middens are among the first and most prominent examples of physical remnants of resource exploitation 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 et al., 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 et al., 2011; Rick et al., 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 most cases, they are representative of the earliest settlement systems, beginning in the Neolithic period (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).

2.8 Warfare

Landform features have also been created for warfare or deface. These features include not only artificial structures, such as fortifications (De Matos-Machado et al., 2015; Ilyés, 2010; Moss and Erlandson, 1992), trenches (Baer and Ashworth, 1981; Houx, 2001; Power, 2009), improvised explosive device (IED) command wires (McDonald and Schumer, 2016), bunkers and missile silos, among others, but also existing underground terrain (Eastler, 2004) or rock defences (Moss and 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 and 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. The contribution of remote sensing

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 this growing body of remotely sensed data can be used to detect and interpret anthropogenic geomorphic features, landforms and landscapes. 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). These techniques have spurred renewed interest in the role of social-ecological systems in shaping Earth's surface (Johnson and Ouimet, 2018), ranging from studies of "archaeological topography" among social sciences (Canuto et al., 2018; Evans et al., 2013; Opitz and Cowley, 2013) to the study of "geomorphometry" among geoscientists (Pike, 2000; Sofia et al., 2016b). 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 reviews) have opened avenues for the analysis of anthropogenic signatures and processes (Tarolli, 2014). In this context, one of the actual challenges is the ability to model the anthropogenic morphologies, quantify them and analyse the links between anthropogenic elements and geomorphic processes. In the following sections, a few examples are provided on how remote sensing data can be used to extract and analyse anthropogenic features and quantify anthropogenic changes on the surface.

