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USING THE PAST TO ENVISAGE A BETTER FUTURE: THE APPROACH OF A QUATERNARY SCIENTIST.

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ABSTRACT: The study of the past is of fundamental importance in understanding the processes that control the functioning of the Earth System and the interaction between ecosystems, human society and natural variability. The Quaternary scientist produces a variety of proxies derived from the investigation of natural, archaeological and historical records covering all time scales of the history of Planet Earth, including current dynamics, and with special focus to extend the calibrations to not instrumentally registered time spans. The COVID-19 pandemic has highlighted not only the vulnerability of our world but it also has made plain for all to see the critical role of humans. On the other hand, it has produced the unexpected conditions for a large-scale experiment on the impact of sudden reduced human activities, pointing to the potential for recovery of the natural environment. In this review, we examine how data from the recent past can provide tools to understand the events taking place today and to forecast their developments in the future.

Keywords: Quaternary, nature-human interaction, ecosystems, risk, interdisciplinary approach.

1. INTRODUCTION

During the last couple of centuries, human activities produced a wide range of environmental changes at unprecedented rates, including changes that are novel to Earth history and that eventually became global in extent (Waters et al., 2016). It has been stated in key streams of scientific literature that the increased anthropogenic activities (i.e., industrialization, nuclear fallout, microplastic contamination) in the last two decades polluted the atmosphere and hydrosphere, and impacted both biosphere and climate more than natural variability could (IPCC, 2018). Yet, before the Industrial Revolution (or Late Anthropocene *sensu* Waters et al., 2016; Steffen et al., 2018) humans modified the biosphere influencing the climate at regional and global scale, causing changes in sediment fluxes and the ecosphere through fires, deforestation, irrigation, dams and farming (Dearing, 2006; Williams et al., 2014), thus supporting the parallel concept of Palaeoanthropocene (Foley et al., 2013). Human beings affect nature in numerous ways, which induce changes in climate, ecosystems, and land vulnerability. The effects of the accelerating human impacts towards the end of the century (Steffen et al., 2015) drove the Earth out of the Holocene epoch in which agriculture, sedentary communities, and eventually, socially and technologically complex human societies developed (Steffen et al., 2018). Human impact could irreversibly alter the Earth system, as the current magnitude and rate of some human changes far exceeds the rates of change driven by geophysical or biosphere forces that have modified the Earth System trajectory in the past, and even abrupt geophysical events do not approach current rates of human-driven change (Steffen et al., 2018).

For example, the Paleocene-Eocene Thermal Maximum (PETM) at 56 Ma BP (before present), a warming event that reached 5-6°C and lasted about 100,000 years, accompanied by a rise in sea level and ocean acidification, drove the extinction of 35-50% of the deep marine benthic foraminifera and led to continent-scale changes in the distributions of terrestrial plants and animals (Schneider von Deimling et al., 2015). The warming was driven by a carbon release estimated to be ~1.1 Gt C y-1 (IPCC, 2013). By comparison, the current human release of carbon to the atmosphere at ~10 Gt C y-1 is greater by nearly an order of magnitude (IPCC, 2013). Cumulative human emissions of CO_2 from 1870 through 2017 have reached ~610 Gt C (IPCC, 2013). Recently the occurrence of the acute respiratory syndrome coronavirus 2 (SARS-CoV-2), linked to coronavirus disease 2019 (COVID-19), has emphasized the need to enhance the mutually-affective connection between humans and nature (Chin et al., 2020; Yunus et al., 2020). In this contest, as Quaternary scientists focused on the interaction between natural and past and present anthropogenic processes, we aim to discuss this topic within the framework of the Italian territory, underlining the need of urgent actions in order to correctly plan a sustainable management of our territory. Indeed, integrated Quaternary research shows that deciphering the complex network of mechanisms driving past environmental change, and the resulting timelines of the dynamic history of the planet, is of crucial relevance to plan appropriate conservation actions and to collect insights into future scenarios for Earth ecosystems.

2. THE QUATERNARY SCIENTISTS OF THE 20TH CENTURY - THE GROWING IDENTITY OF THE SCHOLAR OF THE RECENT PAST

The Quaternary sciences grew up during the 20th century, partly as a reaction to the splitting of natural sciences into their a-biological and biological components and the cultural divergence between the humanistic and the scientific approaches (Izdebski et al., 2016). Interdisciplinary studies are a pre-requisite for the study of the history of the environment and the functioning of ecosystems. In the meantime, a considerable degree of model flexibility is necessary when tackling the natural and cultural history, given that factors and processes vary in time and space. As a matter of fact, modern global change brings about phenomena unreported in the written recorded history, but visible inside the Quaternary record (Elias, 2007). Multifactoriality, connectivity and unpredictable internal variability make history a difficult subject to be modelled and split up, even when humans are not involved.

Quaternary investigations involve researchers from different disciplines in order to integrate information from geology, archaeology, palaeoanthropology, botany, biology, zoology, climatology, chemistry, physics, etc.. The dialogue between different disciplines and the specific interdisciplinary, more than multidisciplinary, approach are the key for the study of the Quaternary. Quaternary studies are focused on the last periods in the stratigraphic scale, including current dynamics, thus also providing fundamental predictive tools to understand the present and suggest future scenarios. This allows for diversified viewpoints on natural phenomena and processes compared to colleagues from other geological disciplines or focused on older periods. Additionally, the Quaternary scientist faces large sets of problems related to the climate / environment / human nexus, developing a particular sensitivity towards natural processes and their repercussions on society, and vice versa (Forman & Stinchcomb, 2015). The research on this interval helps understanding how natural causes of (paleo)climate change strictly interact with human-driven modern climate change. On the other hand, the Quaternary scientist establishes specific synergies with the biological sciences providing a historical long-term perspective (Willis & Birks, 2006; Nogué et al., 2017) that sometimes lacks in the analysis of the living biota and could leverage the past to shape sustainable solutions to the current challenges (Boivin & Crowther, 2021). Thus, a deep integration between biogeophysical Earth System science and social sciences and humanities aims to put the dynamics of human societies in a global perspective.

