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Review Article

# Denudation and geomorphic change in the Anthropocene; a global overview.☆

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## ABSTRACT

The effects of human activity on geomorphic processes, particularly those related to denudation/sedimentation, are investigated by reviewing case studies and global assessments covering the past few centuries. Evidence we have assembled from different parts of the world, as well as from the literature, show that certain geomorphic processes are experiencing an acceleration, especially since the mid-twentieth century. This suggests that a global geomorphic change is taking place, largely caused by anthropogenic landscape changes.

Direct human-driven denudation (through activities involving excavation, transport, and accumulation of geological materials) has increased by a factor of 30 between 1950 and 2015, representing a ten-fold increase of *per capita* effect. Direct plus indirectly human-induced denudation (triggered by land surface alteration) is presently at least one order of magnitude greater than denudation due to purely natural processes.

The activity of slope movements, which represent an important contribution to denudation, sediment generation and landscape evolution, also shows a clear intensification. Frequency of hazardous events and disasters related to slope movements (an indirect measure of process frequency) in specific regions, as well as at continental and global levels, has grown considerably, in particular after the mid-twentieth century. Intense rainstorm events are often related to slope movement occurrence, but the general increasing trend observed is not satisfactorily explained by climate.

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☆ This is a contribution from DENUCHANGE, a Working Group of the International Association of Geomorphologists

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Sedimentation has augmented considerably in most regions and all kinds of sedimentation environments. Although the link between denudation and sedimentation is not direct and unequivocal, it is safe to assume that if sedimentation rates increase in different regions during a given period, denudation must have increased too, even though their magnitudes could be different. This augmentation, particularly marked from the second half of the last century onwards, appears to be determined mainly by land surface changes, in conjunction with climate change.

The changes observed suggest: a) there is evidence at a global scale of a growing response of geomorphic systems to socio-economic drivers, being Gross Domestic Product density, a good indicator of the human potential to cause such impacts; b) Land use/cover changes enhance effects of climate change on global denudation/sedimentation and landslide/flood frequency, and appear to be a stronger controlling factor; c) Our findings point to the existence of a global geomorphic change. This manifestation of global change is especially evident since the "great geomorphic acceleration" that began in the middle of the 20th century, and constitutes one of the characteristics of the proposed Anthropocene.

## 1. Introduction

The effects of land surface modification by human activities on geomorphic processes have been discussed by a number of authors (among others, Brown, 1956; Ter-Stepanian, 1988; Turner et al., 1994; Slaymaker et al., 2009; Zalasiewicz et al., 2014; Brown et al., 2017; Goudie, 2020; Owens, 2020). The possibility that these may represent a "global geomorphic change" has been pointed out (Hooke, 2000; Wilkinson and McElroy, 2007; Rivas et al., 2006; Bruschi et al., 2013; Cendrero et al., 2020). The global character of such modification and its significant effects on the sediment cycle have been discussed in depth by Syvitski et al. (2022). Naturally, changes in geomorphic processes affect denudation, defined as the net and combined effects of land surface weathering and erosion processes (Dixon and Thorn, 2005). It is the main mechanism which determines sediment generation, sediment removal from defined Earth surface areas, and transport, as well as landscape evolution. Geomorphic processes in general, and denudational ones in particular, imply the transfer of solid and/or dissolved materials, by different agents (continental and ocean waters, ice, air, plants, animals, humans) from one place of the Earth's surface to another, under the influence of gravity and wind and water currents. In most landscapes, physical denudation is the main contributor to the process and is recognizable in the landscape as typical landforms. In contrast, it is in general much more difficult to notice the consequences of chemical denudation, which in many landscapes accounts for a small proportion of the materials removed (Millot et al., 2002) and globally represents <20% of sediment fluxes to the oceans (Syvitski et al., 2022). The final results of these transfers include relief reduction (not forgetting possible tectonic or isostatic uplift or volcanism) and deposition of the eroded materials in different sedimentary environments. Of course, there are considerable variations in the distance travelled and time elapsed between initial denudation and final deposition. This has been discussed in relation to sediment routing systems (SRS) that extend from primary production environments (erosion), across the transfer pathways (transport and deposition), and to ocean or lake bottom (deposition), which are the primary locations for the erosional and depositional processes that constitute Earth's sedimentary cycle. (Schumm, 1977; Allen, 2008; Beylich et al., 2016; Liu et al., 2016; Zwoliński, 2016; Nyberg et al., 2018; Caracciolo et al., 2020; Syvitski et al., 2022).

Throughout Earth's history, the processes of erosion, sediment generation, transport, and deposition have been primarily determined by water-ice/solid Earth surface interactions, and experienced considerable changes in extent and intensity, in response, among other factors, to climate and LULC (Land Use and Land Cover) changes (Slaymaker, 2000; Slaymaker et al., 2009; Beylich et al., 2016; Owens, 2020). In the last couple of centuries, especially the last few decades (the period considered by different proposals for the Anthropocene; Steffen et al., 2015; Lewis and Maslin, 2015; Zalasiewicz et al., 2015; Waters et al., 2016; Zalasiewicz et al., 2021), the situation has changed. Humans are becoming an increasingly important geomorphic agent in most regions of the Earth (Dedkov and Mozzherin, 1984; Turner et al., 1994; Piacente, 1996; Hooke, 2000; Douglas and Lawson, 2001; Rivas et al., 2006; Walling, 2006; Syvitski et al., 2020, Syvitski et al., 2022). Human activities ("anthroturbation") also affect marine sediments in different ways particularly on continental shelves and mainly by trawling, mining and construction (Jones, 1992; Puig et al., 2012; Zalasiewicz et al., 2014; Bunke et al., 2019), but this issue is beyond the scope of the present contribution.

In view of increasing global changes, it is clearly important to analyse the extent, rates and causes of denudation and sedimentation over the past few centuries (Oldfield and Dearing, 2003; Hu et al., 2019; Owens, 2020; Syvitski et al., 2022). Considering the geomorphic role of climate, it is reasonable to expect that temperature and precipitation changes must be reflected in the rates, processes, periodicity and spatial patterns of denudation. Climate also affects land cover and its capacity to protect land from erosion. However, land cover and land surface are overwhelmingly affected by human activities - agriculture, forestry, mining/quarrying, infrastructure development, urban sprawl, *etc.*- which in many cases give rise to significant denudation, be it direct ("technological denudation"; Brown, 1956) or indirect. Nearly four decades ago, Sánchez de la Torre (1983) pointed out that, throughout geologic history, most solid materials moved over the Earth's surface have been transported by the system "mountain area-fluvial channel-sedimentation basin", whereas it seems that nowadays this has been substituted by the system "mine/quarry-road/railway/ship-urban industrial complex". Those factors must be taken into consideration when trying to assess global or regional trends in denudation processes and rates.

### 1.1. Objectives

In view of the enormous variation and complexity of the processes involved, this review will focus on the physical and temporal aspects of mechanical denudation and particular intense geomorphic events. Our aim is to use case studies, combined with some global assessments, to provide insights into the role of human activity in geomorphic processes, particularly denudation and sedimentation, over the past few centuries. We will look at the relative roles of climate change and other changes also caused by human activities during the last couple of centuries (Oldfield and Dearing, 2003; Steffen et al., 2007; Hu et al., 2019; Zalasiewicz et al., 2021; Syvitski et al., 2022).

Fig. 1 is a conceptual model depicting the main components of the "denudation to sedimentation system", in which the links we are considering are indicated. Key research questions considered in this study are: (i) Has the magnitude of denudation experienced significant changes over the last decades to centuries due to global anthropogenic changes? (ii) What is the relative importance of climate *vs* human drivers in such changes? (iii) To what extent do anthropogenic climate change and direct human drivers contribute to denudation, relief transformation and sedimentation? (iv) Is this also reflected in other geomorphic processes? (v) Are there any implications for the characterisation and limits of the Anthropocene?

## 2. Technological denudation, human geomorphic footprint and contribution to global denudation

The importance of human activity in the transformation of our environment in general and as a geomorphic agent in particular, has been pointed out many times since the mid-19th century (Marsh, 1864; Stoppani, 1871–73; Thomas, 1956; Ter-Stepanian, 1988; Rivas et al., 2006; Cooper et al., 2018; Zalasiewicz et al., 2014, 2021; Syvitski et al., 2005a, 2022). Changes in LULC provide one widely recognized example, involving the growth over large areas of towns and cities and especially of farmlands, and the decrease in forests, shrublands and grasslands (Prokop and Sarkar, 2012; Abadie et al., 2017; Chen et al., 2019; Liu et al., 2021). These LULC changes often imply direct, deliberate “technological denudation” (Brown, 1956), and intensive transformation of landforms (excavations, accumulations, buildings and other types of hard land cover) as well as indirect erosion due to land cover and land surface disturbance.

Technological denudation and landform construction are by no means something new in human history. Bruschi et al. (2011a) pointed out that “tells” built about four millennia ago in Mesopotamia represent conspicuous “anthropolandforms”. Urban-geomorphological studies in historical sites have shown the contribution of cities and other settlements to the accumulation of anthropogenic deposits and their significance for the definition of the Anthropocene (*e.g.*, Cooke et al., 1982; Rosenbaum et al., 2003; Del Monte et al., 2016; Brown et al., 2017; Zwoliński et al., 2018; Vergari et al., 2020). In this context, Price et al. (2011) discussed the role of humans as geological and geomorphological agents during the Anthropocene, through the study of artificially made ground in Britain. Also in Britain, Terrington et al. (2018) showed that the amount of “artificial ground” generated in central London since 1950 was approximately equivalent to that generated in the two previous millennia. Luberti et al. (2019) compared the thicknesses of anthropogenic deposits in some European historical centres and mining districts, and estimated the thickness of anthropogenic deposits in the historic centre of Rome, where human-made modifications started three millennia ago. In some Polish cities, the thickness of anthropogenic deposits may exceed 7–14 m (Molewski and Juskiewicz, 2014; Zwoliński et al., 2018; Łajczak et al., 2020).

An attempt to assess the contribution of technological denudation to geomorphic processes was presented by Rivas et al. (2006), who analysed the magnitude of excavations and accumulations in several study areas of Argentina and Spain. They proposed the concept of “*human geomorphic footprint*” (HGF), defined as the volume of Earth materials (soil, sediment, rock) directly displaced by activities such as urban sprawl, infrastructure development or mining/quarrying, and the area occupied by newly generated “anthropolandforms” (excavations, accumulations or constructions of any kind). The HGF can be expressed as $m^3$ $person^{-1}$ $a^{-1}$ or $m^2$ $person^{-1}$ $a^{-1}$ or, assuming a uniform distribution over land surface, as a “denudation rate” (mm $a^{-1}$). Rivas et al. (2006) estimated a HGF of 30.4 $m^3$ $person^{-1}$ $a^{-1}$ (Spain) and 6.4 as $m^3$ $person^{-1}$ $a^{-1}$ (Argentina), and a mobilization (technological denudation) rate of 2.4 (Spain) and 0.8 mm $a^{-1}$ (Argentina). As the two countries considered represent one emerging and one industrial economy, they reasoned that

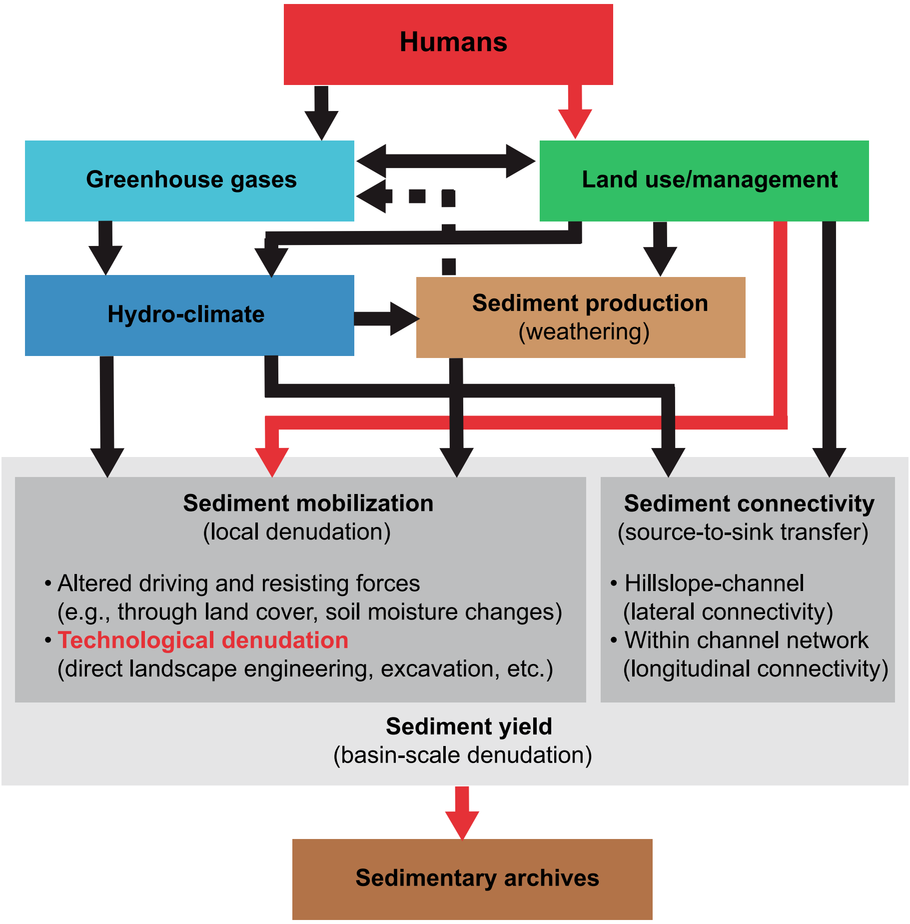

**Fig. 1.** A simple conceptual model of human influence on geomorphic processes and sedimentary archives. The pathways of influence highlighted in red are the primary focus of this article. Dashed line indicates a link occurring at a longer time-scale (slow carbon cycle). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

world averages would probably be somewhere in between, and proposed a conservative average of 1 mm $a^{-1}$. Using a similar, conservative approach, 12 $m^3$ $person^{-1}$ $a^{-1}$ could be a reasonable estimate for global *per capita* HGF.

According to data from several authors compiled by Rivas et al. (2006), those values are 1–2 orders of magnitude greater than the ones due to "natural" denudation rates or sediment fluxes to the world's oceans (both of them highly affected by human activities). Syvitski and Milliman (2007) estimated a global average sediment yield of 154 t $km^{-2}$ per year (slightly under 0.1 mm $a^{-1}$), also over one order of magnitude lower than "technological denudation" indicated above, and Syvitski et al. (2022), estimated that natural processes presently contribute <6% to global sediment load.