3.1 Extraction from imagery

Despite the limitation due to shadowing, angle of incidence or lack of topographic information under vegetation cover (Mostafa and Abdelhafiz, 2017; Quartulli and Olaizola, 2013; Sowmya and Trinder, 2000), archaeologists have made use of radar and satellite images to reveal differences in texture, roughness, moisture content, topography and geometry of features and surfaces related to human activities, for example (Evans et al., 2007; Fowler, 2002; Holcomb, 2001; Holcomb and Shingiray, 2006; Moore et al., 2006; Ricketson et al., 2003). More recently, images from satellites have been used not only in relation to anthropogenic features in the context of urban studies (see Ghanea et al., 2016, for a review), for cadastral boundary extraction (Crommelinck et al., 2016; Wassie et al., 2017) and 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 and localize patterns related to human activities, and they can be used to extract features of interest, such as not only buildings, but also shelters and war/flood/earthquake damaged structures. To illustrate this point we show in Figure 3 a Pleiades satellite image. The study area is spatially stratified in environmentally similar land units (Figure 3(d)) using image analysis techniques (Figures 3(b) and (c)) and, thus, it is possible to identify those areas that are most likely to present anthropogenic landscapes (Figure 3(e)). 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.
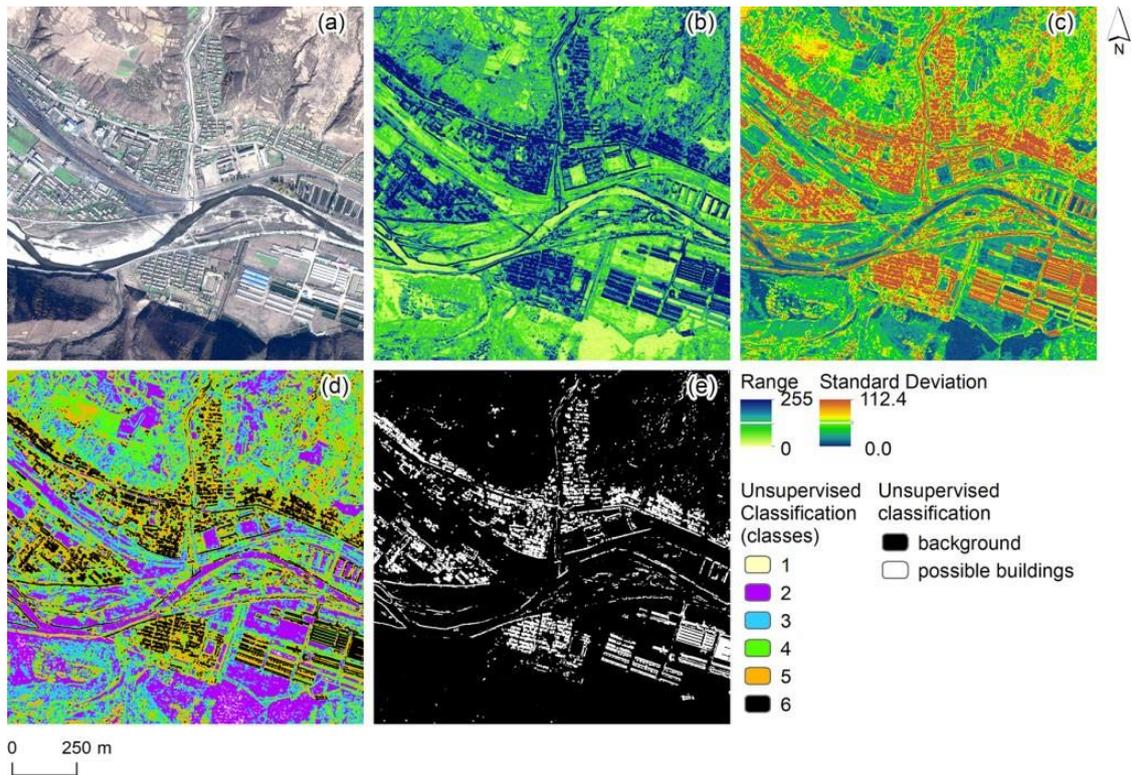
Figure 3. Example of satellite image, derived texture parameters and classification: (a) Pleiades 0.5 m satellite image; (b) local range of values (max–min); (c) local standard deviation of values within a 11 x 11 neighbourhood (Haralick, 1982); (d) iterative optimization clustering procedure implemented by the commercial software ArcGis® (Ball and Hall, 1965; Richards, 2013); (e) extracted buildings.
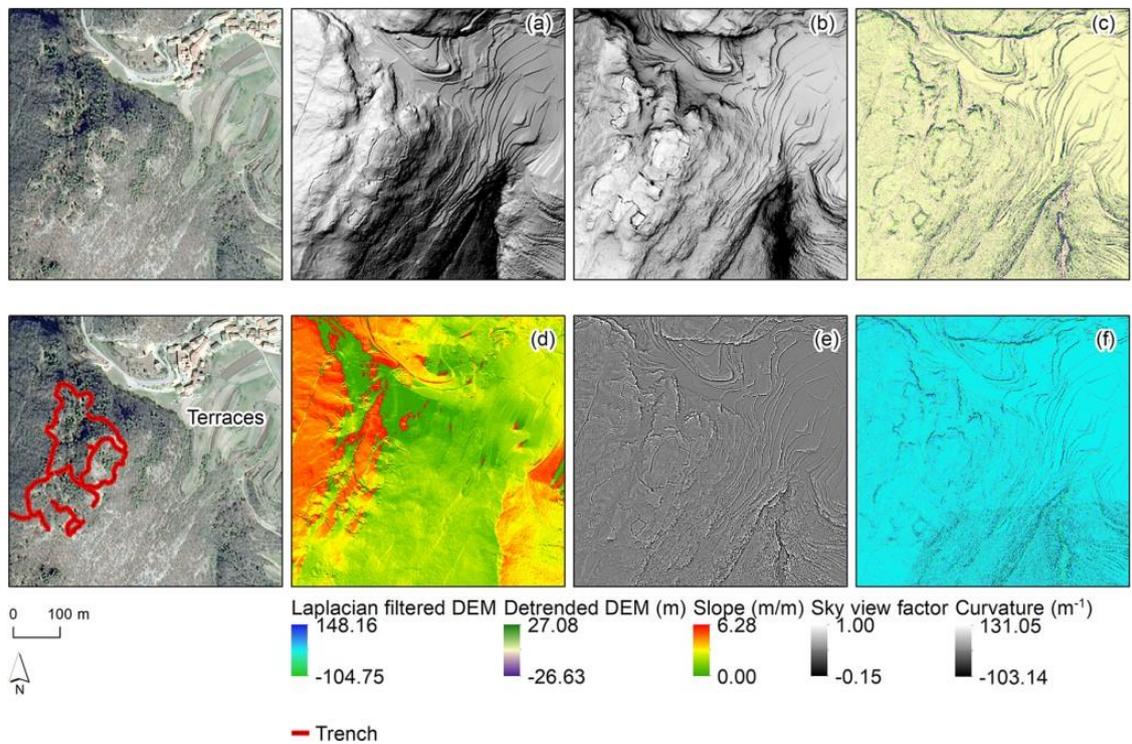
Figure 4. WWI trenches and terraces: (a) hillshade; (b) sky-view factor; (c) detrended Digital Terrain Model (DEM); (d) slope; (e) curvature; (f) Laplacian filtered DEM.
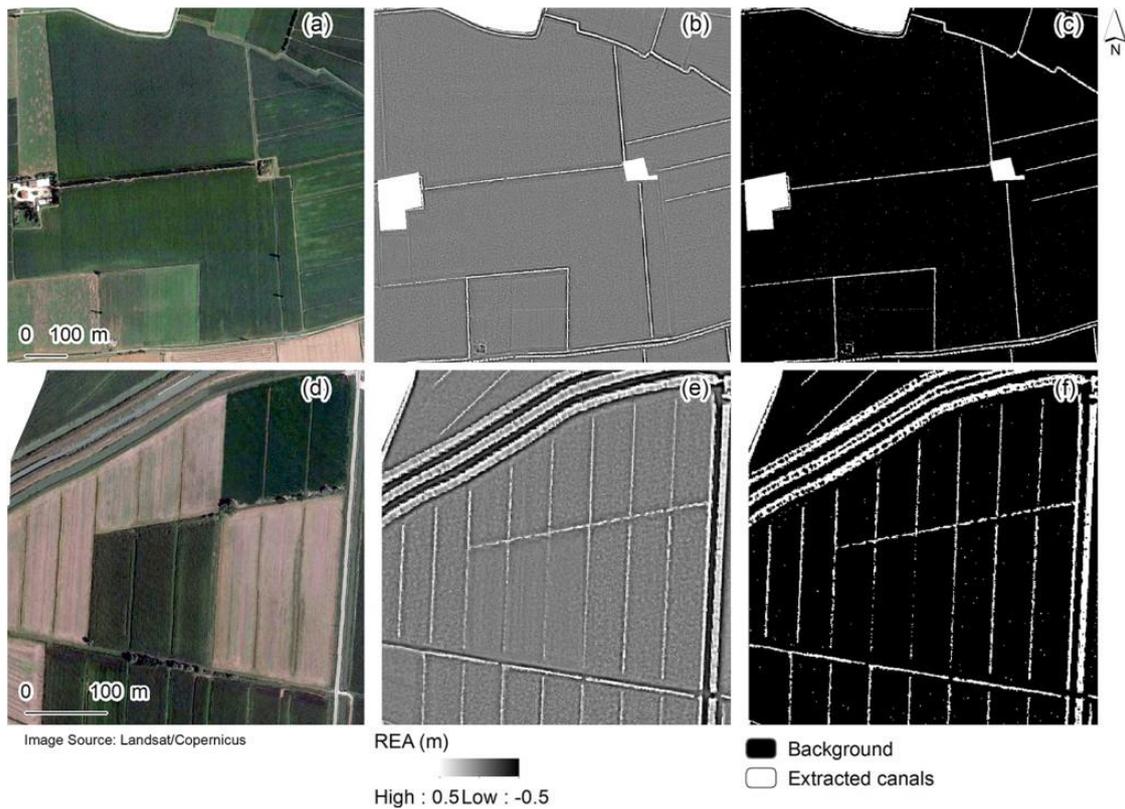
Figure 5. Agricultural practices in northeastern Italy ((a) tobacco; (d) corn). Detrended Digital Terrain Model (REA, Cazorzi et al., 2013) (b), (e) and ditches derived automatically by applying a statistical threshold (standard deviation of Relative Elevation Attribute (REA)) (c), (f).
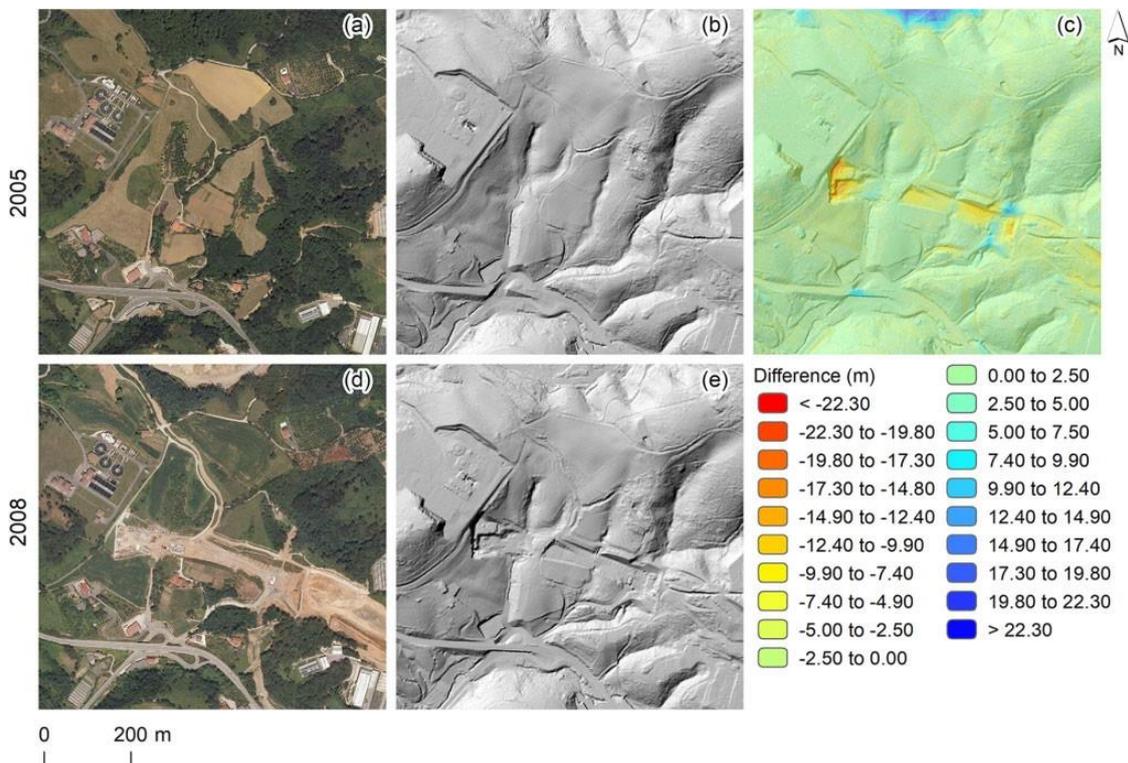
Figure 6. Example of change of detection from LiDAR Digital Terrain Model (DEM). Ortophotos for the year 2005 (a) and 2008 (c), LiDAR DEM in 2005 (b) and 2008 (e) and derived change of detection in m (c).