At present, scientists use models to understand how human activity is affecting the Earth's climate and to provide long-term projections of climate change under different anthropogenic emission scenarios . The models should represent the processes and interactions that drive the Earth's climate, including the atmosphere, oceans, land, and ice-covered regions of the planet. Model agreement and confidence in projections depend on the used variables and spatial and temporal averaging. Additionally, determining which of the multitude of models is most appropriate remains difficult and uncertainties in projected future climate conditions remain a challenge. Forecasts need the observation of climate variability over long time intervals in order to define the different environmental scenarios subjected to changes and to know the subsequent response of the ecosystems.

Current ecosystem processes can often only be understood by looking back even longer. The observation of climate variability over long time intervals is therefore essential for scholars to record the different modes and timing scales of dynamic interactions. International efforts for uncovering hidden processes in ecological research "because they occur slowly" (Magnuson, 1990) generated the Long-Term Ecological Research (LTER) infrastructure: a network of terrestrial, freshwater, transitional and marine sites, now active at European and global scale (Mirtl et al., 2021). LTER represents one of the main novel approaches for analyzing how ecosystems change over time, and for describing and interpreting natural variability as opposed to 'human-made' variability. However, current LTER research is carried out at decadal and secular scale (i.e., at the scale of human generations) and would benefit from longer time scales used by Quaternary scientists through the use of multiple proxies.

The Quaternary approach helps deciphering the Earth system dynamics that are controlled by nonlinear processes, interactions, and feedbacks. The Twentieth century saw tremendous advances in understanding how the world works physically, chemically, biologically, and socially and in the applications of that knowledge to human endeavors. Technology plays an important role in terms of both challenges and solutions, but it is worth of note that the complexity of nature is beyond our means of observation. Both natural and anthropogenic factors intersect mutually and technological action that does not take into account the totality of factors leads to the degradation of ecosystems. Yet the consequences of excess greenhouse gases in the atmosphere are already under our eyes, like climate change and ocean acidification. Innovative approaches to solve the problems at hand in our complex human-environment interactions require closer collaboration between scientists and managers. Inter- and transdisciplinary integration is continuously gaining importance in research programs and Research Infrastructure, development strategies (Mirtl et al., 2021) and all these issues are addressed by Quaternary investigations.

3. THE QUATERNARY HISTORY OF ENVIRONMENT-HUMAN INTERACTION

Since its appearance on Earth, human population grew and bio-culturally evolved up to colonize extreme landscapes. The huge number of traces unveiled from archaeo-anthropological and geoarchaeological records preserves an array of information that allows interpreting the interaction between climatic/environmental changes and humans since the earliest prehistory. Natural archives (e.g. ice sheets, lake, peat, river and marine sediments, speleothems, palaeosoils, loess, tree rings) as much as anthropogenic stratigraphic sequences (open air, underwater and cave/rock shelter archaeological sites), bear palaeoenvironmental proxy data useful to evaluate the responses of ecological communities to (i) shifts from glacial to interglacial conditions or (ii) arid to humid environmental settings, (iii) rapid or gradual landscape changes, and (iv) climate-induced variations in the availability of water and food, which were the main factors driving human migrations (Rotilio, 2015) alongside with other resources. For instance, such evidence includes different adaptation to new environmental settings (Pini et al., 2020), resilience of human groups living in marginal environments, and eventually the collapse of societies or the relocation of entire population with the consequent abandonment of specific regions (Brooks, 2006; Butzer, 2012; Nicoll & Zerboni, 2020). Despite this general trend, a growing number of palaeoenvironmental and archaeological studies distributed world-wide are shedding new light on the climate/environment/human nexus, and especially are highlighting its complexity and non-linearity (Boivin & Crowther, 2021). If we consider early prehistory, the relationships between environmental modifications and human response seem to be generally unidirectional (environment → humankind). Indeed, since the Early-Middle Pleistocene Transition, the increased magnitude of glacial cycles combined with unstable climatic conditions deeply influenced human population dynamics, punctuated by the effects of the "ebb and flow" process. Contractions in population density up to the disappearance of any trace of human presence across vast areas of Western Eurasia were forced by the harshest climatic conditions with the maximum extension of the ice sheets. On the contrary, favorable conditions which occurred during the Middle Pleistocene interglacials promoted the growing of human population (Hublin & Roebroeks, 2009). However, Palaeolithic hunter-gatherers expanded their ecological niches only from the late Middle Pleistocene onwards, as supported by a set of cultural improvements, consisting in the production of fire as energy budget (Roebroeks & Villa, 2011), in more effective technologies in stone knapping than in older times, innovation of domestic toolkits and hunting implements, and others. In the Middle and Late Pleistocene Eurasia, Neanderthal native populations were bio-culturally adapted to survive in an array of environments through the maintenance of equilibrate ecological relations (Conard & Richter, 2011). During the Late Pleistocene, their number contracted until their definitive disappearance around 40 ka cal BP in coincidence with the spread of *Homo sapiens* (Hublin, 2015). Among several hypotheses proposed for identifying the forcing factors responsible of the Neanderthal extinction (Vaesen et al., 2021) disease burden, infections and stress on immune systems (Greenbaum et al., 2019), and UVB radiations increase (Channell & Vigliotti, 2019) have been considered as the most likely. Surprisingly, a recent study revealed how a major genetic risk factor for severe symptoms after SARS-CoV-2 infection is related to a Neanderthal genomic segment that is carried by people in south Asia and in Europe (Zeberg & Pääbo, 2020). Indeed, aside their biological and cultural worldwide affirmation and long-term mixing with native Pleistocene people (Haidinjak et al., 2021), Upper Palaeolithic anatomically modern humans experienced dramatic biological turnovers, with severe population bottlenecks across the Late Pleistocene as well, as attested from discontinuous archaeological record (Djindjian et al., 1999; Bocquet-Appel et al., 2005; Maier et al., 2016) and palaeogenetic studies (Fu et al., 2016; Posth et al., 2016; Bortolini et al., 2021). The multiscale shifts that occurred from the Last Glacial Maximum to the onset of the Late Glacial Bølling interstadial (14.7 ka cal BP) are considered to be among the most important events. Genetic discontinuities due to long-range migrations progressively contributed to shape the nature of the population dynamics that accompanied the modern human re-expansion into the Boreal Hemisphere (Stoneking & Krause, 2011) and the consequent exacerbation of most Pleistocene megafauna from Eurasia (see section 4). Environmental changes associated to rapid climatic shifts are considered the leading factors in these extinction processes. Indeed, since their first appearance in the Boreal Hemisphere, modern humans have also contributed to destabilize megafauna metapopulation structures and to the collapse of the related ecosystems (Cooper et al., 2015).