A global assessment of the magnitude of technological denudation presented by Cooper et al. (2018), concluded that direct human contribution to global sediment generation was in 2015 over 24 times greater than sediment supply by the world's major rivers to the oceans. They proposed that the major acceleration in anthropogenic sediment flux started after World War II, and that humans are now the major global geomorphological driving force. The conservative estimate of the HGF above, based on data from Rivas et al. (2006), is quite similar to the one proposed by Cooper et al. (2018), of about 20 $m^3$ $person^{-1}$ $a^{-1}$. The similarity is quite striking, especially considering the uncertainties involved and the differences in approach and data sources used by these studies. According to Syvitski et al. (2022), in 2010 Anthropocene sediment production was about 17.3 Gt $a^{-1}$ for land to sea sediment fluxes and 175 Gt $a^{-1}$ for what can be considered as "technological denudation". This is equivalent to the value obtained for a world population of $7 \times 10^9$, using the *per capita* HGF of 12 $m^3$ $person^{-1}$ $a^{-1}$, very much the same as the ones discussed above.

An additional comparison can be made with the results presented by Liu et al. (2021) on the expansion of urbanised land for the period 1985–2015. They obtained a value of approximately 10,000 $km^2$ $a^{-1}$ of new urban land globally for the period 1985–2015, compared to an estimate by Rivas et al. (2006) of 40,000 $km^2$ $a^{-1}$, of new "anthropolandforms" (constructions, infrastructures, excavations and accumulations). The former authors considered urban land and used a 30 m cell, whereas the latter extrapolated using *per capita* values, including also land affected by mining/quarrying and infrastructure. This means that the difference is actually much smaller, and surely within the same order of magnitude.

Areas disturbed by excavations and accumulations of loose materials without vegetation are more easily affected by natural erosion agents, and contribute to indirect human denudation. Even though such areas represent a small proportion of the study areas analysed by Rivas et al. (2006), their contribution to total sediment generation was estimated to be at least equivalent to (probably greater than) that of "natural" denudation in undisturbed areas, the latter also affected by farming and forestry activities. In a further analysis of sediment accumulation in lakes of the humid Pampa of Argentina, Forte et al. (2016) indicated that since the beginning of the 20th century, regional erosion and lake sedimentation rates are 1–2 orders of magnitude greater than those prior to European settlement in the region (around 250 years ago). Similar examples are found in river and lake records globally. For example, Kemp et al. (2020), concluded that *"humans have moved as much sediment in North America in the past century as natural processes can transfer in 700–3000 years"*. The global significance of indirectly induced soil erosion has been clearly illustrated by Syvitski et al. (2022), who estimated a three-fold increase between 1950 and 2010.

The case of road construction associated with forest activities in NW North America and its effect on landslides and denudation (indirect technological denudation) is also illustrative (Swanston and Swanson, 1976; Ziemer and Swanston, 1977; Wu et al., 1979; Sidle, 1992; Sidle et al., 2001; Sidle and Bogaard, 2016). Road construction and vegetation removal, with consequent soil compaction, reduced canopy interception and increased exposure of unconsolidated material, have frequently resulted in slope failures as well as road fill and surface erosion. In some cases, roads, especially road fill failures, were observed to be among the dominant sources of sediment mobilized on hillslopes (Wemple et al., 2001). Roads may continue to generate sediment decades after their construction (Switalski et al., 2004; Keppeler and Lewis, 2007). Similar results were obtained by Syvitski et al. (2005b) in Taiwan, where they found a 10-fold increase in sediment flux in rivers following road construction.

In the Polish Carpathians, Froehlich (1982, 1986) showed that, both in agricultural and forest catchments, sediments are supplied from slopes to river channels mainly through erosion of unpaved roads. In the same region, LULC changes and river channelization in the second half of the 20th century, involving the reduction of channel width-to-depth ratio and long-term gravel mining from channels, contributed to increased channel incision by 1 cm $a^{-1}$ in the period 1969–2017 (Wyżga, 2008; Bucała-Hrabia, 2018). In low-relief areas in Finnish Lapland, with very low contemporary mechanical denudation rates, gravel road construction was found to be a comparably important sediment source for measured mechanical denudation (Beylich, 2011).

On the other hand, Brown et al. (2021)*,* examining the role of agricultural terraces in sediment dynamics and sediment connectivity in Europe, showed that they altogether reduce erosion, and Borrelli et al. (2020), assessing the global impact of 21st century land use changes on soil erosion, found a decreasing trend in wealthier countries, driven by more favorable climatic conditions, or soil erosion prevention measures.

In summary, available data show that direct and indirect contributions to technological denudation are presently of paramount importance in driving global denudation fluxes. In particular, the direct *per capita* contribution of the HGF (Rivas et al., 2006) clearly seems to increase with time, especially after the mid-twentieth century (Cooper et al., 2018). Data provided by UN (https://population.un.org/wup/) clearly show that urban population grows much faster than total global population (Steffen et al., 2015); and Liu et al. (2021) indicate that urbanised land (area HGF) is growing significantly faster than population. The values obtained by Cooper et al. (2018) indicate that the amount of excavated materials (volume HGF) is growing even faster.

These results, as pointed out by former contributions, indicate that the bulk of present global denudation corresponds to direct, technological denudation. Quoting Hooke (1994) "…*humans are arguably the most important geomorphic agent currently shaping the surface of Earth.*", Rivas et al. (2006) "*human action has taken over natural processes as the main agent of materials transfer on the Earth surface*"; Cooper et al. (2018) "*Humans are now the major global geomorphological driving force and an important component of Earth System processes of landscape evolution*", or Syvitski et al. (2022) "*..humans have transformed the mobilization, transport and sequestration of sediment, to the point where human action now dominates these fluxes at the global scale"*. The relative detriments and benefits due to increasing technological denudation and sediment transport/deposition should be further assessed.

## 3. Slope movements and denudation

Landslides and other types of slope or mass movements result in the generation of mostly unconsolidated (with some exceptions, as large scale sags) materials which are displaced downslope, in general involving water in one way or another, by distances that might amount to tens of km. Mass movements, particularly on vegetation-covered slopes, are the main mechanism of relief dismantling, extending laterally and upslope the incision caused by watercourses (Richards and Lorriman, 1987; Alexander, 1992; Remondo et al., 2005; Harvey, 2001; Beguería, 2006; Temme et al., 2020). Rock, sediment and soil mobilized by these mechanisms are often further re-worked and transported before they finally deposit, thus contributing to denudation, relief evolution and sedimentation (Peart et al., 2005; Broeckx et al., 2020). Residence and transport time of the materials thus originated varies widely (even in the order of 100 ka), but eventually they will end up in some sort of sedimentation environment. It is thus pertinent, for analysing the magnitude and evolution of denudation, to consider the contribution of slope movements to the displacement of surface materials.

As water is involved in most slope movements, it would be logical to expect that changes in rainfall would be reflected in changing landslide activity, both shallow landslides in response to intense rainfall events and deep-seated ones, more dependent on cumulative rainfall (Borgatti and Soldati, 2013; Micu et al., 2022). But the occurrence of slope movements is often determined by human activities such as infrastructure development, forestry, agriculture, *etc.*, especially in densely populated areas (Goudie, 1993; Glade, 2003; Meusburger and Alewell, 2008; Crozier, 2010; Guthrie, 2015; Gariano and Guzzetti, 2016). The relative role of both types of drivers should therefore be considered.

One parameter that could help to estimate the contribution of landslides (actually, slope movements in general) to denudation is the Relative Landslide Rate (Cendrero and Dramis, 1996), defined as: $RLR = R_{lm}/R_d$ where: RLR = relative landslide rate; $R_{lm}$ = landslide mobilization rate (mm $a^{-1}$); equivalent thickness of mobilized materials if they were uniformly distributed over the whole area considered; $R_d$ = denudation (erosion not attributable to slope movements) rate, also as mm $a^{-1}$. According to Selby (1982), there are two broad types of slopes: (a) weathering-controlled slopes, in which the rate of weathering is less than the potential rate of regolith removal and are usually bare; (b) transport limited slopes, in which transport processes cannot keep up with the rate of regolith production, and on which the regolith accumulates. Transportational slopes are an intermediate case. It would be expected that $RLR > 1$ on transport-limited slopes, $RLR < 1$ on weathering-limited slopes and about 1 on transportational slopes (Selby, 1982). Rough estimates obtained by the former authors in the Cantabrian Range yielded RLR values 0.3–1 for the whole Quaternary and 1–10 for the Holocene. In the Canary Islands, also for the whole Quaternary, they obtained a RLR value of 0.2–1. These are of course rough approximations to what could be the actual values, but do show that landslide contribution to denudation in the two regions could be considerable, in a period with obviously no relevant human influence.

The importance of landslides in the generation of sediment and relief evolution has been described in different regions. Korup et al. (2010) concluded that landslides are the main source of sediment in mountainous terrain. In the Polish Carpathians, Kijowska-Strugała (2019) found that suspended sediment load in channels was significantly higher downstream than upstream of landslides, which appear to be an important sediment source. Increases in sediment generation caused by landslides, with factors between 2 and 10, have been described by Amaranthus et al. (1985) in logged areas of Oregon; O'Loughlin (1972) and Brardinoni et al. (2003) in British Columbia; Swanson and Dyrness (1975) or Swanston and Marion (1991) in Alaska; Imaizumi et al. (2008) in Japan. The significant role of slope movements in denudation and sediment supply has also been illustrated by Koppes and Montgomery (2009) and Korup and Rixen (2014), and by Broeckx et al. (2020), who analysed the relationship between landslide mobilization rate and sediment yield, in different basins of Africa and Europe. In particular, in the case of Europe, where 2509 basins were included in the analysis, they found that "*the correlation between European SY and LMR is clearly significant*" (Fig. 2).

Intensification of slope movements in response to human activities, even in prehistoric times, has been described in quite different areas. In the Mediterranean region, there is evidence that deforestation during the Neolithic triggered shallow landslides, a process that became particularly extensive after the Middle Ages (García-Ruiz et al., 2016). An assessment of the evolution of landslide occurrence during the last 120 ka in N Spain (González-Díez et al., 1996, 1999), and its contribution to the displacement of soil, surface deposits and rocks, showed a significant increase of landslide mobilization rate, about one order of magnitude during the period covered. They detected two periods of significant human influence, one around 6–5 ka BP, coinciding with the settlement of Neolithic populations in the region, and the other starting around 1800 coinciding with the onset of the Industrial Revolution.

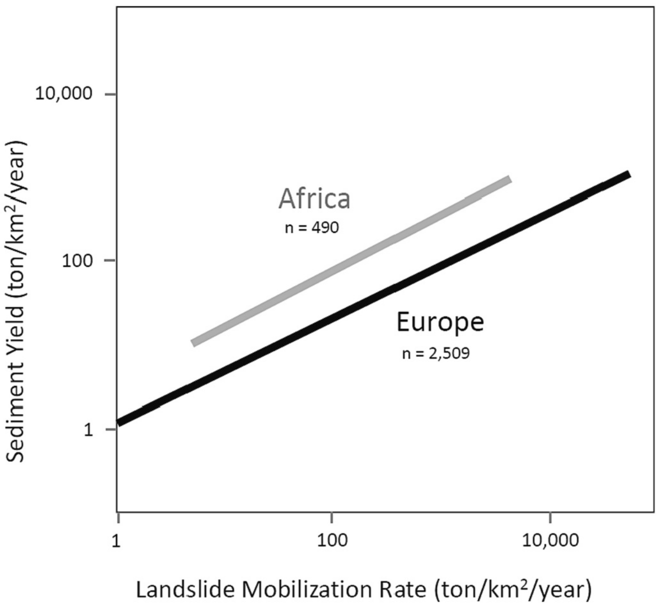

**Fig. 2.** Estimated landslide mobilization rates (LMR) *versus* observed sediment yields (SY) in catchments of Europe and Africa, in metric tons/km$^2$/year (simplified after Broeckx et al., 2020).

In the same region, in the Bajo Deba valley, Remondo et al. (2005) found one order of magnitude increase of both landslide frequency and mobilization rate, during the second half of the 20th century (Fig. 3). The increase showed no relationship with rainfall variations, but it did coincide with the intensification of human activities. A decrease of landslide frequency was detected in the same area during the early part of the present century by Rivas et al. (2022) (Fig. 3). Also in N Spain, Bruschi et al. (2013) analysed the possible relationship between slope movements upstream and sediment deposition in downstream estuaries. Again, the observed increases of landslide mobilization rates showed no relationship with changes in climate parameters, but a fairly good correlation was found between landslide frequency and socioeconomic indicators of the intensity of human activity, such as Gross Domestic Product (GDP) growth, or new home construction. Sedimentation rates in two neighbouring estuaries were determined by means of $^{210}$Pb and $^{137}$Cs dating, and significant increases were found, particularly in the second part of the last century, roughly coinciding with the trend and magnitude of slope movements increase. According to these authors, the evidence suggests that the increases, in both slope movement activity ("denudation") and sedimentation rates, are essentially due to geomorphic changes caused by human action.

Increases of landslide frequency during the last century or so have also taken place in other regions. Local increases related to human activities have been documented since 1969 in the Polish Carpathians (Kijowska-Strugała et al., 2017; Kijowska-Strugała, 2019). Landslide frequency in Italy (Guzzetti and Tonelli, 2004) shows an increase after the 1970s and more so after the 1990s, and a decrease in the last few years of the period registered (Fig. 3). A general growing trend (with episodes linked to both peaks of human activity and rainfall events) has been observed in the German Central Uplands (Damm and Klose, 2015) and also an incipient decrease towards the end of the period covered (Fig. 3).

The frequency of detected large-scale and catastrophic quick clay landslides, *e.g.* in Canada, Norway and Sweden, has increased in modern times, most likely due to a great extent to increased human activity, particularly after World War II (see *e.g.* L'Heureux, 2017; L'Heureux et al., 2018; Heyerdahl and Kalsnes, 2018). The intensification of landslides on the steep slopes of river valleys, gullies, lakeshores or

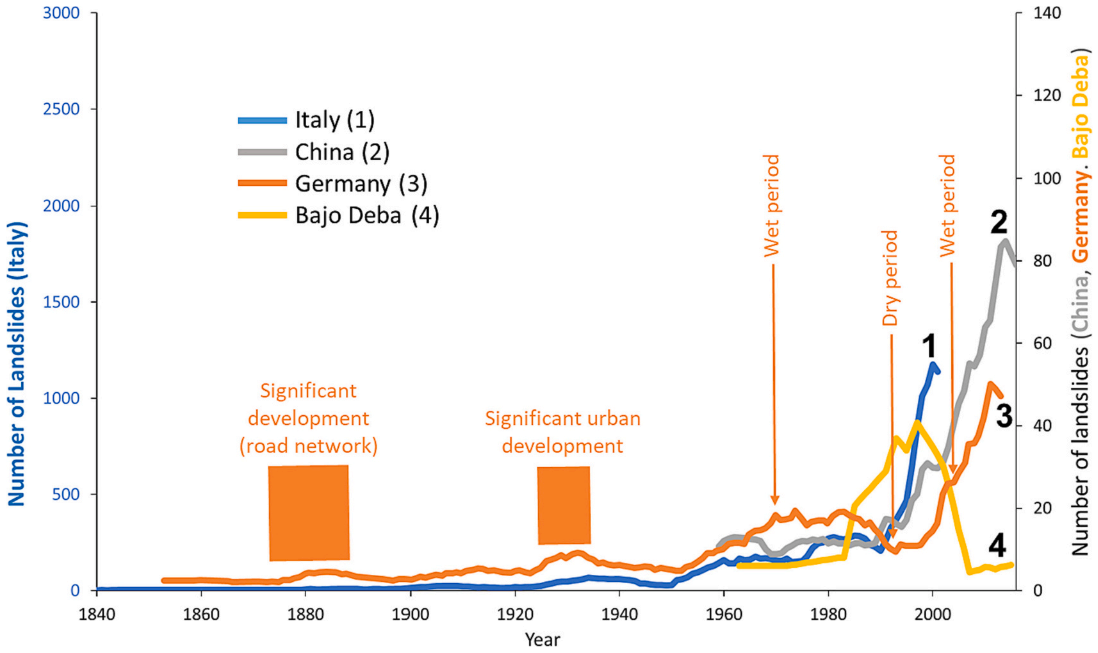

**Fig. 3.** Landslide frequency in Italy, Germany, China and the Bajo Deba valley (Spain). Data obtained after Guzzetti and Tonelli (2004), Damm and Klose (2015), Lin and Wang (2018) and Rivas et al. (2022), respectively.

reservoirs may be associated with land crop abandonment. Soils of abandoned land, overgrown with grassy vegetation and especially forests, better reduce surface runoff (rainfall- or snowmelt-induced) and increase infiltration. More abundant groundwater (higher pore pressure) can intensify landslide processes on these slopes. Several decades ago, studies in the Middle Volga region (European Russia) showed that landslides were more active in forest areas than in treeless ones (Dedkov and Mozzherin, 1996). A similar relationship was observed during the 2018 earthquake in Hokkaido, Japan (https://earthobservatory.nasa.gov/images/92832/landslides-in-hokkaido). Conversely, studies conducted at Cinque Terre (Liguria, Italy), where diffuse catastrophic shallow landslides occurred in 2011 as a consequence of extreme rainfall events, showed that landslide susceptibility is up to 15% higher in abandoned terrace fields than in vineyards (Galve et al., 2015), and that reforestation appears the most suitable and cost-effective measure to stabilize the slopes in that area (Galve et al., 2016). That is, human-driven land cover changes significantly affect slope movement activity.