3.2 Extraction from three-dimensional surfaces

A further step in feature extraction is allowed by the availability of three-dimensional (3D) models (Digital Terrain Models – DEMs). When DEMs are available, the most straightforward approach to anthropogenic feature analysis is visualization, namely the use of hillshade or shaded-relief maps (Figure 4(a)), for example (Bennett et al., 2012; Chase et al., 2014; Deforce et al., 2013; Doneus et al., 2008; Golden et al., 2016; Harmon et al., 2006; Johnson and Ouimet, 2016, 2018; Menze et al., 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 (Figure 4(b)) (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 not only 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 (Figure 4(c)), for example (Cazorzi et al., 2013; Hesse, 2010; Howey et al., 2016; Luscombe et al., 2015; Schindling and Gibbes, 2014; Sofia et al., 2014c). 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 (Figure 4(d)), (e.g. McCoy et al., 2011; Riley, 2012), slope and also exposure under a water surface (Cappucci et al., 2017) and curvature (Figure 4(e)), (Drăguţ and Blaschke, 2006; Sofia et al., 2014a; 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 – Figure 4(f), Sobel's filters, SLLAC – Slope Local Length of Correlation) (Sofia et al., 2014b, 2016; Stal et al., 2010; Štular et al., 2012). These enhancing techniques can be the basis to segment and detect anthropogenic patterns and features using GEOBIA (GEOgraphic-Object-Based Image Analysis) (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. Figure 5).