Holocene records suggest that human transformation and landscape management increased since the Neolithic Revolution (Hole, 1984; Robb & Van Hove, 2003; Zanchetta et al., 2013; Cremaschi, 2014; Zerboni & Nicoll, 2019). Human agency in shaping Earth ecosystems played a long-term and increasing role (ArchaeoGLOBE Project, 2019) and its effects influenced our planet at different resolution scales, from local to global. Their influence on geomorphological processes included the enhancement of slow ongoing natural surface processes, the establishment of new geomorphological processes, and changes of the natural interactions in the critical zone (Price et al., 2011) resulting in an intentional and un-intentional human agency on ecosystems. The transition from the subsistence of hunters-fishers-gatherers based on the collection of natural resources, to the economy of food production - the so-called Neolithic Revolution (Childe, 1936) - and its consequent demographic increase (Bocquet-Appel, 2011) onset the positive feedback mechanism of a continuously increasing demand of resources. Food production (either based upon cultivation or herding) increased since the Neolithic Revolution, which occurred at different times in each region of the planet. The common effect on the environment was the progressive modification of pristine ecosystems and the introduction of new ones (Cremaschi, 2014; Pini et al., 2017; ArchaeoGLOBE Project, 2019; Boivin & Crowther, 2021).

Land use shifts and human agency like wood clearance and deforestation, timberline depression, grazing, farming, exploitation of water resources, and modification of natural hydrography (Evans, 1998; Sadori et al., 2011; Cremaschi et al., 2016; Henry et al., 2017; Regattieri et al., 2019; Mariani et al., 2020; Morrison et al., 2021) had several effects on the landscape that included changes in soils, shallow aquifers, atmosphere composition, vegetation turnover and overall biodiversity (Odgaard, 1999; Perego, 2017; Nogué et al., 2021). In the last two centuries, human forcing over the natural climate variability became evident, as a consequence of the abnormal increase of greenhouse gases in the atmosphere, which was promoted by anthropogenic emissions (Crutzen, 2002).

4. THE ECOSYSTEM ANSWER TO PHANEROZOIC CHANGES AND THE PRESENT-DAY GLOBAL CHANGE: RESILIENCE AND/OR SIXTH EXTINCTION?

The impact extent of anthropogenic factors on present-day ecosystem functioning and biodiversity integrity is a matter of an endless debate among scientists. Biodiversity is declining globally at rates unprecedented in human history - and the rate of species extinctions is accelerating. Based on the recently published IUCN report (IUCN, 2020), about 67.64% of animal species disappeared from the wild during the last 70 years. Available evidence points out the process acceleration as expected due to the continuous intensification of ecological stressors directly or indirectly linked to human activities. For instance, the monitoring of almost 21,000 populations of mammals, birds, amphibians, reptiles and fishes observed around the world between 1970 and 2016 shows a reduction of about 62%-73% (WWF, 2020). Moreover, since the actual status of a number of species and subspecies is unknown and various species have been not formally identified/described, the magnitude of the contemporary biodiversity depletion may be underestimated (Palombo, 2021). Consequently, also considering the current number of critically endangered and vulnerable species (IUCN, 2020), the idea of an ongoing sixth mass extinction became popular (Barnosky et al., 2011; Dirzo et al., 2014; Payne et al., 2016; Ceballos et al., 2017 and references therein).

Species extinction was a recurrent phenomenon during the 560 Myr-long history of the Phanerozoic, but the decline of biodiversity was generally outweighed by the appearance of new species, except for five geologically short times (End-Ordovician ~440 Ma, Late Devonian ~370-350 Ma, End-Permian ~250 Ma, End-Triassic ~220-200 Ma, and End-Cretaceous ~65 Ma) when the Earth lost more than three-quarters of its species (Raup & Sepkoski, 1986; Jablonski, 1994; Bambach, 2006; Barnoski et al., 2011). Although these "Big-Five" mass extinctions differed in magnitude, temporal extent, and complexity of dynamics, all were triggered by natural events sometimes synergically acting (e.g. sea-level and climate change, including global warming, ocean anoxia and acidification, volcanism, large meteorite impacts, and other abiotic changes in the biosphere) (Palombo, 2021). Their cascading effects protracted for hundreds of thousands to millions of years, followed by millions or tens of millions of years of biological recovery and biodiversity increase (Erwin, 2001).

Climate forcing, acknowledged for most pre-Quaternary extinction events, was the crucial factor driving flora and fauna turnovers during the Pleistocene, inducing structural changes and latitudinal displacements in terrestrial biomes that greatly influenced flora and fauna dynamics. Mammal species, for instance, mainly reacted to ecosystem disturbances by varying their geographic range. The Pleistocene climatic oscillations (including glaciations, as well as periods of increasing aridity), triggered the secular, long-distance dispersal of several mammal species that entered and colonized new territory, upsetting the equilibrium of the pre-existing communities, leading to the extirpation/replacement of stenoecious/less competitive species and stimulating new individual responses in other species. As a result, ecosystems significantly restructured during a long recovery period, though no real extinction events occurred (Palombo, 2021). The Late Pleistocene/Early Holocene megafauna extinction (LPME) was an exception, but it was an event of very small magnitude if compared to the Palaeozoic and Mesozoic mass extinction events. The LPME causal mechanisms are still debated.

Two main counterpoised hypotheses have been proposed that consider climatic changes and human hunting (overkilling) as the most likely drivers of LPME (Monjeau et al., 2017). Although prehistoric hunters likely increased the risk or accelerated the process of extinction for species already stressed by environmental changes, the available evidence indicates the latest Pleistocene climatic changes as one of the dominant factors causing local extirpations, global extinctions and loss of biodiversity.