Time series of slope movement events are not frequent for large areas, but they are available for disasters (that is, events causing damages or casualties) related to them. The latter depend not only on the hazard (event frequency or intensity, related to process activity) but also on exposure and vulnerability, both of them related to human factors. Nevertheless, they provide an indirect, approximate image of process activity. Landslide-related disasters in China (Fig. 3) (Lin and Wang, 2018), show a trend very much similar to the one of landslide events in Italy or in the Bajo Deba valley, N Spain (Fig. 3). The same has been reported for geomorphic disasters in general (related to slope movements and floods, the latter being the main contributor) (Fig. 4) in the five continents and most regions within them (Forte, 2017; Cendrero et al., 2020).

Of particular interest is the case of the NW Pacific coast of North America, where the effects of land cover transformation resulting from the settlement of populations of European origin is relatively recent and well documented. Prior to the European settlement, this heavily forested region was subject to relatively small impacts from land management by Indigenous Peoples, mostly in the form of localized burning (Johnson and Swanson, 2009; Whitlock et al., 2015). As a result, there is every indication that the degree of anthropogenic land transformation was very modest and the major events which could promote widespread slope movement activity were likely earthquakes (Barth et al., 2020) and land cover disturbances due to volcanic eruptions, wildfires or, especially, heavy rainfall and fast melting of snow (Walling et al., 1996; Alaback et al., 2013). Large stand-replacing fires were especially important in the southern and inland portions of the region and less common in much wetter and cooler climate along the coast.

Even though the arrival and explorations by non-Indigenous people in this region have been well-documented since the 17th century (but may date perhaps as far back as the 16th century), a more intensive and extensive land management did not begin until the 19th and 20th century (Whitlock et al., 2015). Widespread harvest using disruptive methods, driven by high demand for lumber, has dramatically altered the disturbance regime across that NW region (Johnson and Swanson, 2009). Significant erosional activity observed in the logged areas, often taking the form of mass slope failures, has motivated intense research efforts in the second half of the 20th century to understand the magnitude of geomorphic response as well as the mechanisms that underpin it. Key groups of mechanisms identified were: reduced mechanical stability of the slope, altered drainage conditions, and inherent erodibility of unconsolidated aggregate used for road construction (Ziemer and Swanston, 1977; Wu et al., 1979; Sidle et al., 2001; Sidle and Bogaard, 2016; Bell et al., 2021; Shvarev et al., 2021). The relative magnitude of these mechanisms varied across the region, reflecting somewhat different geological, topographic and climatic conditions (Jordan, 2001; Jordan et al., 2010). However, in many cases, road-related failures were observed to be among the dominant sources of sediment mobilized on hillslopes (Swanson and Dyrness, 1975; Wemple et al., 2001). In a recent study, Cienciala et al. (2022) found that – similar to the findings of research reviewed above – a mountainous basin affected by such timber harvest operations experienced one order of magnitude changes in sediment yield. Over time, better management practices, associated with a changing regulatory and policy framework, seem to have moderated the impact of forest operations on slope stability in the region (Amaranthus et al., 1985; Beschta and Jackson, 2008; Cristan et al., 2016; McEachran et al., 2021).

Something similar has been observed in many Mediterranean areas, where, after extensive deforestation activity during the Middle Ages, agriculture abandonment in the last few decades led to increasing vegetation cover, contributing to a reduction of slope failures and fluvial

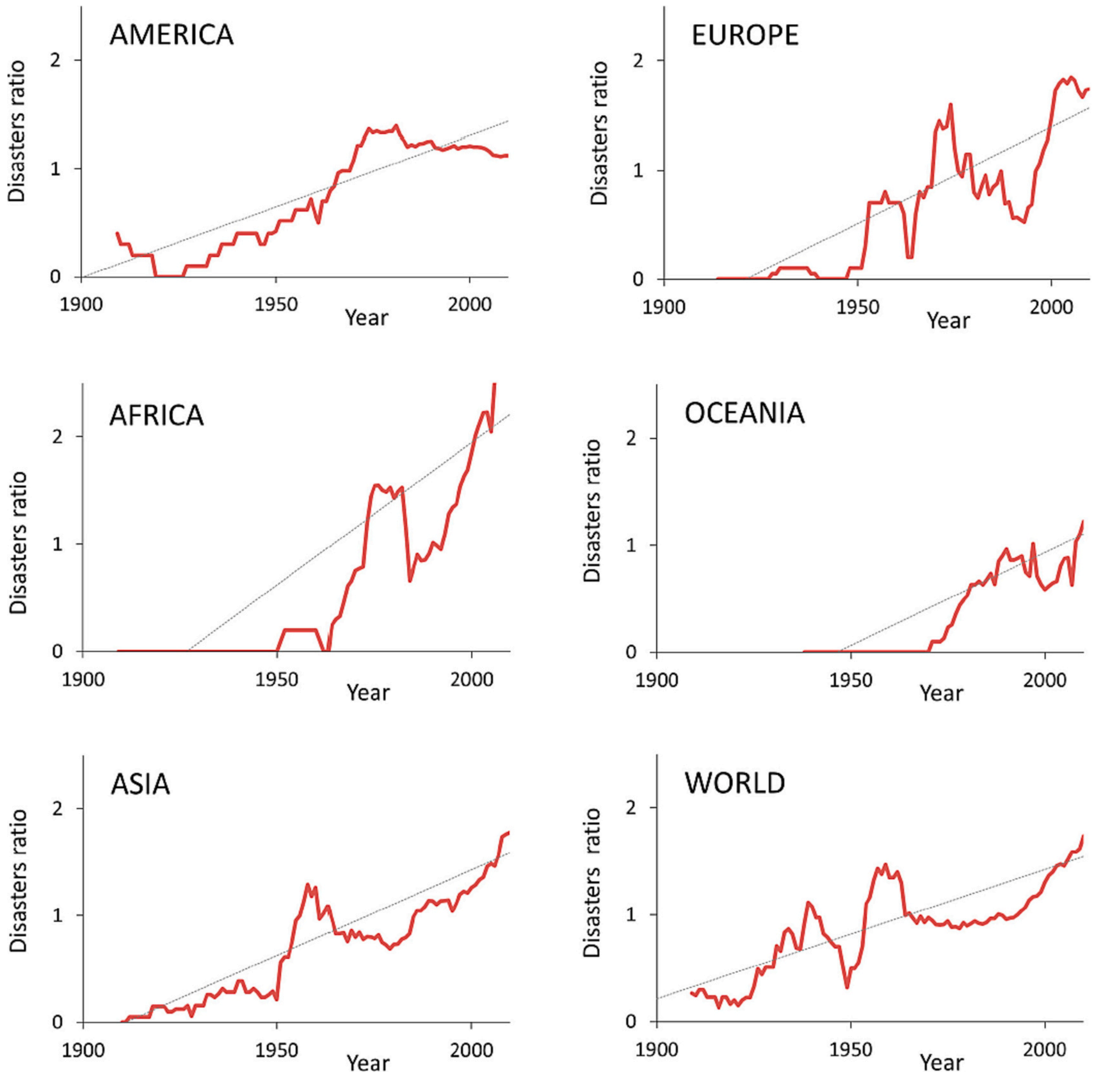

**Fig. 4.** Ratio of the frequency of hydrogeomorphological disasters over the frequency of purely climatic disasters, in the five continents and the world (red line: 10-year moving average; data from EM-DAT). Thin black line: linear trend. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sediment transport, especially in the upper sectors of river basins (García-Ruiz and Lana-Renault, 2011; Comiti and Scorpio, 2019).

However, records of landslide activity must be considered with caution. After a review of the content, structure, accuracy, and completeness of the Catalogue of Landslide Occurrences in the Emilia-Romagna Region (Italy), recording 14,026 for the period 1850–2018, Piacentini et al. (2018) concluded that records of small and secondary phenomena increased with time, but whether this should be interpreted as an increasing trend in mass movement activity is not so clear (perhaps a higher frequency of warnings and better records?). On their part, Cendrero et al. (2020) pointed to the possible bias of landslide frequency records, due to increasing population and human exposure or improved and more complete reporting with time.

### 3.1. *Slope movements and climate change*

In some cases, intense rainfall events (not necessarily attributable to climate change) are clearly related to event occurrence (1983 in N Spain; Rivas et al., 2022; 1965–66 and 2002 wet periods in the German Central Uplands; Damm and Klose, 2015) but the general increasing trends described are not satisfactorily explained by climate. As pointed out by Sidle and Dhakal (2002) or Gariano and Guzzetti (2016), the direction and magnitude of other drivers, and of their effects, may outweigh changes in landslide activity due to climate change. The fact that climate might not be the main driver of the growing frequency of slope movement events and disasters and floods is supported by data provided by EM-DAT (Fig. 4), representing the ratio between the frequencies of "geomorphic" disasters (including landslides and floods, the latter being the most frequent) and the frequency of purely climatic disasters (those not related to land surface processes). It is clear that the ratio has grown considerably (about twofold), in the five continents and at global level, during the latter part of the twentieth century. Disasters recorded depend, on the one hand, on the frequency and severity of natural events. But, also on human exposure/vulnerability and data gathering completeness, which have increased with time. In any one region, exposure/vulnerability and data gathering are obviously the same for both types of processes. Climate change can surely affect "geomorphic" disasters frequency, but even more so the frequency of disasters related to droughts, cold and heat waves, windstorms, *etc.* ("climate" disasters). The evolution of climate factors in a given region during any period is obviously the same for all types of disasters. Therefore, there must be some additional factor, and the most likely one, in this case, is land surface alteration or geomorphic change, which affects the former but not the latter.

In the case of N Spain, Rivas et al. (2022) found that landslide frequency decreased during the present century. But rainfall (both total precipitation and rainstorm frequency/intensity) did not change significantly. On the other hand, better practices and a reduction of human activities that affect land surface were observed. It is interesting to point out that a decreasing trend in the frequency of both slope movements and related disasters has also been observed (Fig. 3) in the last few years in several regions (Guzzetti and Tonelli, 2004; Damm and Klose, 2015; Lin and Wang, 2018; Cendrero et al., 2020; Rivas et al., 2022) as well as at global level (EM-DAT, n.d.). If climate change were the main driver, it would be difficult to explain such decrease. A more likely explanation is that better mitigation measures and practices for activities that imply land transformation are being implemented, as suggested by the environmental Kuznets curve, EKC (Dinda, 2004; Bojo et al., 2013; Shabhz et al., 2013). According to the EKC, as Gross Domestic Product (GDP) increases environmental degradation increases too, until a point at which it begins to decline, due to better conservation practices. The result is an inverted U-shaped curve of environmental degradation. It could be that we have been following a similar trajectory with respect to land transformation (and its effects on geomorphic processes).

However, it must be kept in mind that decreasing frequency and magnitude of landslides with time may be related to the reduction of slope angle due to repeated slope movements or the adjustment of landslide phenomena to the existing conditions, *e.g.* precipitation, human activity, *etc.* (Coe, 2016). The adjustment processes do not contradict the possibility of sudden, extreme and catastrophic landslides that may occur at any time and space as a result of an exceptional event exceeding the threshold values of stability, strength, compactness or moisture in the bedrock or soft substrate (Jania and Zwoliński, 2011). Such unexpected phenomena can be triggered by natural causes, mainly extreme climate events (less frequently, volcanic eruptions or earthquakes), as well as human activities, such as LULC changes.

Factors affecting slope stability and mass movements of different types are many and varied (lithology, structure, topography, climate, land cover, human activities, tectonism, *etc.*). Moreover, studies and records of landslide activity tend to concentrate in populated areas, and there has been limited or no recording of events, particularly those of smaller magnitude, in thinly populated areas (although this is nowadays changing, due to satellite coverage). Therefore, it should not be expected that the increasing trend described is found in all regions. It thus appears that: (i) slope movements have become more and more frequent since the mid-twentieth century (with a recent decrease); (ii) human-driven landscape modification has a strong influence, probably greater than climate, on the frequency of slope movements; (iii) the contribution of slope movements to denudation and relief evolution is growing significantly. Further analyses are desirable for determining to what extent the “human factor” is of greater or lesser importance than the “climate factor”.

## 4. Sedimentation as an indirect approach to assess the evolution of denudation

Sedimentation is the normal consequence of denudation in self-organising systems. Although the spatial and temporal link between both depends on very different factors and can vary widely, the evolution of sedimentation rates can be used to obtain an insight into the evolution of denudation and the degree of human influence on it (Rohel, 1962; Costa, 1975; Brierly and Stankoviansky, 2003; Schiefer et al., 2013; Owens, 2020). We cannot directly determine past denudation rates, but sediment records provide a record (often continuous) of sediment accumulation in the past (Walling, 1996, 2006; Cisternas et al., 2001; Dearing and Jones, 2003; Carrera et al., 2005; Bonachea et al., 2010). Extraction and dating of sediment cores enable the determination of past sedimentation rates, and their comparison with factors affecting sediment generation.