3.3 Quantitative assessment of features

Extractions carried out with thresholding or object-oriented approaches, although able to detect the two-dimensional (2D) 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., 2014c; Sofia and Tarolli, 2017; Sofia et al. 2019), or the extent of 2D features. In addition, high-resolution 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., 2016a). A further step in anthropogenic features characterization is offered by change detection techniques or time-series data analysis, which 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; Xiang et al., 2018; Yucel and Turan, 2016). Figure 6 shows an example of geomorphic change detection evaluated considering the Wheaton et al. (2010) approach. For this area, multitemporal orthophotos (Figures 6(a) and (d)) and LiDAR DEMs (Figures 6(b) and (e)) are freely available (Institut Cartografic De Catalunya (ICC), 2005, 2008) for the years 2005 and 2008. From these maps, it is possible to compute a volumetric difference (Figure 6(c)), taking into account the errors that might be present in the DEMs themselves (see Lane et al., 2003, for specification on the method).

3.4 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).

4. Decoding palimpsest: From features to fingerprints

Few existing landforms are formed solely through natural or anthropogenic geomorphic processes operating within a single discrete time period. By and large, landforms tend to incorporate multiple interwoven and entangled layers of materials, both natural and anthropogenic, generated by different processes at different times, written and rewritten repeatedly by various combinations of natural and anthropogenic processes: landscapes are palimpsests (Johnson and 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 historical modifications under specific social conditions or natural geomorphic processes that are no longer present in that region. Some other features may be entirely "relictual" because they were formed at some point in the past when social conditions, processes or environments were substantially different or operated at a different magnitude to those of the present time.

While remote sensing together with algorithmic methods enable the detection and identification of anthropogenic and other features, researchers are rarely able to observe or interpret these features across the scales of time or space in which the societies that formed them operated, although reconstructions of these long-term changes have long been a major focus of archaeological research (e.g. Butzer, 1982b; Dincauze, 2000). This remains the central challenge of anthropogenic geomorphology: to interpret anthropogenic features as diagnostic fingerprints of the societies and social processes that formed them, both locally and across the entirety of the regions where these societies were located. To meet this challenge requires an integrated social-geophysical approach combining the theories, frameworks and methods of geomorphology, archaeology and ecology.

4.1 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 (Figure 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 (Figures 1 and 8).

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.
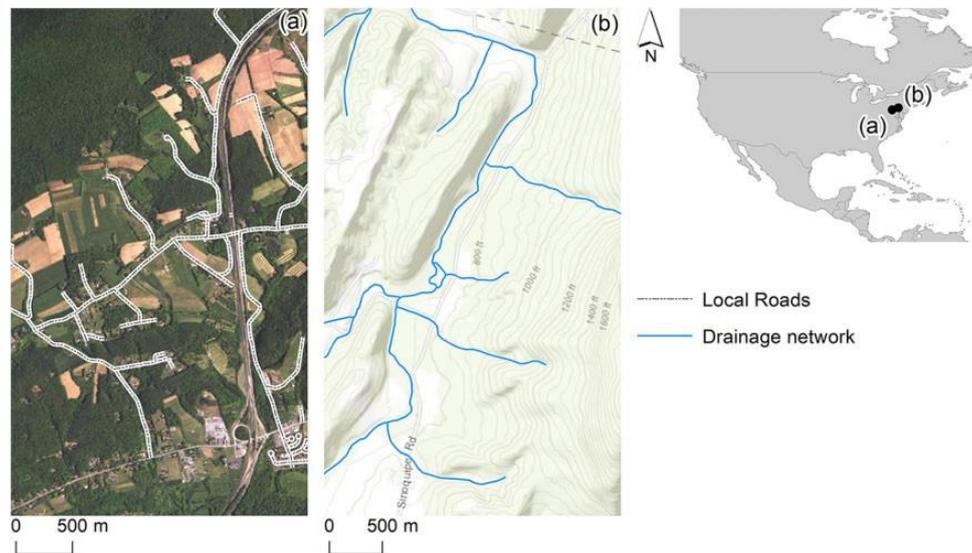

Figure 7. Example of similarity between anthropogenic and natural features: (a) local road network; (b) flowlines in Pennsylvania (USA).

While the full range of sociocultural patterns, processes and dynamics observed across human societies (Figure 1) is far larger than those occurring within any particular landscape, Figure 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.