The current global warming can be regarded as one, but possibly not the major factor causing the ongoing biodiversity depletion. The actual impact of climate warming on flora and fauna (particularly on the less ecologically flexible) and its related effects on other species and ecosystem functioning is quite difficult to determine (Botkin et al., 2007). Nonetheless, it could be argued that it might be more important than during most of the Quaternary due to the magnification effect produced by anthropogenic ecological stressors (e.g., Palombo, 2021). Human activities prompted profound modifications of natural community structure, merging human-introduced invasive exotic species (including pathogenic organisms) and native species, confining wild species within modified habitats, overharvesting terrestrial and marine resources, conditioning how mammals live and move through the human-altered landscape, causing the destruction and fragmentation of the world's richest ecosystems, such as tropical forests, wetlands and savannahs. Irreversibility on a human time scale (which is what we are interested in) likely has crucial effects on short-term environmental sustainability, with consequent impacts on human well-being because it affects the amount and availability of ecosystem resources and services that we require to survive (Díaz et al., 2020). In addition, as stressed by Ceballos et al. (2020) a further threat for human health and well-being would be the spread of viruses linked to wildlife trade (a concurrent cause of population and species extirpations and extinctions). A recent example is the current pandemic coronavirus disease (COVID-19). Human population is rapidly growing and human pressure on the biosphere and human-caused extinction is likely to accelerate. The species surviving in regions with high human impacts, under the action of anthropogenic ecological stressors and related feedbacks will likely further reduce their population number and size and ultimately disappear, triggering regional biodiversity collapses. In the near future, many severely endangered species will likely disappear all over the world as evidenced by data on the Biodiversity Intactness Index trend in different regions, particularly influenced by the effects of land use and related pressures (Scholes & Biggs, 2005; Newbold et al., 2016; WWF, 2020). Deconstructing the complex network of mechanisms driving fauna and flora dynamics during the Pleistocene, deciphering the relationship between extinction selectivity and extinction intensity, and understanding the past causal factors promoting ecosystem dynamics and the resilience of vulnerable ecosystems to Quaternary climate changes is of crucial relevance for better understanding the actual extent of the role of human activity in amplifying the already significant negative effects produced by global warming. Understanding the processes that regulated the impact of Pleistocene climatic change on biodiversity dynamics, flora and fauna turnovers, species replacement and extirpation could provide interesting clues to predict the current effects of climate change on biodiversity loss (Barnosky et al., 2011; Willis & MacDonald, 2011; Palombo, 2021).

A lesson from the recent past as the Pleistocene fauna dynamics, highlights the relevance of landscape connectivity and the dangerous role of invasive species in preserving the vitality of wild population. It enables us to better understand the actual meaning of the present defaunation and plant biodiversity loss and to promote suitable conservation actions for the conservation of biodiversity in view of the ongoing climate warming and modifications of ecosystems.

5. NATURAL HAZARDS, RISK AND HUMAN PRESENCE (CASE STUDIES IN ITALY)

Natural hazards are among the "environmental problems" currently capturing so much public attention: they are naturally designed to modify ecosystems, but, in many cases, they reflect the impact of humans on their environments, and can largely affect human populations. The switch from hazard to risk occurs when a hazardous phenomenon turns into a disaster and becomes responsible for a great loss of assets and even for casualties (UNISDR, 2009). Correct practices of territorial planning and management are hence needed to reduce damaging effects. It is well known that under certain circumstances and conditions, the action of humans can actively determine - or at least strongly contribute to determine hazard related to natural phenomena to which humans get exposed. These events are actually "human-made natural hazards".

In order to reduce vulnerability and achieve sustainable development targets, humans need to improve their knowledge of the environmental dynamics of the territory they live in and of the related hazards. The Natural Hazard Risk Atlas (2015) reports Italy as the eighth country in the world, and the first in Europe, in terms of exposure to natural hazards.

In this contest, we focus here on the Italian territory on view of its peculiar geological, morphological, and climatic characteristics (Fig. 1). The position of the Italian peninsula at the convergence of the Eurasian and the African Plate causes intense seismicity in most of the Italian territory. Additionally, geomorphological conditions along with land use changes and the frequent extreme rainfalls induced by climate change (Fisher & Knutti, 2016) make Italy very prone to flooding and landslides. Furthermore, wide sectors of the ca. 7500 kilometers long Italian coastline is exposed to coastal flood hazard expected to become even more dangerous in the next decades due to sea level rise (Bonaldo et al., 2019; Antonioli et al., 2020). In 2014, a significant flood episode occurred in Genova (Liguria, N Italy) strongly related to the dense urbanization of the terminal sections of streams and rivers. In general, streams and river beds constrained into small artificial channels or even entombed underground into undersized human-made tunnels (Acquaotta et al., 2019) are the principal causes of flood disasters in the present climatic phase characterized by abrupt and extreme rainfall events (Pfahl et al., 2017). During the mid-Holocene, an increase of precipitations determined an increase of the rate of landslide events in Europe (Soldati et al., 2004; Patton et al., 2019). Similarly, the melting of permafrost determines an increase of local gravitational instabilities (Matthews et al., 2018).

Nonetheless, human-made alteration of slope natural profiles, intense deforestation or even construction of infrastructures can make a slope gravitationally unstable and expose humans to risks caused by their own practices. A well-known case is represented by the Vajont landslide, whose occurrence was favored by the realization of an artificial dam and the creation of an artificial hydrologic basin at the toe of Mt. Toc (Genevois & Tecca, 2013).