The link between denudation and sedimentation is not direct and unequivocal (Meade, 1982; Bracken et al., 2014; Cienciala et al., 2020b; Cienciala, 2021). Sedimentation rates in one particular site (a lake, an estuary, *etc.*) will not necessarily say much about denudation processes in its whole catchment. As Walling (2006) indicated “ …*the aggregation and buffering effects that operate in larger basins, can cause damping and even removal of signals of increasing flux within the upstream basin*…”. However, it is reasonable to assume that if sedimentation shows a general increase or decrease at different localities, denudation must have done too, even though their magnitudes could be different. Sedimentation rates could thus provide an approximate, “coarse grain” image of denudation rates.

This approach was used by Bonachea et al. (2010), to analyse sedimentation rates in the Rio de la Plata basin (Brazil-Argentina) and their relationship with natural and human drivers during the last century. Cores were extracted and dated ($^{210}$Pb and $^{137}$Cs), and density-corrected sedimentation rates were obtained in different types of sedimentation environments: one reservoir near Sao Paulo, fourth largest megacity in the world; three lakes in the Pantanal, a huge wetland in southern Brazil; a lake in a remote area of the Andean region, around 3500 m altitude, very thinly populated and with almost no human activity; and the Rio de la Plata estuary. Increases of sedimentation rates (nearly one order of magnitude in about half a century) were found in all cases, except in the Andean lake (as was expected). The increases were particularly marked after the 1970s–1980s. The evolution of sedimentation rates was compared with rainfall and several indicators of the intensity of human activity. No similarity was found with the former, but the magnitude and trends of indicators such as population, Gross Domestic Product (GDP), energy or cement consumption (all of them closely related to activities which imply land disturbance) were quite similar (Fig. 5). The conclusion was that changes observed in sedimentation rates could be better explained by land disturbance and land-use change rather than climate change.

A similar analysis performed in N Spain, through the determination of sedimentation rates in eight estuaries and comparison with potential natural and human drivers (Bruschi et al., 2013), yielded quite similar results (Fig. 6). Sedimentation rates showed an increase in 11 out of 14 cores, particularly after the 1960s. Rainfall (and river discharge) in the region decreased after the late 1970s, but population as well as construction of new homes increased practically in all the basins analysed, and so did GDP (national and for the region) and cement consumption. Again, results obtained pointed to land disturbance due to human activity as the most likely cause of growing sediment supply (and denudation).

An assessment of the situation at global level was attempted by Cendrero et al. (2020). Data on sedimentation rates since the second half of the 19th century were obtained from the literature for over one thousand locations in five large countries/regions: China, India, USA, Europe, Australia. Periods covered and time resolution of the data from the different sources varied widely, but could be grouped into three broad periods: pre-1900, 1900–1950, post-1950. The results were analysed grouping the points with data in two different ways, by sedimentation environments (lakes, reservoirs, fluvial channels, floodplains, wetlands on fluvial valleys, deltas, coastal wetlands, bays and estuaries, coastal platforms) and by geographical areas within each country/region analysed (between 4 and 9 geographical areas, depending on the region/country). Therefore, the data cover a wide range of geographical settings, with different geological, geomorphological, climatic and socio-economic conditions. At some of the points, sedimentation rates could be obtained for the three periods indicated, but not in others. A total of 120 groupings of points were thus obtained (59 sedimentation environments and 61 geographical areas; including all points with data and only points with data for the three periods considered). All of them but one showed an increase from pre-1900 to post-1950. With very few exceptions, rates increase from the first to the second period and from this to the third. A reduction of sedimentation rates from the first to the

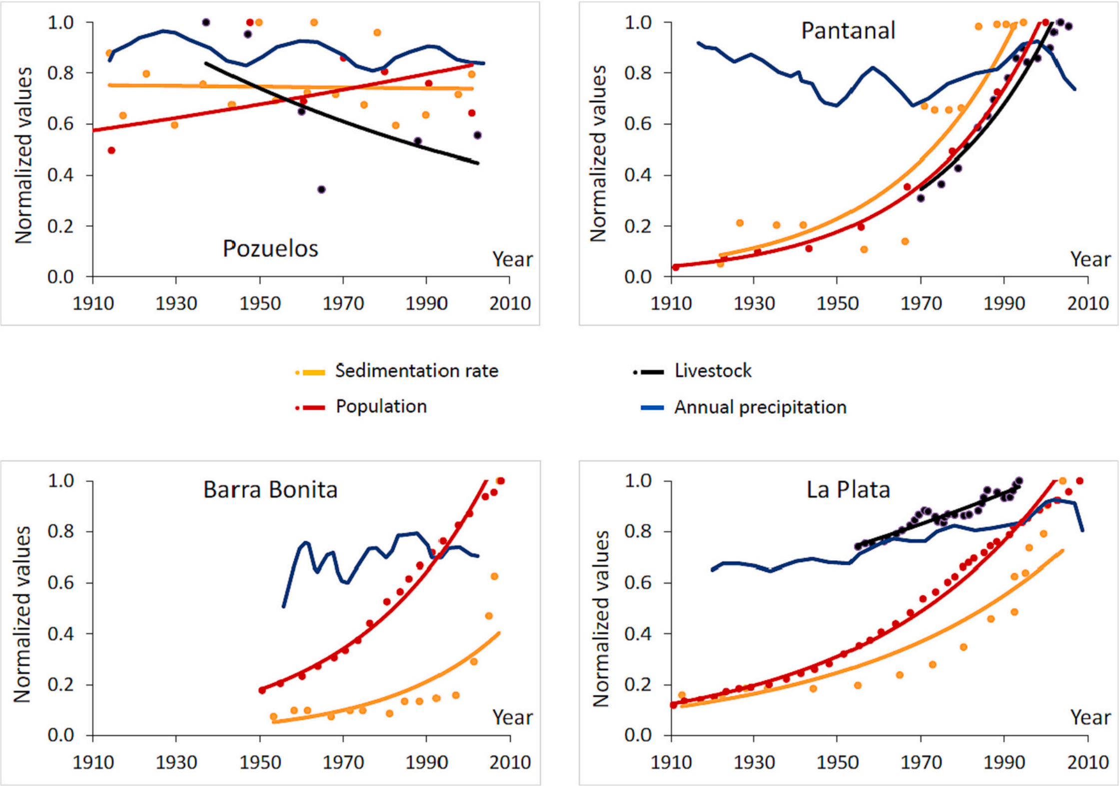

**Fig. 5.** Sedimentation rate, annual rainfall (5 year moving average), population and livestock data for different areas in the Rio de la Plata Basin (Laguna de Pozuelos, Pantanal, Barra Bonita and Rio de la Plata estuary). Data modified after Bonachea et al. (2010). Normalized values with respect to the maximum of each variable.

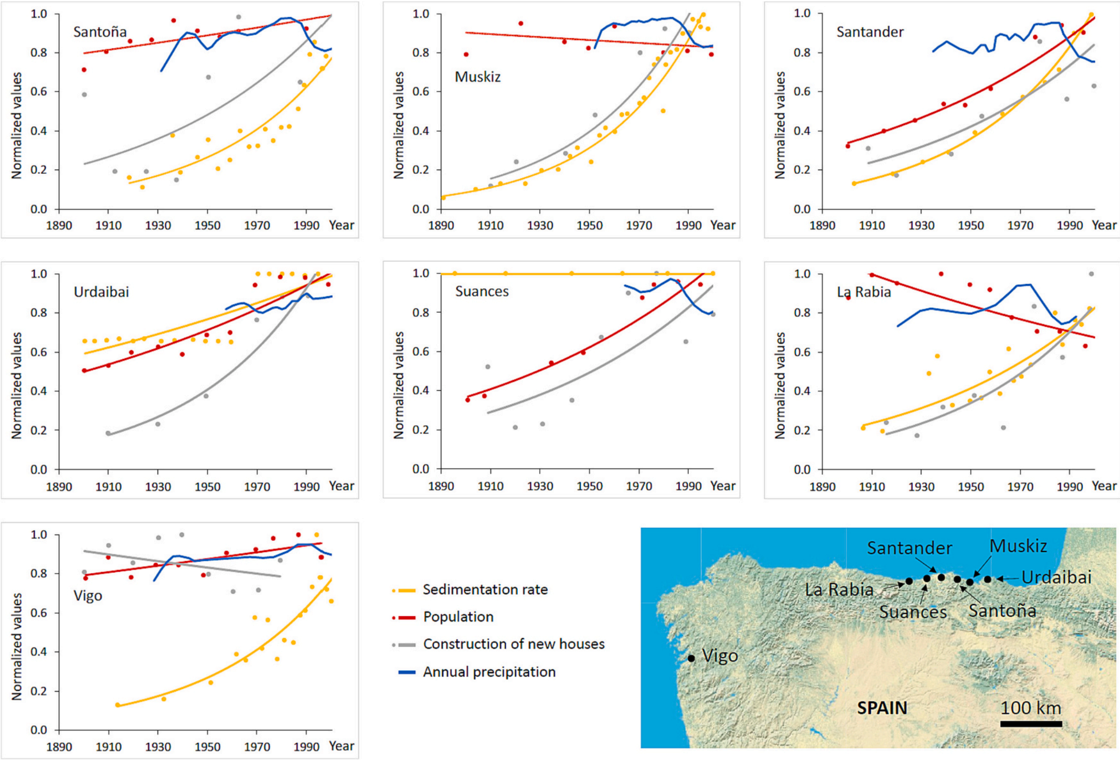

**Fig. 6.** Sedimentation rate, population, construction of new houses and annual precipitation (5 year moving average) data in various estuaries in northern Spain. Data modified after Bruschi et al. (2013). Normalized values with respect to the maximum of each variable.

second period was found in two cases, and from the second to the third in six cases. The exceptions corresponded normally to groupings with very few data. The increase was in the vast majority of cases greatest after 1950. Increase factors for the whole period covered varied between 3 and 33. This general intensification of sedimentation suggests there was a general increase of denudation by all sorts of geomorphic processes in very different geographical areas (under very varied natural and human conditions), especially after the mid-twentieth century.

The evolution of sedimentation rates in the five areas analysed is summarised in Fig. 7. The acceleration of sediment supply is quite clear in all of them. The figure also includes comparison with rainfall and GDP. As shown, rainfall did not show important changes. It shows slight rainfall decrease in Asia, an even smaller increase in N America and no clear trend in the other regions. GDP, by contrast, increased without exception, and with relative trends roughly similar to those of sedimentation rates. These results do suggest that the observed acceleration of sedimentation (in principle reflecting increasing denudation) is due mainly to physical land surface transformation, rather than climate change.

Analyses of sediment records in Canada, through determination of sedimentation rates by means of $^{210}$Pb (Schiefer et al., 2013), also found that lake sedimentation rates in western Canada have steadily increased during the late 20th century. They also found that “*Although sedimentation was highly variable, increasing trends in accumulation corresponded with cumulative land use and, to a lesser degree, with climate change. Road density was the most important variable, but the inclusion of timber harvesting density further improved model fits significantly*.”

Sediment records from Iberian lakes also show an increase of sediment flux interpreted as a product of greater erosion during the 19th century, coinciding with the expansion of cultivated lands, followed by another pulse in mid-20th century, reflecting the intensification of soil erosion and subsequent sediment delivery due to farming mechanization (Valero-Garcés et al., 2006; Morellón et al., 2011; Navas et al., 2014; Barreiro-Lostres et al., 2017). Determinations of erosion rates by means of $^{137}$Cs (Gaspar et al., 2013; Navas et al., 2013; Lizaga et al., 2018a) in a variety of catchments also indicate that cultivation was the main factor controlling soil loss during the second half of the last century.

Land abandonment in many mountain regions led to important changes in land use and soil properties (Nadal-Romero et al., 2016; Navas et al., 2017a). Croplands abandoned after harvest leave soil unprotected, thus intensifying soil erosion. As a consequence, high sediment accumulation was recorded in Iberian reservoirs, particularly after 1960–80. Sedimentation in the Barasona (Valero-Garcés et al., 1999; Navas et al., 2004) and Yesa reservoirs (Navas et al., 2009) reached annual rates of up to 30 and 20 cm, respectively. This trend was reversed after the 1980’s, with the natural recovery of vegetation, which protected the soil surface and modified the connectivity index in the last decades (Lizaga et al., 2018b). Although there is a reduction in sediment delivery due to the lesser extent of cultivated lands, mountain agriculture continues to be one of the most important contributing sources of sediment (Gaspar et al., 2019; Lizaga et al., 2020). Lower sediment production and connectivity changes (Lizaga et al., 2018b), together

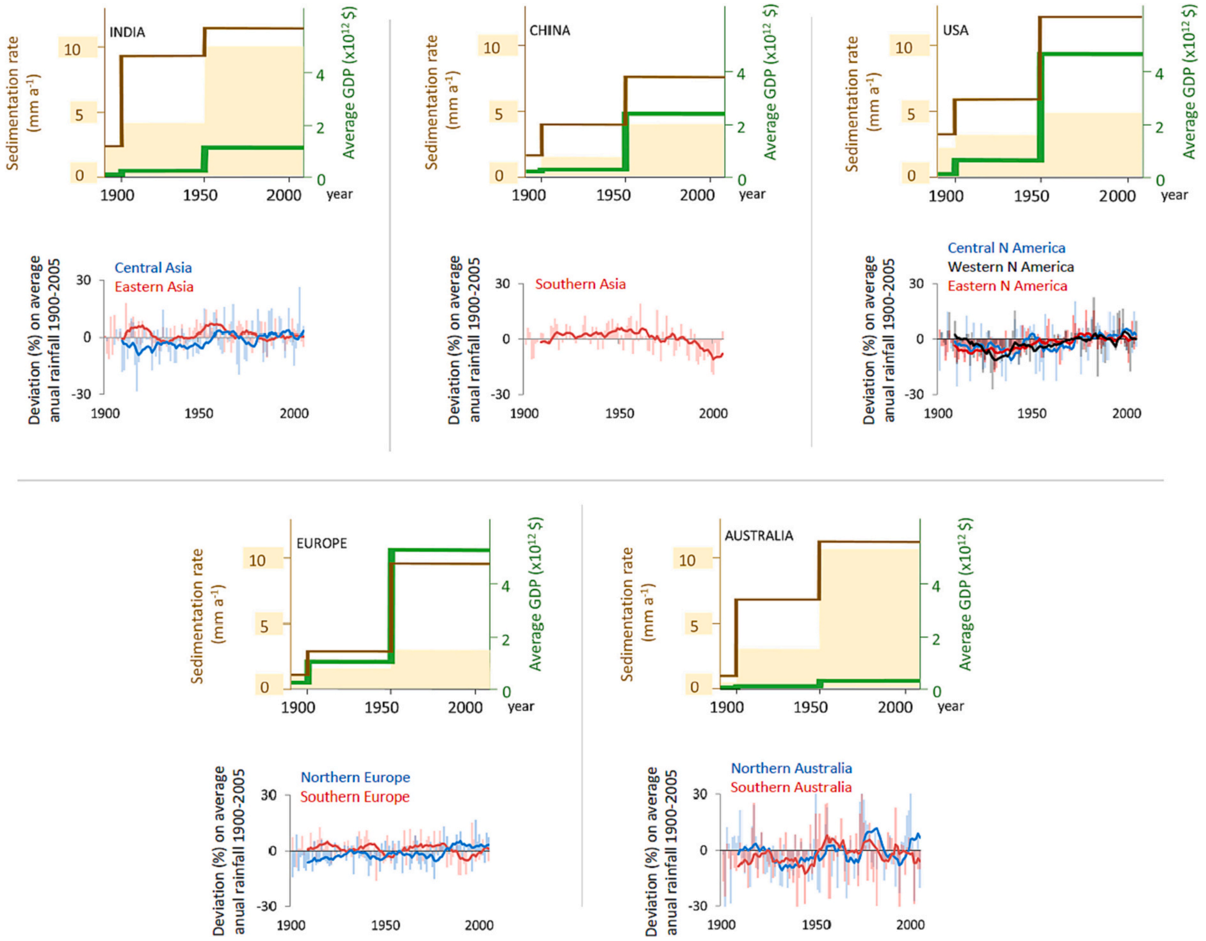

**Fig. 7.** Sedimentation rates and possible drivers. Sedimentation rates (averages; yellow: all points with data; brown: points with data for the three periods considered); GDP (Geary-Khamis dollars, 1990; Bolt and van Zanden, 2013); rainfall evolution (IPCC, 2014; thin lines, annual mean; thick lines, 10-year moving average) in the regions analysed. (Modified after Cendrero et al., 2020). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with dam construction, have reduced sediment supply towards the coasts.