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.
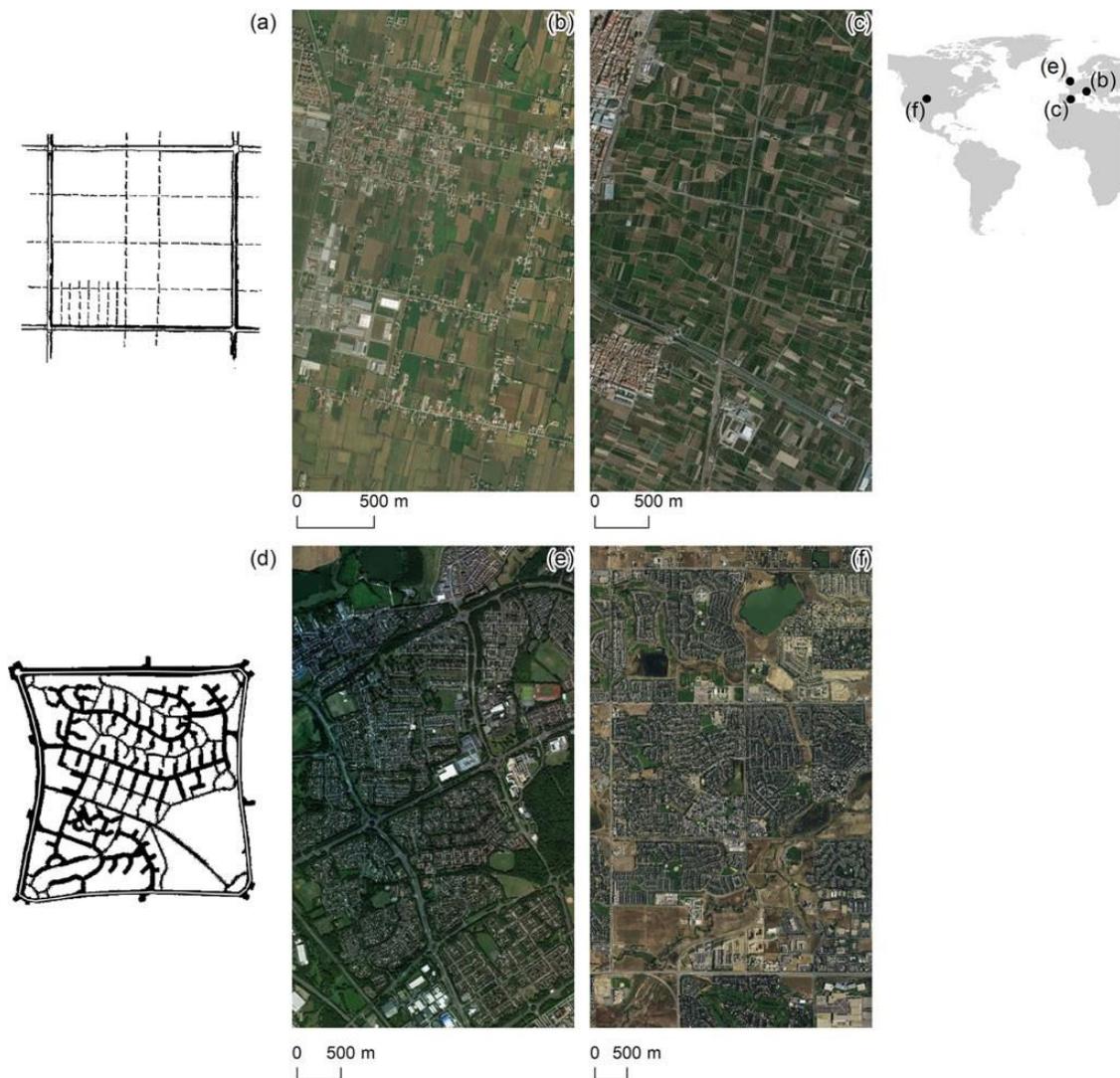
Figure 8. Different patterns (a), (d) highlight different cultural settings. Roman centuriation of an area near Padua (Italy (b)) and Valencia (Spain (c)), and modern residential areas in Milton Keynes (UK (e)) and Boulder (USA (f)).

A 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.