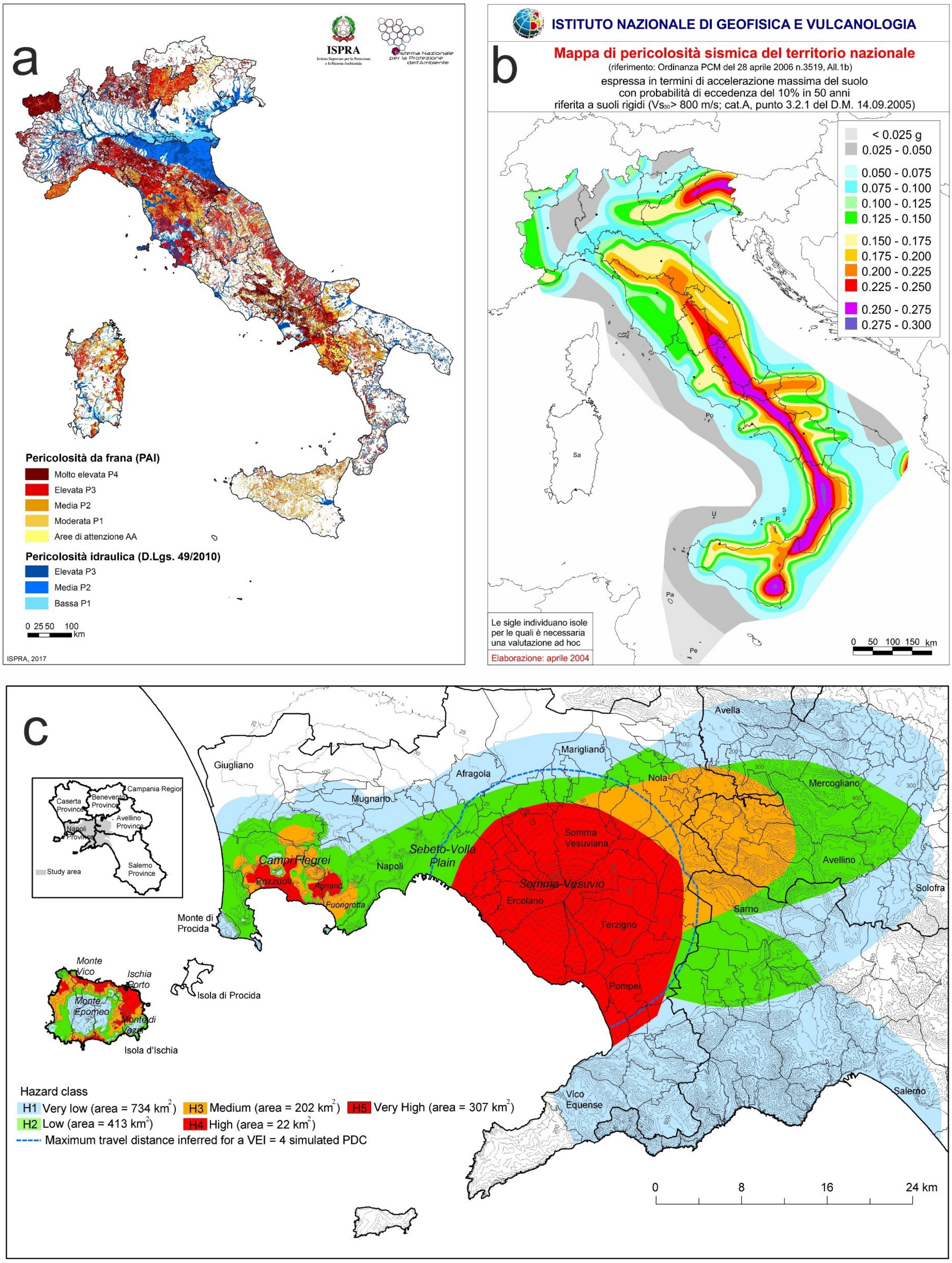

Fig. 1 - Maps of some of the geological "hazard" of the Italian territory. In detail: a) map of landslide and hydraulic hazard (ISPRA, ISPRA Rapporti 287/2018); b) map of seismic hazard (Stucchi et al., 2004; Ordinanza PCM n. 3519_2006); c) map of volcanic hazard of the Campania multi-source area, for possible future explosive eruptions of Campi Flegrei, Ischia Island or Somma-Vesuvius (from Lirer et al., 2010).

Another vulnerability of the Italian territory is represented by sinkhole risk. Sinkholes commonly occur as features of karstic processes (dissolution of carbonate rocks) and their evolution into paroxysmal collapses of portions of ground surface. However, in anthropogenic environments and urbanized areas, the construction of underground infrastructures, lifelines or pipelines (such as aqueducts or sewer nets) can determine the conditions (i.e., underground erosion, water under-excavation) that can lead to human-induced local and abrupt subsidence, potentially resulting in the generation of sinkholes (Gutiérrez et al., 2014).

Concerning the seismicity risk, although it is not possible to deterministically predict and prevent earthquake occurrences, environmental protection guidelines and correct practices could mitigate the risk associated to earthquakes (i.e., ground shaking, landslides, surface faulting). In the past decades an increasing number of proofs testifies to the occurrence of seismicity - small-to-moderate magnitude seismic events - in areas interested by human activities. Such a phenomenon is referred to as induced and/or triggered seismicity, that means earthquakes induced or triggered by human exploitation of underground natural resources, fluid extraction or injection, wastewater disposal. One of the largest known seismic events of this kind is represented by the Mw 5.8 earthquake occurred in 2016, in Oklahoma (Moschetti et al., 2019). Wastewater injection into a high-rate well in the Val d'Agri oilfield (southern Italy), the largest in onshore Europe, has induced swarm microseismicity since the initiation of disposal (Improta et al., 2017).

It is worth of note that Quaternary tectonic studies are essential for modern seismic hazard assessment because they represent an important tool to determine the seismic potential of seismogenic faults over much longer time periods than instrumental measurements, historical catalogues or onshore paleoseismic records (Nelson et al., 2012). Moreover, as a specific field of application, Quaternary stratigraphy in the paleoseismological perspective of coastal, marine and lake environments has provided essential input to seismic and tsunami hazard assessments of coastal areas threatened by the effects of local and distant earthquakes (Gràcia et al., 2013).

The activity of the volcanoes that punctuate the Italian territory (Ischia, Campi Flegrei, Somma-Vesuvius, Etna, Stromboli and Vulcano at Aeolian Islands) represents an important source of risk, as well. Nonetheless, in our country as in most of the Mediterranean area the fertility of soils generally associated to the favorable geographic location (mostly along the coastline) of active volcanic areas encouraged human settlements over time (Cottrell, 2015; Freire et al., 2019). Differently from earthquakes, which are instantaneous phenomena whose occurrence cannot be temporally predicted to date, volcanic eruptions have several precursory signals (principally seismic shakes, ground deformation, heat flux, compositional changes in volcanic gas and fluids) that, when correctly monitored, allow to forecast the occurrence of an eruption. Thanks to the accurate and timely monitoring of these signals, the frequent volcanic crises linked to paroxysmal phases of open-conduit activity at Etna and Stromboli are successfully managed by the Italian Civil Protection. In as much, very detailed pre-event evacuation plans have been prepared in conjunction with Campania Region authorities for the areas possibly endangered by future explosive eruptions of Somma-Vesuvius and Campi Flegrei. Planning an evacuation is always a difficult task, mostly because of the uncertainty in the occurrence of an eruption, and it is even more difficult when evacuation plans involve several hundreds of thousands of people. People preparedness joined to a performing network of volcanic surveillance for the short-term forecast are essential to prevent disasters at active volcanoes. Recent studies have improved volcanic risk management by advancing the basic scientific and technological skills employed in risk assessment and mitigation, producing updated computer models, vulnerability databases, and probabilistic risk assessment protocols (Thierry et al., 2015).