## 5. Human activities, erosion and sediment fluxes

The relationship between human activities, such as those related to land clearance and agriculture, and sediment generation, has been well documented (Swanston and Swanson, 1976; Sidle et al., 2001; Wang et al., 2007; Jordan et al., 2010; Whitlock et al., 2015; Wang et al., 2011; Cienciala et al., 2020a; Syvitski et al., 2022). Factors affecting denudation, sediment generation, transport and deposition are many and varied, and it should not be expected that denudation rates increase in every basin or region. However, it seems that LULC changes play a very significant role in those processes (Walling et al., 1996; Walling and Fang, 2003; Lambin and Geist, 2006; Vanmaercke et al., 2015).

### 5.1. Human influence in antiquity

Human influence on erosion/sedimentation has been increasingly important since the 19th century, but there is also evidence of similar effects in the past. Evidence of increased erosion in the Iberian Peninsula, attributed to human activities during the Late Holocene, particularly after the 1st century CE, has been presented by Barreiro-Lostres et al. (2017). The impact of human activity in the landscape since the Neolithic (approximately 5500–3000 BP) has been described by Utrilla (2002), Remondo et al. (2005), Carrión et al. (2010), López-Merino et al. (2010) and Bernabeu et al. (2018). According to Gutiérrez and Peña (1992) and Peña et al. (2004) human action, in combination with the characteristics of the Mediterranean climate, caused erosion and infill of valleys in the central Ebro basin during the Neolithic, and later impacts during the Iberian-Roman period, between approximately 200 BCE and 400 CE, led to increased erosion in the central gypsiferous landscapes.

Changes in land use within the river catchment during the last 2500 years have been identified in the Ombrone River delta, Italy (Innocenti and Pranzini, 1993). Delta extension phases were related to deforestation and extensive agriculture performed during the Roman Empire and, later, to periods of mismanagement and overgrazing during the Middle Ages. The Little Ice Age climate changes seem to have had only a secondary influence. The influence of agriculture on the intensification of the sediment flux of the Yellow River (Huang He) after 740–960 CE has been documented (Chen et al., 2015).

Rapid deforestation in the Late-Middle Ages (10th to 15th centuries CE) to enlarge summer grasslands in response to a general expansion of livestock and transhumance in Spain, resulted in increasing erosion and sedimentation rates (García-Ruiz et al., 2020). LULC changes 700 years ago modified hydrological regimes and connectivity, and intensified soil erosion (González-Sampériz et al., 2019). Sediment sequences retrieved in Spanish lakes document episodes of topsoil erosion following burning likely linked to farming practices during the second half of the 13th century (Morellón et al., 2011). Likewise, human activity related to irrigation and agriculture developments was identified as a key factor affecting the sedimentary dynamics during Medieval times in the Iberian Peninsula, with examples in Lake Chiprana (NW Spain; Valero-Garcés et al., 2000) and Lake Zoñar (S Spain; Valero-Garcés et al., 2006). Deforestation since the 12th century was paralleled by the enlargement of the Ebro River delta, a process intensified during the 18th–19th centuries with the expansion of cultivated areas in response to population growth (Maldonado, 1972; González-Sampériz et al., 2019). Contemporaneous sediment accumulation and widening of littoral plains have also been recorded in southern Italy (Bruckner, 1986) and Greece (Bintliff, 1976).

### 5.2. LULC changes and sediment generation

Farming and forestry activities, and associated LULC changes, continue to be an important factor affecting sediment generation and fluxes. Agriculture, as expressed by the proportion of cultivated land in a region, has a very important influence on the catchment sediment budget. This is particularly the case for the large areas of arable lands in central North America and in Eastern Europe. Land cultivation in plain and lowland areas considerably increases surface runoff and, consequently, denudation and sediment fluxes. A result is that sheet, rill, ephemeral gully, and bank gully erosion rates may increase 2–3 orders of magnitude with respect to non-cultivated areas (Sidorchuk and Golosov, 2003; Sidorchuk et al., 2006). However, soil conservation measures can considerably reduce these effects and related soil loss (Trimble, 1974, 1983; Trimble and Lund, 1982).

The case of the southeastern East European Plain is illustrative of this point. Intensive cultivation in this part of Russia began in the early 18th century in the forest-steppe zone and early 19th century in the steppe zone. In the northern part of the forest-steppe zone, bank gully growth reached a maximum in the mid-19th century, when cultivated land was up to 70% of total area, including even short steep banks of small river valleys. Sediment yield reached $0.888 \times 10^6\ \mathrm{m}^3\ \mathrm{a}^{-1}$. Some arable lands were abandoned later and gully erosion was considerably reduced. Increasing sediment supply to small streams led to aggradation of river channels and considerable reduction of channel length due to siltation of river beds and transformation of river valleys into dry valleys without a permanent watercourse (Golosov and Panin, 2006). A major component of the sediment washed away from cultivated lands is redeposited in dry valley bottoms. In recent decades, the overall rate of erosion on the East European Plain has decreased due to both climate and land use change, the latter driven by changing policies (Golosov et al., 2018; Gusarov et al., 2018a, 2018b). The accumulation rates at the bottoms of dry valleys decreased by 1.4–5.4 times in the period 1986–2016 compared with 1963–1986, which is associated with a decrease in runoff and washout during the snowmelt period due to climate warming, as well as changes in crop rotations (Golosov et al., 2017, 2018). The contribution of climate changes to a greater extent affected the reduction of erosion rates in the south of the forest zone. Also in this zone, the abandonment of arable land led to a significant reduction of total soil loss. Accordingly, much less sediment was washed away from arable slopes to permanent watercourses. Therefore, no significant changes in the length of permanent streams were observed during the second half of the 20th century (Golosov and Panin, 2006), and rate of gully formation, as well as sediment generation decreased to, $0.3 \times 10^6\ \mathrm{m}^3\ \mathrm{a}^{-1}$, pre-18th century levels (Moryakova, 1988; Sidorchuk and Golosov, 2003).

In total, the volume of eroded material from arable lands with chernozems in the Russian part of the East-European Plain, during the period 1830–1940, was $25.34 \times 10^9\ \mathrm{m}^3$, equivalent to a 0.22 m thick layer ($2\ \mathrm{mm\ a}^{-1}$) for the whole study area (Golosov et al., 2021). Based on historical land use data, if we take the total soil loss from erosion for the period 1696–1980 as 100%, then in the periods 1696–1796, 1796–1887 and 1887–1980, this soil loss amounts to 20%, 37% and 43% of the total, respectively (Sidorchuk and Golosov, 2003). This case study illustrates the important contribution of erosion on cultivated lands (primarily in the large plains of the temperate zone) to global sediment budgets and landscape transformation.

Studies of mechanical denudation rates on slopes in the Polish Carpathians have shown significant changes in the last 50 years, reflecting the transition from a centrally planned to free-market economy in Poland since 1989 (Bucała-Hrabia, 2018; Kijowska-Strugała et al., 2018; Kijowska-Strugała, 2019). LULC changes were mainly related to the abandonment of cultivated lands and to the increase in afforestation and grassland areas, which were reflected in a sediment yield reduction of up to 60%. Similar changes in the supply of sediments from the catchment area to the riverbeds were observed in other areas of Poland, as a result of political and socio-economic changes in the 1980s and 1990s (Kostrzewski et al., 1997). Also, in other central and eastern European countries (Bičík et al., 2001; Munteanu et al., 2014), where cultivated land has been mostly replaced by grassland and then by forest: Czechia (Bičik et al., 2012), Slovakia (Bezak and Mitchley, 2014), Hungary

(Jordan et al., 2005), Slovenia (Andrič et al., 2010) and forest zone of European Russia (Levers et al., 2018; Gusarov, 2021).

Other assessments have shown that the agricultural transformation of natural landscapes significantly changed the intensity of erosion and suspended sediment yield in rivers. Erosion and sediment generation increased significantly in lowlands compared to mountain areas, due to extensive plowing and cultivation (Dedkov and Mozzherin, 1984). Human activities intensified erosion and radically changed its nature, increasing the ratio between basin (mainly soil-gully erosion) and riverbed erosion (Dedkov and Mozzherin, 1984; Gusarov, 2015). Moreover, the anthropogenic transformation of erosion and river sediment yield had well-defined zonal features. For example, in the river basins in the temperate zone of Eurasia and North America, sediment yield data show that the most significant intensification of erosion occurred in the river basins of the broadleaf forest landscape zone (Fig. 8), where there is still sufficient water runoff combined with a high degree of plowing of soils. This effect was especially clear in the East European Plain, in the Middle Volga region, at the junction of the zone of broadleaf forests, forest-steppe, and steppe, a region considered as an erosion “hot spot” of the plain in the 1960s–1980s (Mozzherin and Kurbanova, 2004). In recent decades, this part of European Russia has shown the highest rates of reduction in the intensity of erosion and river sediment yield, reflecting a combination of climate change (reduction of snowmelt runoff, more marked in the southern area) and LULC changes. The latter is mainly a decrease of cultivated land area, due to changing socioeconomic conditions, more important in the northern area of the region (Gusarov, 2020, 2021).

Grazing and connected vegetation cover changes have in modern time significantly increased mechanical denudation in Scandinavia, for instance in large areas of Iceland (Beylich, 1999, 2011). In boreal environments of central Norway, agriculture and forestry are increasing mechanical denudation on certain areas, whereas artificial stream channel steps and dams are reducing sediment connectivity and fluvial mechanical denudation rates at the drainage basin scale (Beylich and Laute, 2018, 2021).

The effects of land use and topographic changes on sediment connectivity in semi-natural Mediterranean catchments were analysed by Llena et al. (2019) and Peña-Angulo et al. (2019). They found that the majority of the mountain areas in the region experienced depopulation during the second half of the 20th century, with subsequent agricultural abandonment and vegetation cover increase, reflected in a reduction of sediment supply. In other regions of the Mediterranean, agriculture is a main driver of soil loss in a range of environments. In the Iberian Peninsula, estimates by fallout $^{137}$Cs revealed that the highest soil erosion rates occur in cultivated fields despite their location on low-gradient slopes, in contrast to steep slopes that maintain the natural vegetation. Records in a variety of environments in Spain, from semiarid (Quine et al., 1994), to subhumid (Gaspar et al., 2013; Navas et al., 2013; Lizaga et al., 2018a) and temperate (Navas et al., 2005) confirm that rates in cultivated areas can be up to 40 times higher than in naturally vegetated ones. Similar patterns were observed in agricultural areas of the Southern Mediterranean in the Rif Mountains of Morocco (Sadiki et al., 2007). A main indirect impact is the accelerated siltation of lakes and reservoirs connected to agricultural catchments, such as the 45 cm deposited in about 40 years in an endorheic lake in the southern Pyrenees (Navas et al., 2014). Even higher infilling rates leading to complete siltation occurred in small reservoirs in the Rif region of Morocco (Faleh et al., 2005).

### 5.3. Badlands

Erosion in badland areas is also very much affected by human activities. Moreno-de las Heras and Gallart (2018) suggested that badland development is controlled by four factors related to topography, lithology, climate and disturbance of vegetation or changes in environmental conditions. The authors highlighted that human action plays a significant role, and can ultimately lead to the initiation, stabilization or rejuvenation of badland areas. Torri et al. (2018), using multidisciplinary data, investigated the origin of badlands in southern Tuscany (Italy). LULC changes within the Ombrone River catchment (Innocenti and Pranzini, 1993) have been considered as the possible trigger of the present-day “biancane” badland areas, and related high denudation rates, in the catchment. The important role of human activity (LULC changes) on the recent landscape evolution of these areas is confirmed by the evolution of badlands observed during the last decades. For instance, in some areas of Italy, a reduction of badlands due to land levelling related to cropland abandonment and grazing changes has been observed (Aucelli et al., 2016; Amici et al., 2017), or to land use changes related to an increase in forest cover as a consequence of reduction of agricultural land (Coratza and Parenti, 2021). These processes are apparently not related to climate changes (Giaccone et al., 2015), but rather human-driven LULC changes.

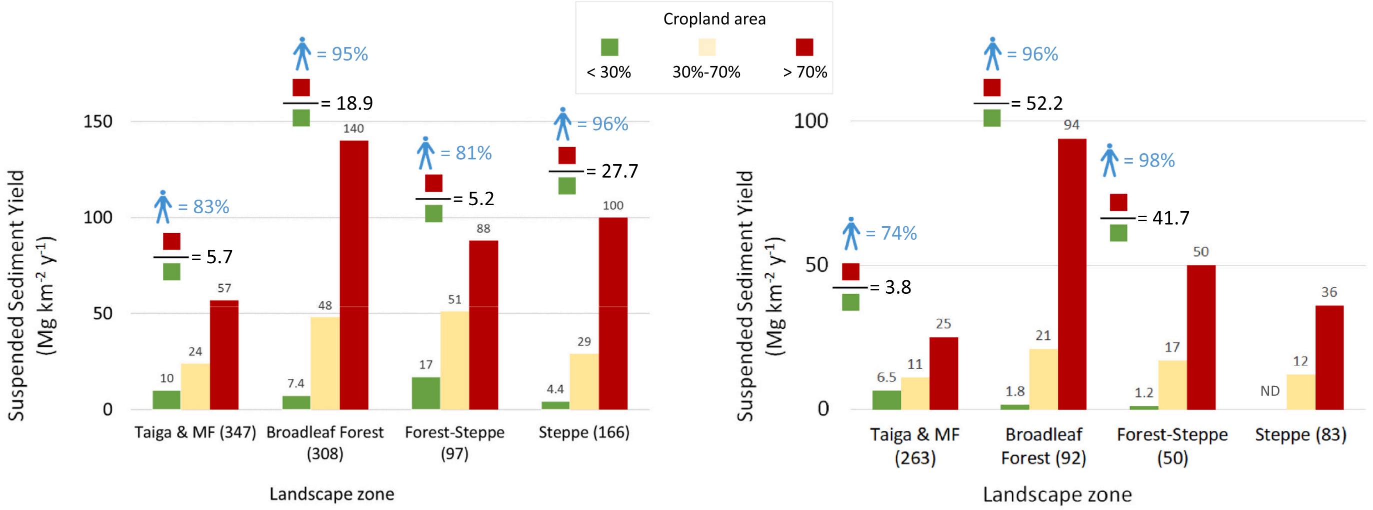

**Fig. 8.** Changes in suspended sediment yield (SSY) in river basins (left graph – small river basins, <5000 km$^2$; right graph – medium-sized and large river basins, >5000 km$^2$) of different landscape zones of the temperate zone of the Northern hemisphere (calculated based on data, mainly for the 1940s–1970s, from Dedkov and Mozzherin, 1984). The human figure is an anthropogenic component of SSY in river basins with >70% of cropland. Notes: 1) Total number of analysed river basins is between brackets; 2) MF, mixed forests; 3) ND, no data.