4.2 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 (Figure 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 (Figure 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 (Figure 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).
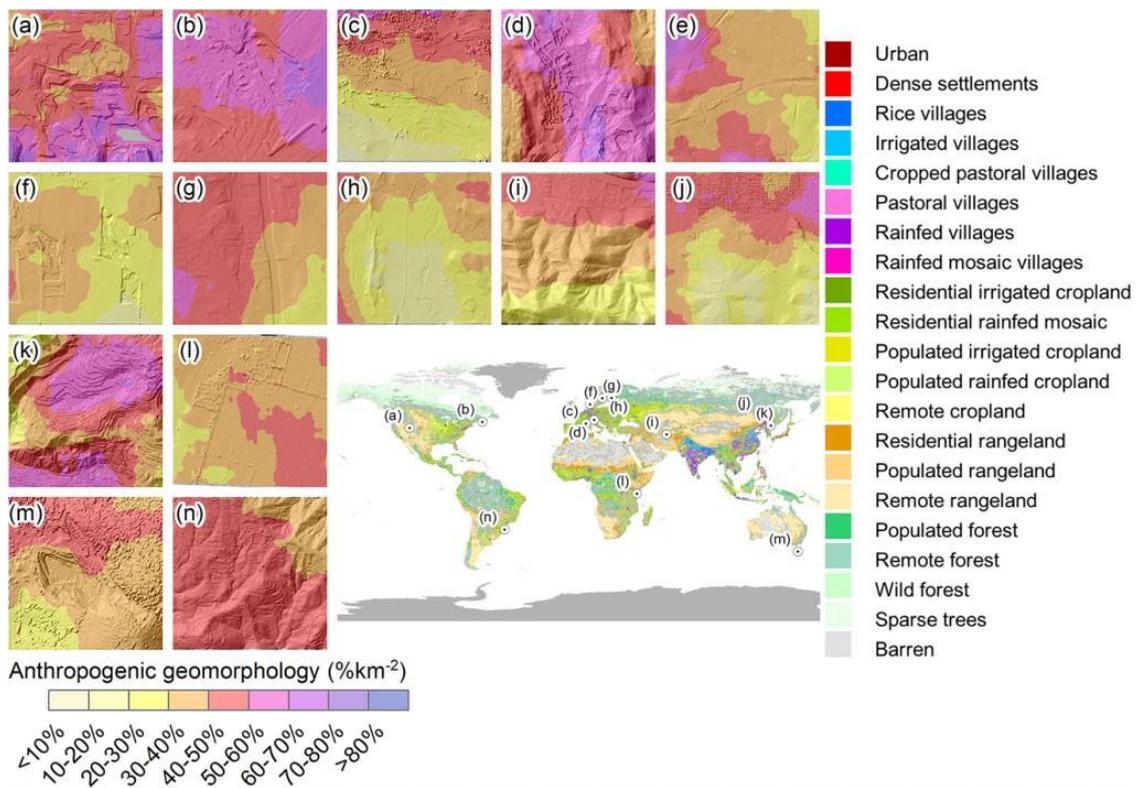

Figure 9. Local-scale percentage of anthropogenic geomorphology, as compared to anthropogenic biomes (Ellis and Ramankutty, 2008). Dataset credit: (a) Minnesota Geospatial Information Office (MnTOPO®); (b) Halifax Regional Municipality – Canada; (d) Autonomous Province of Trento (Provincia Autonoma di 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 Lantmäteriet (Sweden); (c), (i), (j), (k), (l) data from CNES© Distribution Airbus DS; (m) TERN© AusCover; (n) OpenTopography Facility with support from the National Science Foundation under NSF Award Numbers 0930731 & 0930643 FAPESP grant 2009/17675-5

4.3 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.

Analysing 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 (Figure 8). Centuriation (Figure 8(a)) is typical of regions historically conquered by Romans (such as Italy (Figure 8(b)) and Spain Figure 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 (Figure 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 (Figures 5(c) and (f)) support different cultivation practices (e.g. tobacco (Figure 5(a) and corn Figure 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. Figure 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 Figure 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 (Figure 9), may offer a general sampling framework for the global mapping and quantification of anthropogenic geomorphic change.

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.

5. Concluding remarks

Human societies, across millennia, have reshaped Earth's geomorphology, producing distinctive anthropogenic landforms that now cover the vast extent of Earth's surface. These anthropogenic patterns directly and indirectly alter Earth surface processes while reflecting the sociocultural conditions of the societies that produced them. As a result, both archaeological and contemporary assessments of Earth's surface morphology reveal 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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