Sea level has risen from the Last Glacial Maximum (LGM) to nowadays and strongly modified the landscape, covering wide areas that are presently submerged, such as large part of the Adriatic Sea, or many submerged natural bridges, such as the one between Calabria and Sicily (Antonioli et al., 2014). Human constructions located along the coasts are exposed to flooding risk. Nonetheless, for millennia humans have exploited coastal areas since they supply resources and provide a space for trading, as testified by hundreds of historical and archaeological structures at or below sea level. The recent increasing rate of sea level rise, if not slowed down or inverted, could cause an increase in the frequency of flooding events in many coastal regions interested by low-lying coasts and affect most of the human activities there. The fragility of the city of Venice and its inestimable geological, cultural, historical, and artistic heritage represents a paradigm in the interaction between natural and human-induced high-water phenomena and the need to preserve the valuable city (Zanchettin et al., 2021).

The knowledge of the quoted hazardous phenomena (through the comprehension of the predisposing and triggering factors) and the awareness of the role of humans in potentially being a “risk” for themselves is the key to correctly plan the use of territories, in the view of a desirable sustainable development. The final aim of this correct behavior is leaving to natural phenomena the role of “potential hazards” and preventing them to become “risks”. Thus, adequate preventive policies towards catastrophic events are strongly needed, along with a punctual regulation of the construction of buildings and infrastructures and in general of respect for the environment.

6. CLIMATE CHANGES, HUMAN HEALTH AND PANDEMIC DISEASE

Understanding the potential interaction between pandemic disease and climate is complex, as pointed out by many studies carried out in different areas of the world including the Mediterranean region (McMichael, 2012; Luterbacher et al., 2020). Throughout the Late Holocene, the atmospheric CO_2 concentration trapped in ice-cores documents an increasing trend (Rubino et al.,

Fig. 2 - An unprecedented water transparency Venice (Northern Italy) was determined by the reduction of boat traffic and tourism (Braga et al., 2020). The top image, captured 13 April 2020, shows a distinct lack of boat traffic compared to the image from 19 April 2019. (Image credit: contains modified Copernicus Sentinel data (2019-20), processed by ESA, CC BY-SA 3.0 IGO).

2019). Some short-term drops (decades or more in duration) of this record, detected during the past two millennia are associated by some scientists with pandemic events responsible for high human mortality (Ruddiman, 2007, 2010). Based on this idea, the CO_2 decreases (corresponding to cool-to-cold events) detected at ca A.D. 540 and 1350, are related with the pandemics occurring during the Roman period (the Plague of Justinian, in A.D. 540 to 542 and the "Black Death" between 1347 and 1352). Another significant drop in CO_2 around 1500 to 1800 coincides with the catastrophic consequences of the arrival in America of Europeans since 1492, inducing smallpox and other diseases in pre-Columbian populations. The consequences of these pandemics as reported by several historical sources are expressed, first of all, by massive mortality rates (Crosby, 2003; McMichael, 2012; Koch et al., 2019). This in turn provoked widespread abandonment of rural villages and farms, reduced agricultural activity, and forests recovery (estimated in just 50 years). As a consequence, during pandemics the restored forests could have sequestered sufficient carbon to reduce concentrations of CO_2 in the atmosphere as attested in palaeorecords. On the other hand, the end of the pandemic episodes promoted the reestablishment of the population in abandoned areas and the recovery of agriculture (deforestation, etc.) with the consequent increase of atmospheric CO_2 (and temperature) values. This hypothesis (Ruddiman, 2007) clearly refers to global scale effects and require careful analyses of the geographical extent of pandemics and real mortality rates. This *subject* has been a matter of considerable *debate* in *recent* years (i.e., for the Justinian plague, Mordechai et al., 2019).

The importance of the fossil record is also evident from recent discoveries that highlighted the role played by pathogens in the history of ancient empires and civilizations by isolating the genetic sequence of viruses and bacteria from human remains (Wagner et al., 2014; Rascovan et al., 2019; Spyrou et al., 2019a, b). Most of the pandemics cited above were caused by the bacterium *Yersina pestis,* including the European Neolithic catastrophe about 5,000 years ago, when early Bronze age populations came down from the steppe to take the place of the Neolithic farming communities of Europe (Close, 2021). Instead, the cocoliztli pandemics that devastated the Aztec empire were caused by bacteria belonging to the *Salmonella* genus (Close, 2021).

The possibility that the geological record offers to identify and document (i) pandemic events over a long period of time, (ii) the source-areas of diffusion, and (iii) their effects on populations and environments, are especially relevant for the contribution to medical research, today much more prepared than in the past in the fight against pathogens. However, despite the remarkable progress of science in various fields, including the fast development of a vaccine for COVID-19, the current environmental context, i.e., fast and easy global/interplanetary travels (communications, interchanges, etc.) and climatic conditions marked by short-term drastic events, open up new challenges. Among them, the different rate of forcing (fast worldwide spread of pandemics) vs (slower human) response is one of the main critical aspects.