On the other hand, land levelling of badland areas in several parts of the world, as reported by Poesen (2018), has reduced erosion and soil loss. A recent trend towards reduction of hillslope denudation has been highlighted in different Mediterranean badlands, such as in the Central Pyrenees (Llena et al., 2019), Northern Apennines (Bosino et al., 2019; Coratza and Parenti, 2021) and in Central and Southern Italy (*e.g.* Piccarreta et al., 2006; Aucelli et al., 2016; Amici et al., 2017). These reductions of sediment supply at hillslope scale can be related to the observed channel adjustment trends of the last decades (Surian and Rinaldi, 2003; Scorpio and Piégay, 2021) and, together with human interventions along the rivers and human-driven LULC modifications at the catchment scale, implying vegetation cover increase, seem to have strongly contributed to sediment supply reduction.

### 5.4. *Sediment fluxes*

Data on sediment fluxes from major Chinese rivers (Table 1) show, with very few exceptions, a marked reduction in suspended sediment loads transported by fluvial streams (Chen et al., 2015). And also with very few exceptions, that human activities contribute much more than climate change to the reduced fluvial sediment loads. Sediment fluxes in the Yellow River basin are displayed in Fig. 9. It was detected that sediment fluxes increased by approximately one order of magnitude during the last millennium, reflecting an increase in denudation. This has been explained by large-scale farming in the China's Loess Plateau, and not by climate change (Chen et al., 2015). Then, in just over half a century, a sharp reduction took place, again also of approximately one order of magnitude and attributed to multiple human activities (*e.g.* terracing, dam construction, and vegetation restoration), not to climate change. Recent studies in the Yellow River show that terracing and dam construction played a much more important role in reducing the sediment fluxes than vegetation restoration and climate change (Wang et al., 2015; Zhang et al., 2016; Shi et al., 2017). Thus, human activities appear to be a more significant factor than climate change for explaining the denudation changes observed in this region, in particular the intensification of changes after the end of World War II. On the other hand, in areas with extreme climate and relatively low population density, such as the Jinsha River Basin, in the uppermost reaches of the Yangtze River Basin, climate variations (increasing precipitation and snow and glacier melt) dominate runoff changes, whereas human activities, in particular cascade damming, are the governing factor for sediment load changes (Li et al., 2018a).

Although human influence appears to result, in most cases, in higher mechanical denudation rates, in other cases, such as areas with agricultural terraces and dams in water courses, reductions of denudation and sediment generation and transfer have been established. This is, for

**Table 1**
A summary of the relative contributions of climate change and human activities to the variation in sediment fluxes (QS) in major Chinese Rivers (Miao et al., 2011; Wu et al., 2012; Lu et al., 2013; Liu et al., 2014; Zhao et al., 2017; Li et al., 2018a; Li et al., 2018b).

| *River basin* (gauging stations) | Period | Changes in $Q_S$ (Mt) | Changes in $Q_S$ (%) | Contributions | | Methods | References |
|---|---|---|---|---|---|---|---|
| | | | | Climate change | Human activities | | |
| *Songhua River* | | | | | | | |
| Jiamusi | 1991–2007 *vs.* 1955–1990 | 3.32 | 29.4% | −41.7% | 141.7% | Double mass curve | Lu et al. (2013) |
| Jiamusi | 2000–2016 *vs.* 1954–1968 | −3 | −20.8% | 3.0% | 97.0% | Sediment identity approach | Li et al. (2018b) |
| *Liao River* | | | | | | | |
| Tieling | 1991–2007 *vs.* 1953–1990 | −7.87 | −55.3% | 61.0% | 39.0% | Double mass curve | Lu et al. (2013) |
| Tieling | 2000–2016 *vs.* 1954–1968 | −30.99 | −96.2% | 6.0% | 94.0% | Sediment identity approach | Li et al. (2018b) |
| *Hai River* | | | | | | | |
| Haihezha | 1991–2007 *vs.* 1963–1990 | −0.21 | −100% | 4.0% | 96.0% | Double mass curve | Lu et al. (2013) |
| Haihezha | 2000–2016 *vs.* 1954–1968 | −0.62 | −100% | 4.0% | 96.0% | Sediment identity approach | Li et al. (2018a) |
| *Huai River* | | | | | | | |
| Bengbu | 1991–2007 *vs.* 1952–1990 | −5.71 | −55.5% | −5.0% | 105.0% | Double mass curve | Lu et al. (2013) |
| Bengbu+Linyi | 2000–2016 *vs.* 1954–1968 | −8.4 | −67.7% | 6.0% | 94.0% | Sediment identity approach | Li et al. (2018b) |
| *Min River* | | | | | | | |
| Zhuqi | 1991–2007 *vs.* 1950–1990 | −4.07 | −56.3% | −10.4% | 110.4% | Double mass curve | Lu et al. (2013) |
| Zhuqi | 2000–2016 *vs.* 1954–1968 | −4.7 | −65.3% | −7.0% | 107.0% | Sediment identity approach | Li et al. (2018b) |
| *Qiantang River* | | | | | | | |
| Lanxi | 2000–2016 *vs.* 1977–1985 | 0.3 | 14.3% | 25.0% | 75.0% | Sediment identity approach | Li et al. (2018b) |
| *Yellow River (Huang He)* | | | | | | | |
| Lijin | 1970–1979 *vs.* 1950–1959 | −323 | −26.5% | 126.0% | −26.0% | Simple linear regression | Miao et al. (2011) |
| Lijin | 1980–1989 *vs.* 1950–1959 | −582 | −47.7% | 68.0% | 32.0% | Simple linear regression | Miao et al. (2011) |
| Lijin | 1990–1999 *vs.* 1950–1959 | −831 | −68.1% | 70.0% | 30.0% | Simple linear regression | Miao et al. (2011) |
| Lijin | 2000–2008 *vs.* 1950–1959 | −1078 | −88.3% | 46.0% | 54.0% | Simple linear regression | Miao et al. (2011) |
| Lijin | 1991–2007 *vs.* 1957–1990 | −698.62 | −71.7% | 370.0% | −270.0% | Double mass curve | Lu et al. (2013) |
| *Yangtze River* | | | | | | | |
| Panzhihua | 1985–2010 *vs.* 1966–1984 | 19.8 | 50.4% | 18.0% | 82.0% | Double mass curve | Li et al. (2018a) |
| Panzhihua | 2011–2015 *vs.* 1966–1984 | −29.8 | −75.8% | −7.5% | 107.5% | Double mass curve | Li et al. (2018a) |
| Baihetan (Huatan) | 1999–2010 *vs.* 1952–1998 | −32.1 | −18.0% | 13.4% | 86.6% | Double mass curve | Li et al. (2018a) |
| Baihetan (Huatan) | 2011–2015 *vs.* 1952–1998 | −104.3 | −58.5% | 8.7% | 91.3% | Double mass curve | Li et al. (2018a) |
| Pingshan (Xiangjiaba) | 1999–2010 *vs.* 1954–1998 | −82.8 | −32.3% | 10.8% | 89.2% | Double mass curve | Li et al. (2018a) |
| Pingshan (Xiangjiaba) | 2011–2015 *vs.* 1954–1998 | −214.6 | −83.8% | −2.3% | 102.3% | Double mass curve | Li et al. (2018a) |
| Datong | 1986–2013 *vs.* 1953–1985 | −202 | −44.4% | 13.0% | 87.0% | Double mass curve | Zhao et al. (2017) |
| Datong | 1970–1979 *vs.* 1953–1969 | −73.1 | −14.7% | 29.0% | 71.0% | Double mass curve | Liu et al. (2014) |
| Datong | 1980–1989 *vs.* 1953–1969 | −62.4 | −12.6% | 25.0% | 75.0% | Double mass curve | Liu et al. (2014) |
| Datong | 1990–1999 *vs.* 1953–1969 | −154.8 | −31.2% | 8.0% | 92.0% | Double mass curve | Liu et al. (2014) |
| Datong | 2000–2010 *vs.* 1953–1969 | −320.1 | −64.4% | 10.0% | 90.0% | Double mass curve | Lu et al. (2013) |
| *Pearl River* | | | | | | | |
| Gaoyao+ Shijiao+Boluo | 1970–1979 *vs.* 1957–1969 | 8.7 | 11.4% | 27.6% | 72.4% | Simple linear regression | Liu et al. (2014) |
| Gaoyao+ Shijiao+Boluo | 1980–1989 *vs.* 1957–1969 | 12.3 | 16.1% | −39.0% | 139.0% | Simple linear regression | Liu et al. (2014) |
| Gaoyao+ Shijiao+Boluo | 2000–2011 *vs.* 1957–1969 | −38.5 | −50.5% | 12.7% | 87.3% | Simple linear regression | Liu et al. (2014) |
| Gaoyao+ Shijiao+Boluo | 1970–2011 *vs.* 1957–1969 | −4.2 | −5.5% | 0.0% | 100.0% | Simple linear regression | Liu et al. (2014) |
| Gaoyao+ Shijiao+Boluo | 2006–2009 *vs.* 1957–2005 | | | 14.0% | 86.0% | Simple linear regression | Wu et al. (2012) |
| Gaoyao+ Shijiao+Boluo | 1991–2007 *vs.* 1957–1990 | −20.68 | −26.1% | −10.6% | 110.6% | Double madd curve | Lu et al. (2013) |

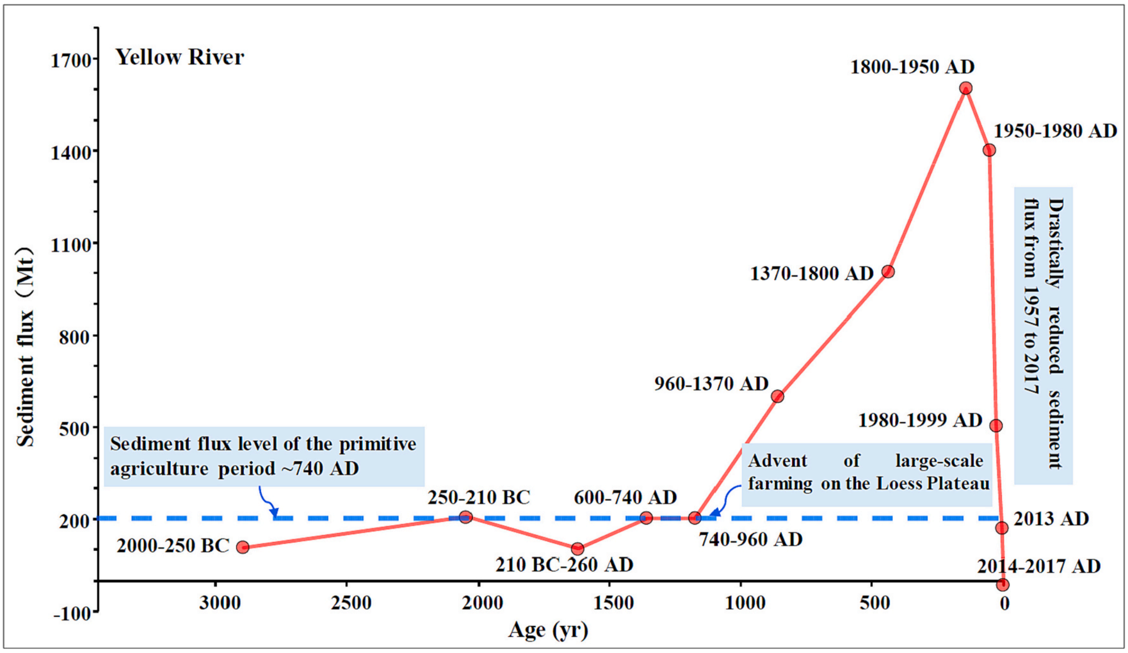

**Fig. 9.** The Yellow River (Huang He) used to transport the highest annual sediment flux (~1.6 Gt/yr over 1800–1950) among the world's big rivers, but its sediment flux decreased sharply in recent decades due to terracing and dams. (Updated from Chen et al., 2015). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

instance, the case of agricultural terraces in Europe (Brown et al., 2021), even dating back to the Bronze Age (Asins, 2006) in the Mediterranean, and continuing until the 19th century (Kinnaird et al., 2017) in coincidence with the greatest population growth, or in Ethiopia, where Mukai et al. (2021) showed how soil erosion, accelerated by anthropogenic LULC changes, has been partly offset by the implementation of soil and water conservation (SWC) measures.

In the basin of the Vyatka River, one of the largest rivers in the boreal forest zone of the East European Plain (Russia), the river's suspended sediment load has decreased by almost 40% over the past 60 years due to a nearly 47% reduction in the area of cultivated land in its basin (Gusarov et al., 2021). Based on field, hydrological and modelled data, it was concluded that a reduction in surface runoff during the snowmelt period, an increase in the proportion of arable land under perennial grasses, and a decrease in the area of cultivated land, are key factors in reducing soil loss in river basins within the forest, forest steppe and steppe zones of the East European Plain (Mal'tsev et al., 2019; Gusarov, 2019).

Assuming average erosion rates of 0.7 t $km^{-2}$ $a^{-1}$ (Gerlach, 1976) for soil erosion in Carpathian forests and 1.48 t $km^{-2}$ $a^{-1}$ in cultivated lands (cereals, potatoes) and grasslands (Gil, 2009), mechanical denudation in the Polish Carpathians has likely decreased by about 10% since the 1980s. On the other hand, river channelization in the second half of the 20th century, involving the reduction of channel width-to-depth ratio, long-term gravel mining from channels that only stopped in the 1970s, and LULC changes, contributed to intensive channel incision by 1 cm $a^{-1}$ in the period 1969–2017 (Wyżga, 2008; Bucała-Hrabia, 2018). Within the Bystrzanka catchment (13 $km^2$) in the Polish Carpathians, cultivated land has decreased in area since the 1970s and grassland has increased, and this has resulted in a decrease in soil erosion from 830 t $km^{-2}$ $a^{-1}$ (1970s) to 220 t $km^{-2}$ $a^{-1}$ (2010s) (Kijowska-Strugała, 2019).

Associated decreases in suspended sediment yield reflect changes in sediment sources, associated with intensification of landslides and new forms of human activity, including construction works near or in river channels. In forested catchments of the Carpathians, up to 95% of channel sediments come from unpaved roads and wood transport rills (Froehlich, 1982), whereas in a small, half-agricultural half-forested catchment, unpaved roads deliver about 70% of suspended sediment load (Froehlich, 1986). Other studies also highlight the significance of local conditions such as road density or practices (direction of plowing, layout and size of field plots and field terraces) for sediment generation (Gil, 2009). For example, Gerlach (1966) showed that slope terraces retain 35% of eroded sediment.