7. THE RECENT ENVIRONMENTAL CONTEXT AND CONSERVATION PALEOBIOLOGY

The COVID-19 pandemic has produced the unexpected conditions for a large-scale short-term experi-

Fig. 3 - Examples of waste accumulation at the mouth of the Tiber River (Latium, Italy). Top image the Tiber River sediment plume in the Tyrrhenian Sea (Image credit: contains modified Copernicus Sentinel data (2019-20), processed by ESA, CC BY-SA 3.0 IGO). Bottom left image: face mask waste along the beach of Fiumicino (17 April 2021). Bottom right image: plastic waste accumulation at Fiumara Grande (29 December 2020) (both images courtesy of Martina Pierdomenico).

ment on the impact of sudden reduced human mobility on land, at sea (Rutz et al., 2020) and in the air. Italy, being the first European country to perform a country-wide lockdown from March 11th until May 4th 2020, has experienced two months of unprecedented reduction of human disturbance in the industrial period. Satellite images have shown a dramatic improvement of air quality (data from Copernicus Sentinel-5P about fluctuation of NO_2 concentrations across Europe from 1-1-2020 until 11-2-2020, www.esa.int/ESA_Multimedia/Videos/2020/03/Coronavirus_nitrogen_dioxide_emissions_drop_over_Italy) and recent studies have shown a significant reduction of PM_{10}, $PM_{2.5}$, BC, benzene, CO and NO_x in Milan (Northern Italy) as an effect of the lockdown during last spring (Collivignarelli et al., 2020). The exceptional conditions that emptied Venice of millions of tourists and thousands of gondolas and vaporetti (Fig. 2), together with natural seasonal factors, produced unprecedented low levels of suspended sediment and water transparency conditions (Braga et al., 2020). Limitations in human mobility have provided benefits to wildlife in general (Manenti et al., 2020), although the records are always biased toward more appealing and visible taxa (Batt, 2009) and trends of invertebrates and plants need to be investigated. A potential way to understand how ecological resilience is maintained even in the face of drastic changes is represented by the conservation biology merged with palaeobiology (Fordham et al., 2020). This emerging discipline applies geohistorical records to the conservation and restoration of biodiversity and ecosystem services. Since geologists can study times well beyond the limited frame of direct human observations, the use of geohistorical records could lead to a long-term perspective on ecosystems, species and communities of the recent past. A study about the opportunistic bivalve *Corbula gibba* in the Gulf of Trieste, has demonstrated that the youngest fossil record (Holocene-Recent) could document the abrupt ecological changes affecting benthic communities during the 20th century (Fuksi et al., 2018). The *C. gibba* size variations (from 5 to 10-15 mm) were probably driven by a transition towards higher frequency of seasonal hypoxia (Tomašových et al., 2020). The foraminifer and ostracod assemblages of the Po River coastal plain were investigated with a conservation palaeobiology approach (Barbieri et al., 2020) providing a high-resolution palaeoecological record under the influence of Holocene sea-level rise, in analogy with the present-day global change. The recently discovered collapse of the native molluscan biodiversity along the Israeli Mediterranean shelf (Albano et al., 2021) has been related both to the fast pace of warming of sea water and the Lessepsian migration through the Suez Canal. With their palaeobiological conservation approach, Albano et al. (2021) provided a snapshot of an irreversible change defined as “novel ecosystem”. It is not possible to estimate the extent of the impact of COVID-19 as there is no robust data on hand for the analysis of trends in sedimentation rates, heavy metal contamination, algal blooming, invertebrate benthic community changes. Although pollution in general is decreased, the worldwide resurgence in the use of disposable personal protective equipment (PPE) and of disposable items in restaurants and other businesses to operate safely is a new potential source for microplastic pollution (Espejo et al., 2020). For Italy alone, a country with 60.4 million inhabitants, PPE needs for the population during deconfinement has been estimated as 1 billion face masks and 0.5 billion gloves per month. This sums up to the average amount of plastic waste released in the environment that normally accumulates on land, in the lakes, rivers and along the coasts of Italy (Fig. 3). On the contrary, household waste production has generally decreased during the pandemic, falling by 28% in Milan (Prata et al., 2020). We could be relatively certain that the COVID-19 pandemic will leave a clear signal in the sediments. Not only such a signal will be temporally well defined and globally distributed but could be an excellent test to examine the response mechanisms of living populations to different stress factors.

8. CONCLUDING REMARKS: RECONSIDERING THE RELATIONSHIPS BETWEEN HUMANS AND ECOSYSTEMS ON THE ITALIAN TERRITORY

It is evident that we are in a strongly transient phase in which human societies, the biosphere and the climate system are all changing at very rapid rates and our usual activities are necessarily modified. The diffusion of the COVID-19 virus highlighted the weakness of our actions towards the protection of our planet as well as our dysfunctional relationship with nature.

During the global 2020 lockdown, when population was confined home for a long period of time ranging from a few weeks up to a few months and with nearly the total absence of activities influencing the Earth atmosphere and oceans, the answer of nature gave us a great lesson about its resilience and capacity for rapid recovery. The reduction of air pollutants and heavy metals, the unusual transparency of waters in lagoonal areas such as Venice, the occurrence of animals in the cities are among the evidence observed by everyone. These observations highlight the importance of long-term ecological observation and monitoring in order to discriminate how ecosystems change and adapt in response to climate variability and human activity (Fig. 4). It is urgent to reconfigure our view about nature (Fig. 4). We feel that new prospects on human adaptation should respect the independence of natural dynamics, thus developing nature-based solutions through investments in green growth (Mandle et al., 2019).

The current crisis generated by the health state and the consequent restrictions offers the opportunity for novel insight and makes imperative to adopt sustainable options by reconciling the needs of citizens with the characteristics and vulnerabilities of the territory. Even if the peculiarities of the Italian territory are particularly prone in originating hazards and risks, several anthropogenic factors have contributed in a decisive way to trigger or intensify their consequences. Recently, urbanization, settlement in hazardous areas, and unsustainable land use have put more people and wealth in danger. Thus, it is necessary to reconsider urban expansion and space planning. Investments in monitoring and surveillance systems are essential for tracking changes in the environment, particularly those factors that affect human