Other examples of sediment load reduction in rivers, due to human activities, have been described by different authors (Graf, 2006; Dang et al., 2010; Gupta et al., 2012; Wu et al., 2018; Yang et al., 2015; Zhou et al., 2016; Latrubesse et al., 2017; Golosov and Walling, 2019; Gusarov, 2019, 2020, 2021).

Modification of river courses, particularly by construction of dams, reduce connectivity between erosion areas in basins and channels (Nilsson et al., 2005; Magilligan et al., 2013; Petts and Gurnell, 2013; Liu et al., 2017; Beylich and Laute, 2021) and, consequently, solid load transported by rivers to the oceans may diminish (Vörösmarty et al., 2003; Syvitski et al., 2005a; Walling, 2006; Syvitski and Kettner, 2011; Walling, 2012; Scorpio and Piégay, 2021). For instance, Vörösmarty et al. (2003) found that 53% of sediment load in regulated rivers in different parts of the world was trapped in dams, and Yang et al. (2015) concluded that the reduction of sediment load observed in the Yangtze River in the periods 1950–1968 and 2003–2012 was due to reservoirs (approx. 88%), other human activities (approx. 7%), and rainfall reduction (approx. 5%). Other studies highlighted that sediment supply reduction and decrease of sediment connectivity in mountain areas are related to LULC changes, such as natural revegetation after cropland abandonment and afforestation practices (Calsamiglia et al., 2018; Llena et al., 2019, 2020). Reductions of sediment supply commonly result in delta retreat (Syvitski, 2007; Syvitski et al., 2009; Syvitski and Kettner, 2011; Besset et al., 2017, 2019).

Thus, although reductions in the amount of sediment transported by rivers have been observed in many cases, there is evidence of growing denudation and sediment generation. As shown by Syvitski et al. (2022), if it were not for sediment sequestration by dams, particulate loads in the world's rivers would have increased by 212% between 1950 and 2010. That is, erosion and sediment fluxes are nowadays overwhelmingly dominated by human influence. The varied evidence provided here also indicates that land surface transformation by human activities can be considered as the main driver behind denudation changes in most terrestrial areas of the Earth. However, the role of climate change on denudation and sediment generation is obvious and should not be dismissed. For example, in cold climate environments, contemporary climate change is a major driver of increased denudation, *e.g.* through glacier retreat and permafrost degradation (Zwoliński, 2007; Costa et al., 2018; Li et al., 2020; Morino et al., 2021).

### 5.5. *Influence of climate change*

In a range of regions with limited human presence, the contribution of climate change to denudation seems to be more significant than that due to the effects of human activities. This is the case, for instance, of changes in fluvial channels (Kociuba et al., 2019) and the high sediment supply from recently deglaciated surfaces to the ocean in circumpolar regions (Kostrzewski et al., 1989; Szpikowski et al., 2014a, 2014b; Navas et al., 2020). Also, on the Tibetan Plateau (Li et al., 2021), or in glacier-connected valleys of the fjord landscape of western Norway, the increases of mechanical denudation caused by anthropogenic activities are less important than the increases caused by climate change (Beylich and Laute, 2015, 2021; Beylich et al., 2017; Storms et al., 2020). In glacierized areas of the Caucasus Mountains, exceptional weather events seem to be the main sediment-generation factor (Tsyplenkov et al., 2021). In the arctic-oceanic mountain region of northern Swedish Lapland, human impact through reindeer husbandry and tourism-related activities was detected. On the other hand, in some relatively remote areas, which in recent decades have not experienced significant anthropogenic pressures, legacies of historical land use may continue to strongly condition the geomorphic processes (Cienciala et al., 2020a, 2022).

Land transformation by human activities can significantly enhance the effects of climate change. Areas modified by human activities are particularly sensitive to the growing frequency of extreme events during the ongoing climate change. An increase of mechanical denudation has been detected in some of such areas in Scandinavia (Beylich, 1999, 2011; Szpikowski et al., 2014a, 2014b; Beylich and Laute, 2018). While human impact can increase mechanical denudation significantly at particular locations, in many cases the overall impact is found to be small as compared to the increases of denudation caused by climate change (Beylich et al., 2005; Beylich, 2011). This was also reported from Antarctica, where glacier retreat is exposing new surfaces to physical and chemical denudation (Zwoliński, 2007; Navas et al., 2017b; Oliva et al., 2019).

The analyses described indicate that, whereas climate change has an obvious influence on denudation and in most cases enhances it, the signal of sediment fluxes and accumulation illustrates that LULC changes, at continental to global scales, have a much higher influence on the sediment variations observed during the last century.

## 6. Human geomorphic pressure and geomorphic change

An important caveat with the studies discussed herein is that their data are of different types, scales and resolutions, and from different sources or study sites with widely different natural and human conditions. Thus, local-scale variability of denudation processes and rates are increasingly controlled worldwide, and particularly after the mid-20th century, by human activities affecting the land surface. Despite a dominant pattern of increasing denudation -mediated in certain locations by climate change- there are cases where human activities (revegetation, agricultural terraces, dams, *etc.*) have decreased denudation or sediment transport, such as in the Yellow River (Chen et al., 2015); Iberian Peninsula (Lizaga et al., 2018a, 2020); Polish Carpathians (Bucała-Hrabia, 2018; Kijowska-Strugała, 2019); boreal Norway (Beylich and Laute, 2018, 2021); and areas with agricultural terraces (Brown et al., 2021). Of course, climate change also has an influence and its role should be considered (Knight and Harrison, 2011, 2012). This is particularly important in polar regions (Zwoliński, 2007; Navas et al., 2018; Oliva et al., 2019), or other thinly-populated areas with extreme climate conditions (Beylich, 2011; Beylich and Laute, 2018; Costa et al., 2018; Lizaga et al., 2019; Li et al., 2020; Tsyplenkov et al., 2021). But such activities or influence do not seem to result in a dominant imprint globally (Cendrero et al., 2020; Syvitski et al., 2022).

This human-driven “geomorphic dimension of global change” (Cendrero and Douglas, 1996; Rivas et al., 2006) is thus considered more significant than climate change for the functioning (often acceleration) of some geomorphic processes. Socioeconomic indicators may provide a useful way of assessing the influence of human activity, which can be applied consistently over spatial scales. Fig. 10, shows four different parameters: Gross Domestic Product density (GDP, as $ km$^{-2}$ a$^{-1}$; Gallup et al., 1999), illumination intensity at night (NASA), global human modification (Kennedy et al., 2019; Riggio et al., 2020), and terrain subsidence due to ground water withdrawal (Herrera-García et al., 2021). Total (not *per capita*) GDP (Fig. 10 A) of any one territory is the result of population, technology and economy (Cendrero et al., 2006; Kolbert, 2011). It is an expression of our capacity to carry out all sorts of activities, and affect the environment. Thus, GDP density (expressed as $ or € km$^{-1}$ a$^{-1}$) could be considered to express our potential to produce changes, including the modification of land surface. The intensity of the changes would thus depend on the number of people as well as their *per capita* capacity. That is probably why the maps show similar effects in low population density but high income areas and areas with high population density and low income. The second map (Fig. 10 B) shows a physical effect, whose relationship with the former is well known, and has been used in economics as a proxy for economic activity and growth data (Chen and Nordhaus, 2011; Henderson et al., 2012). The third one (Fig. 10 C) is “*a cumulative measure of human modification of terrestrial lands based on modelling the physical extents of 13 anthropogenic stressors and their estimated impacts*” (Kennedy et al., 2019), and is also very similar to the other two. Terrain subsidence (Fig. 10 D) due to ground water withdrawal (a geomorphic manifestation of our potential to affect the environment) is also quite similar to the other three, even though subsidence depends to a great extent on terrain characteristics. The conceptual model in Fig. 11 represents the possible relationship between human drivers and their effects on geomorphic processes through what may be termed “human geomorphic pressure” (HGP) or, more generally, “human environmental pressure” (HEP).

Data and results presented by Cendrero et al. (2020), suggest that global geomorphic change not only implies greater denudation, but also a growing frequency of disasters related to water/land surface interaction (“geomorphic disasters”). This is reinforced by the graphs in Fig. 4, showing the ratio geomorphic disasters frequency/climate disasters frequency. The former has increased much more than the latter, about twofold since mid-20th century, at both global and continental level. Different factors which can affect the number of disasters registered, such as better event reporting, greater human occupation (exposure) or vulnerability, or greater frequency of extreme climate events, are obviously the same for both groups of disasters, because they refer to the same geographical areas and time frame. Land surface transformation by human activities affects geomorphic processes, but not purely climate events such as cold or heat waves, windstorms, *etc.* The increasing frequency and/or severity of hazardous geomorphic events is therefore attributable to geomorphologic change.

Fig. 12 shows the great similarity between the evolution of global population, GDP and HGF (expressed as tonnage of Earth materials displaced; Cooper et al., 2018) since 1900. As shown by the slope of the curves, GDP grows much faster than population, and geomorphic impact (expressed as mass/volume HGF) grows even more. Growth factors for 1950–2015 are, respectively, 2.9–8.8-31.6. HGF reflects not only population growth, but also greater technological and economic capabilities over time (Cendrero et al., 2006; Kolbert, 2011). These capabilities result in a steep growth of *per capita* HGF, which has experienced a tenfold increase in just over half a century, and is shown by a much faster growth of HGF/population ratio compared to GDP/population

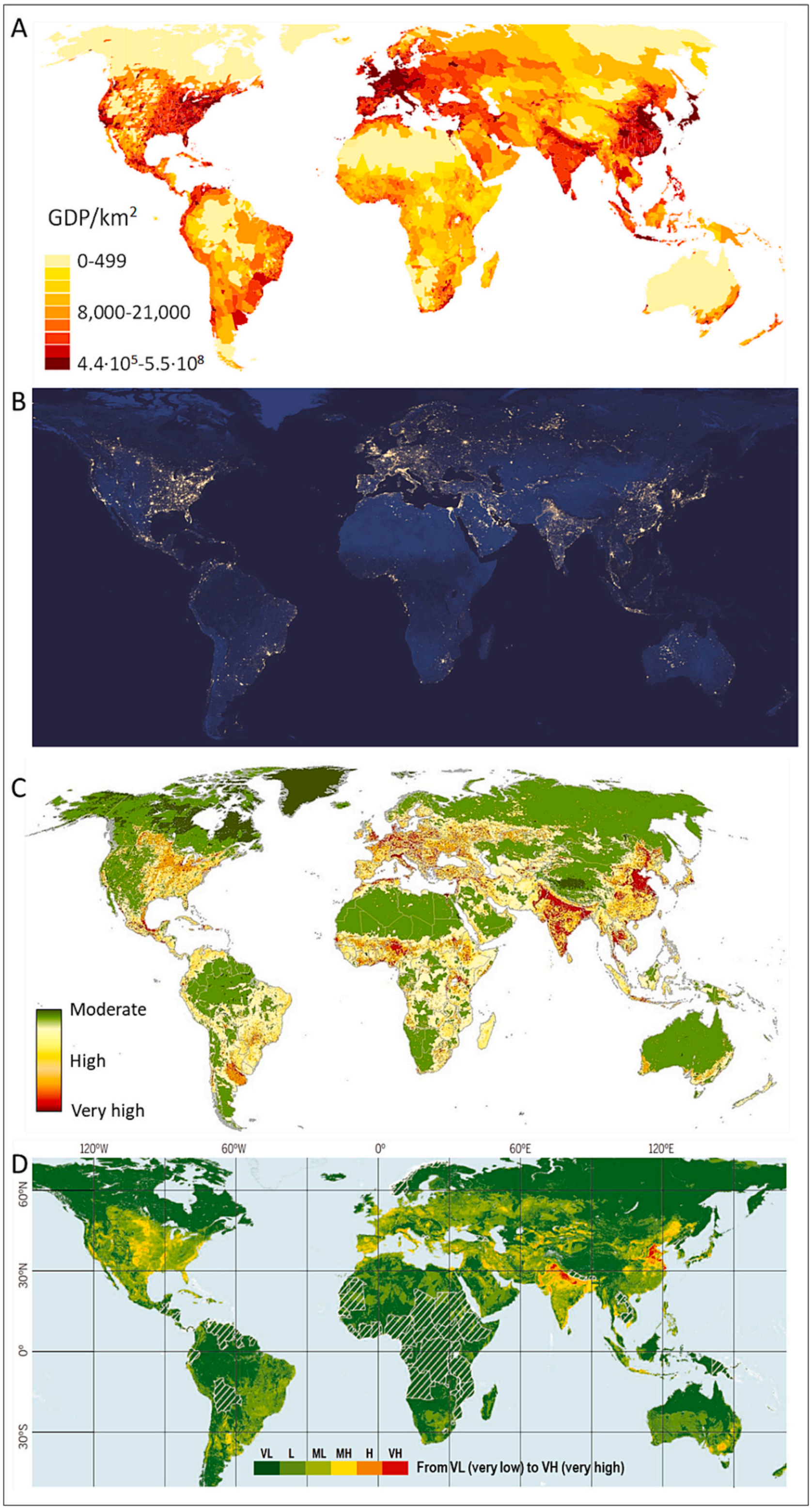

**Fig. 10.** Maps of: A, GDP density (Gallup et al., 1999); B, illumination at night (NASA, 2021); C, global human modification (Kennedy et al., 2019); D, potential subsidence due to groundwater withdrawal; white hatched polygons indicate territories where groundwater data are unavailable, and potential subsidence only includes information on susceptibility (Herrera-García et al., 2021).

ratio. This is reflected in the growth of technological denudation (HGF), sedimentation rates and frequency of geomorphic disasters.

Results obtained by Cendrero et al. (2020) show that the frequency of disasters related to geomorphic processes increased by a factor of 35.16 between the periods 1900–1950 (pre-Anthropocene) and 1950–2000 (Anthropocene). According to data presented by the same authors, average sedimentation rates (unweighted averages for all types of sedimentation environments and geographical areas) after 1950 ("Anthropocene") grew by a factor of 3.4–32.3 with respect to those prior to 1900 (pre-"Anthropocene").

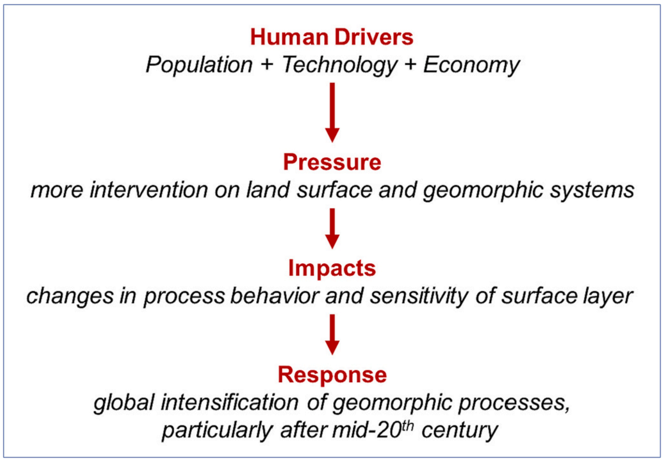

**Fig. 11.** Possible chain of increasing effects linking socio-economic drivers and response of geomorphic systems (after Cendrero et al., 2006).

As indicated in section 3, a reduction of geomorphic disasters frequency has been detected in recent years, suggesting that better land management and disaster mitigation practices are being implemented and, whether intentionally or unintentionally, they are producing a decoupling between growing "human geomorphic pressure", resulting from GDP growth, and geomorphic change. Perhaps too because economic growth is nowadays linked to a greater extent to activities such as information and telecommunication technologies and services, with very limited impact on land. The small decrease of total materials excavated (Fig. 12, technological denudation, HGF) in the last few years, a result of the economic crisis, which obviously implies a lower degree of land transformation, might be an expression of this.

## 7. Geomorphic change and the Anthropocene

Climate change has a significant influence on landscape dynamics in general and denudation/sedimentation processes in particular (Slaymaker et al., 2009; Beylich et al., 2016; Owens, 2020). However, on the basis of the evidence presented, we conclude that, at continental to global scales, sediment dynamics, S2S (source to sink) systems, patterns and rates of denudation/sedimentation and associated aspects of landform change and geomorphic hazards may be driven more by land transformation than by climate change.

Changes in denudation rates and sediment yields appear to be controlled mainly by anthropogenic land surface modification, including excavation, transport and deposition of geological materials. This direct "technological denudation" seems to be at least one order of magnitude greater than denudation by natural agents alone (Rivas et al., 2006; Cooper et al., 2018; Syvitski et al., 2022). Moreover, indirect effects of human activities on denudation appear to be at least of a similar magnitude as natural factors (Remondo et al., 2005; Syvitski et al., 2005a, 2022; Cendrero et al., 2006, 2020). This means the net result of direct and indirect effects of human activities on denudation are likely to be one to two orders of magnitude greater than purely natural denudation. This represents an enormous quantitative change over less than one century: something extraordinary in Earth's history. Other manifestations of geomorphic processes, such as hazards related to floods and slope movements (Cendrero et al., 2020) and ground subsidence (Herrera-García et al., 2021) or the well-known case of coastal processes, also show the important role of anthropogenic actions.

As pointed out by Bruschi et al. (2011a, 2011b), the end of World War II could mark the initiation of this new geological epoch. This (or, more broadly, the mid-twentieth century) would therefore represent an important date for both human and Earth history, The date indicated has been proposed by several authors as the starting point for of the Anthropocene (Bruschi et al., 2011a, 2011b; Steffen et al., 2015, 2016; Zalasiewicz et al., 2015, 2021; Waters et al., 2016; Cooper et al., 2018), and coincides with the "Great Acceleration" (Steffen et al., 2011, 2015), which appears to include a "great geomorphic acceleration" (Cendrero et al., 2020). Of course, the incorporation of a new epoch into the chronostratigraphic scale would require the definition of a suitable stratigraphic marker. Referring to the question raised by Steffen et al. (2015) "*…whether present state of the Earth System is clearly different from the Holocene*", in the case of denudation and geomorphic processes, the data presented indicate that the answer should be affirmative. Fig. 13 represents some significant changes (from a geomorphic point of view) between pre-Anthropocene and Anthropocene.

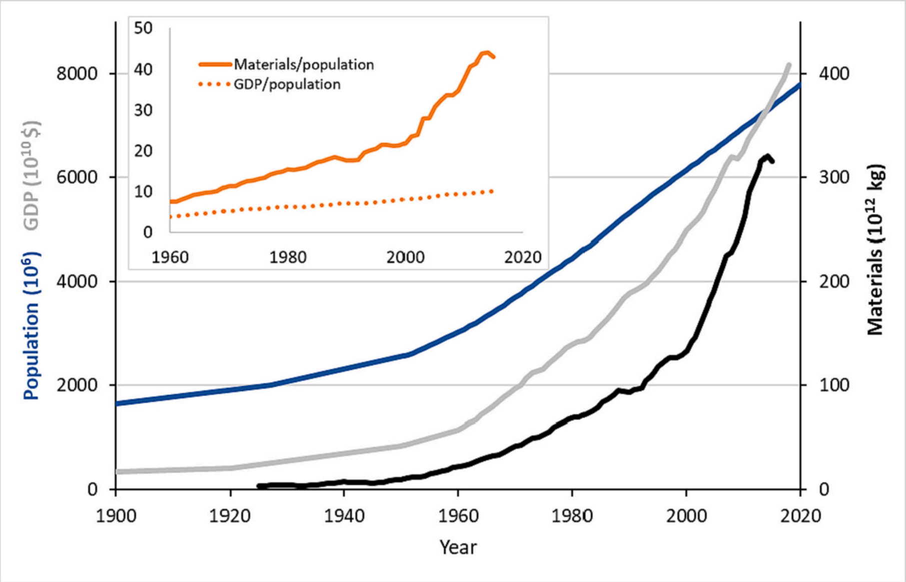

**Fig. 12.** Comparison between global population (World Bank, 2021a), GDP (current US$, World Bank, 2021b) and amount of geological materials excavated (technological denudation) by human activities (Cooper et al., 2018). Inset, ratios GDP/population and materials (technological denudation, HGF)/population. Note the much greater growth rate of the latter.

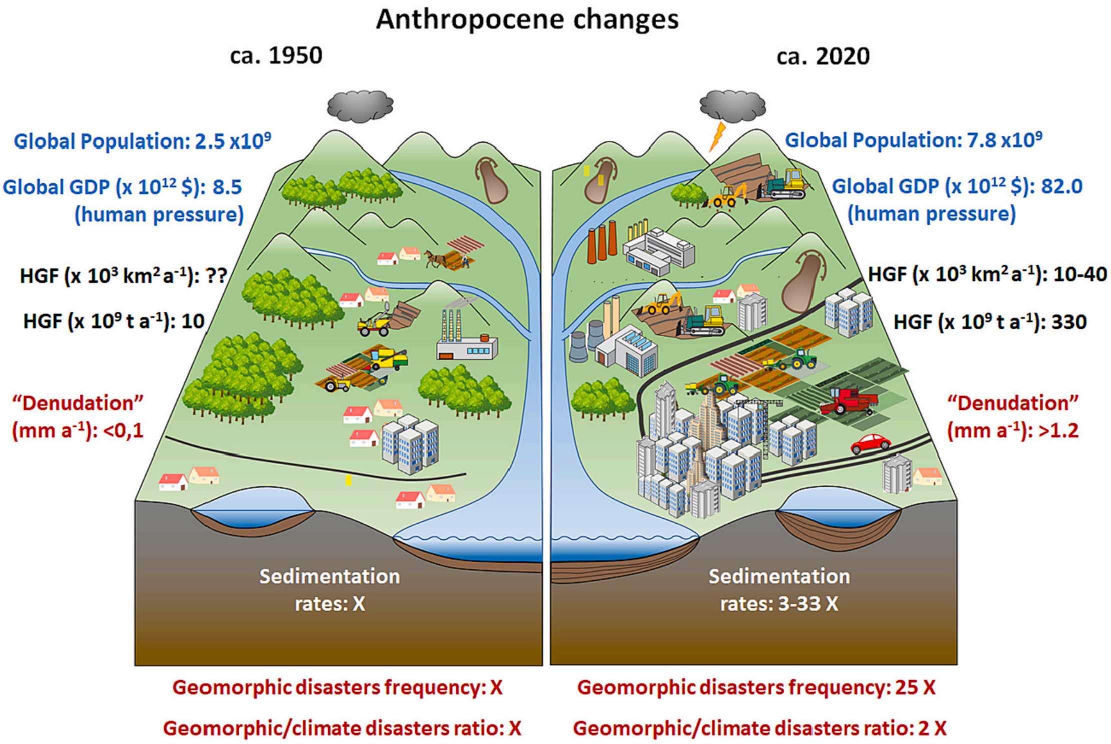

**Fig. 13.** Schematic representation of changes between the period just before the Anthropocene (pre-1950; left) and the present situation (around 2020; right).

## 8. Perspectives

The results presented indicate that a considerable modification of geomorphic processes is a substantial part of the Anthropocene, and this has some implications worthy of consideration.

The much faster growth of HGF/population ratio compared to GDP/population ratio, mentioned above (Fig. 12), makes it reasonable to assume that increasing GDP density will lead to an even greater growth of the human geomorphic footprint, expressed in terms of increasing technological denudation (Brown, 1956; Cooper et al., 2018) and urbanisation (Liu et al., 2021). This, in turn, may be reflected in an increase of indirect effects on geomorphic systems responses, affecting other denudation processes, chemical weathering or geomorphic hazards. To what extent this will actually take place needs to be determined by future work.

The coupling between human activity, global warming and climate change is well established (IPCC, 2014, 2021) and international efforts are under way to produce a decoupling (Kyoto and Paris Agreements). There seems to be a similar coupling between HGP and global geomorphic change, and some data suggest a decoupling is taking place, to some extent. Several lines of evidence point in this direction: reduction of landslide frequency in the last 10–20 years mentioned by Rivas et al. (2022), clearly not attributable to rainfall decrease; lower frequency of slope failures observed in the Pacific NW (Beschta and Jackson, 2008; Cristan et al., 2016; McEachran et al., 2021); global reduction of disasters related to geomorphic processes in general, during the last decade (Cendrero et al., 2020). They are all scarcely explainable by rainfall change, and suggest that impacts on land are being reduced, or mitigation measures implemented. As indicated above, exposure and vulnerability are essential factors contributing to disaster occurrence, and they clearly depend on human actions (or lack of them). This has been explained, in a wider context, by the Environmental Kuznets Curve (EKC; Dinda, 2004; Bojo et al., 2013; Shabhz et al., 2013). Research is needed to establish past trends in other regions and to follow up future evolution, and to analyse relationships with human activities, as well as rainfall patterns (particularly frequency/intensity of rainstorm events).

Taking as a basis the results presented in former sections, we can attempt some extrapolations. Obviously, there are important uncertainties concerning both population and GDP growth and, even more so, their effects on HGF. Therefore, the values presented here should be considered as rough estimates.

If future trends were similar to the ones observed since mid-twentieth century (Fig. 12), by 2050 world population, global GDP and technological denudation (mass/volume HGF) could be in the order of 10,300 × $10^{6}$ people, 15,400 × $10^{10}$ \$ and 895 × $10^{9}$ tons, respectively. The values in 2100 would be 14,500 × $10^{6}$ people, 25,000 × $10^{10}$ \$ and 1800 × $10^{9}$ tons. Population extrapolations by the UN (https://www.un.org⟩ population) yield lower figures, about 9,750 × $10^{6}$ and 10,900 × $10^{6}$ people by 2050 and 2100, respectively. The latter values, although subject to great uncertainties (Adam, 2021), are probably more realistic, considering the different factors affecting population growth. The magnitude of technological denudation would therefore be lower.

In the case of area yearly occupied by new "anthropolandforms", on the basis of *per capita* values from Rivas et al. (2006) and UN population predictions (https://www.un.org⟩ population), for 2050 we obtain an HGF of 10.7 $m^{2}$ $person^{-1}$ $a^{-1}$, equivalent to about 104,000 $km^{2}$ $a^{-1}$. That is, by the middle of the present century we would be occupying, yearly, an additional area comparable to countries such as Cuba, South Korea or Portugal. Using similar assumptions, at the end of this century area HGF could be 17.6 $m^{2}$ $person^{-1}$ $a^{-1}$ and total, yearly occupied area of 192,000 $km^{2}$ $a^{-1}$, equivalent to the extent of Belarus, Senegal or Uruguay.

Average denudation (lowering rates for all continental areas, excluding Antarctica) could be >3 mm $a^{-1}$, by the middle of the century, and sedimentation rates could increase by one order of magnitude. The frequency of geomorphic disasters could also increase (due to both climate and geomorphic change) but, as mentioned above in relation to the EKC curve, there are signs indicating some mitigation is taking place. Detailed analyses of trends in the years to come would help to determine to what extent the results presented here can be confirmed, and contribute to a better understanding of the relationships discussed.

Although, we insist, the estimates presented are subject to important uncertainties, they do show that the potential magnitude of geomorphic change could be very considerable in the near future. One such uncertainty concerns sedimentation rates, normally expressed as mm $a^{-1}$, without explicitly stating whether density has been considered for the calculations. It would therefore be of great interest to carry out analyses restricted to studies in which mass accumulation rates (or density-corrected thickness) have been obtained.

This "geomorphic dimension of global change" (Cendrero and Douglas, 1996; Remondo et al., 2005; Cendrero et al., 2006; Rivas et al., 2006; Bonachea et al., 2010) has often been overlooked. However, as we have shown, it has significant implications for human wellbeing, such as slope stability, soil loss, sediment supply to rivers, lakes, reservoirs or coastal waters, beach erosion, or frequency/severity of geomorphic hazards.

It appears that the mid-twentieth century marks the beginning of a "new model of geomorphic evolution" (Rivas et al., 2006; Cendrero et al., 2006) or a new "Anthropocene geomorphology" (Goudie and Viles, 2016; Brown et al., 2017; Cooper et al., 2018; Goudie, 2020) and if the observed trends were to continue, the intensification of geomorphic processes would be very considerable in the decades to come.

In the light of these profound anthropogenic effects, an understanding of the contemporary dynamics of geomorphic systems requires the explicit consideration of direct and indirect human impacts, including "technological denudation" (Brown, 1956) and "anthroturbation" in general (Zalasiewicz et al., 2014). Such a viewpoint does not suggest that climate change is not important but rather that the interplay of climatic forcing and human activities should be considered.

Unlike in the case of climate change, mitigation actions against geomorphic change can be implemented, and effects obtained, at national or local levels, independently to a great extent of what is done in other regions. Research in areas where reductions of denudation or frequency of geomorphic disasters have been observed, and analyses of their potential relationships with climate and human drivers, would help to determine the suitability of mitigation measures.

In this context, it is pertinent to consider the call by Ashmore (2015) for research which would take into account the interactions between biophysical and social processes in Earth surface dynamics, something akin to socio-hydrology (Sivapalan et al., 2012, 2018). Evaluating the impacts and trajectories of net denudation on global landscapes requires an integrated and multidisciplinary approach. Local field-based studies provide site-specific sedimentary, geomorphic and paleoecological data relevant to human impacts in specific settings. By contrast, global-scale studies using field data (such as river sediment yield) and remote sensing data may be based on incomplete datasets of variable quality, and modelling approaches may make assumptions of denudation rates or sediment yield based on climate alone and not consider the intersection of Earth systems with the human environment, as discussed above. Thus, reconciling and integrating datasets and methodologies, across spatial and temporal scales, is a promising direction for future research. We hope this study, in demonstrating the pivotal role of human activity in denudation (and geomorphic processes in general), will help to develop a framework for forecasting and managing its effects on erosion and sedimentation, and other processes. Therefore, we fully agree with the proposal by Syvitski et al. (2022), to launch an "Earth Sediment Cycle Grand Challenge", for a comprehensive assessment of all aspects of the sediment cycle. And, we would add, other aspects of geomorphic processes.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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