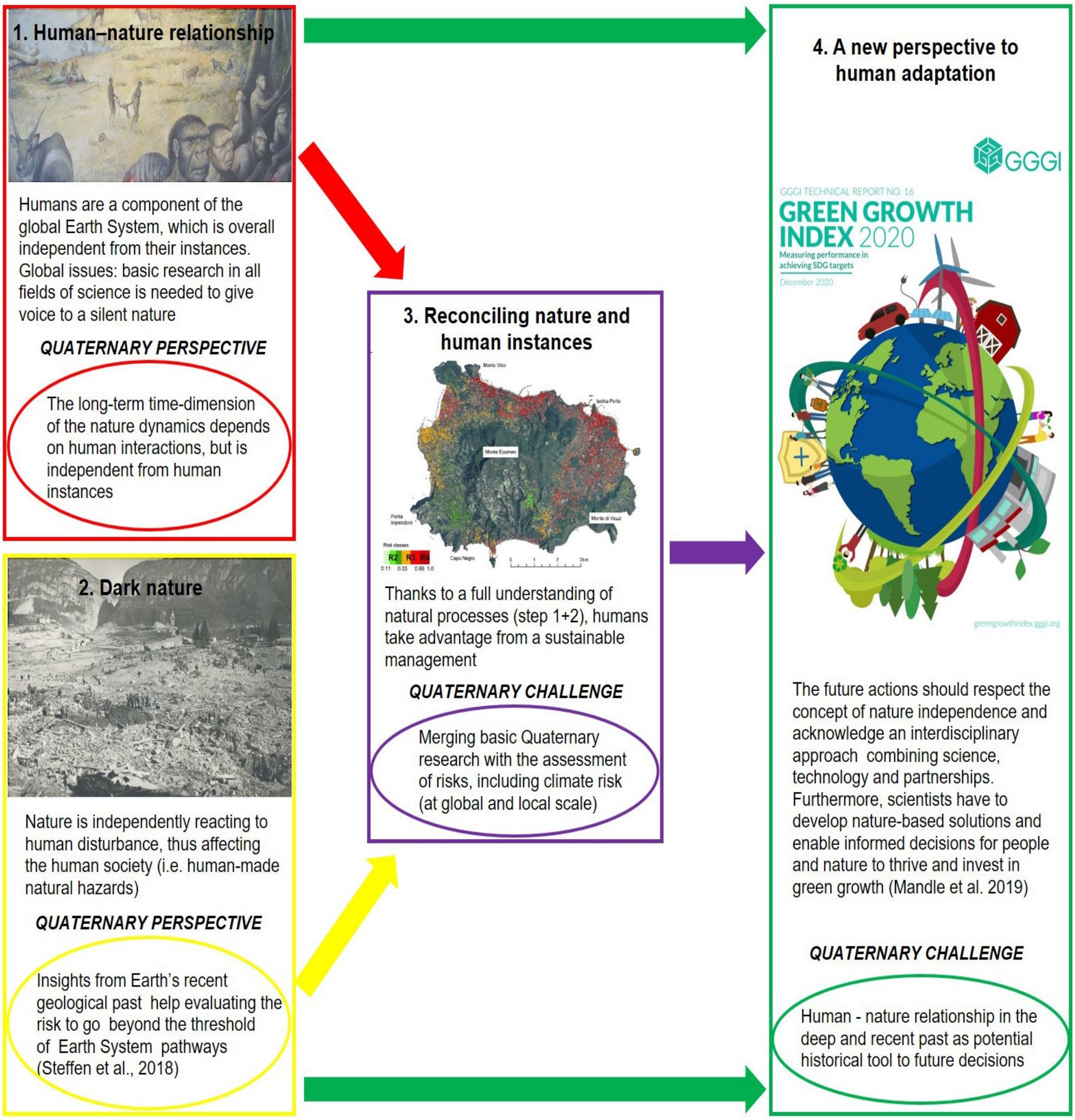

Fig. 4 - Changing views about nature over the past 50 years reconfigured the human-nature relationship over time, resulting in four main frameworks - (1) Nature for itself; (2) Nature despite people; (3) Nature for people; (4) People and nature (Mace et al., 2014; Folke et al., 2021). Perception of these concepts needs a solid scientific basis to which all geoenvironmental disciplines are urged to contribute. We declined frameworks (1) to (4) in a fully Quaternary narrative, focusing on the role of Quaternary science in terms of perspectives and challenges. We look forward after the narrow perspective of a single human generation (see Steffen et al., 2018); we feel that new perspectives to human adaptation should respect the independence of nature dynamics, thus developing nature-based solutions investing in green growth (Mandle et al., 2019) (4). Image step 1- Image courtesy of M. Lopez-Herrera via The Olduvai Paleoanthropology and Paleoecology Project and Enrique Baquedan from www.newhistorian.com/2016/03/13/scientists-reconstruct-habitat-early-human-ancestors/ Image step 2 - Disastro del Vajont, 1963. Fonte: Ansa from www.mountainblog.it/redazionale/la-tragedia-del-vajont-streaming-non-dimenticare/. Image step 3 - Volcanic risk map for Ischia Island active volcanic area from Lirer et al. (2010). Image step 4 - Green Growth Index 2020: Measuring performance in achieving SDG targets from gggi.org/report/green-growth-index-2020-measuring-performance-in-achieving-sdg-targets/

Fig. 5 - World cloud of the main conceptual terms used in the text. It highlights the fact that the global environmental crises lift the curtain on the intrinsic relationship between humans, climate and nature.

health. Additionally, changes in frequency and intensity of climate anomalies in the recent past contributed to increase the occurrence rate and magnitude of natural disasters. This highlights the importance of analysing the historical rainfall series and generating spatially precise climate simulations in order to develop adequate adaptation strategies and plans (Spano et al., 2020). The interaction between scientific research and technology helps in proposing suitable and sustainable interventions. For example, to contrast the negative effects of sea level rise, river flooding, and landslides, it is mandatory to reduce built areas, which cause soil loss and reduce water infiltration leading to soil erosion and floods.

A darker scenario at a global scale emerges from the latest reports from the ERSL Global Monitoring Laboratory of the NOAA, which monitors trends in atmospheric carbon dioxide. "Can we see a change in the CO_2 record because of COVID-19?" (gml.noaa.gov/ccgg/covid2.html) (browsed September, 2nd, 2021). It seems that CO_2 keeps increasing at the same rate recorded in previous years. Therefore, we are urged to make investments in renewable energy and in natural carbon long-term storage such as proforestation. Proforestation is the practice of purposefully growing an existing forest intact toward its full ecological potential and is a nature-based solution where existing forests are protected as intact ecosystems to foster continuous growth for maximal carbon storage and ecological and structural complexity. This is a powerful climate solution which may be adapted at regional scale (Leverett et al., 2021; Mack et al. 2021) and may be managed regionally by the collaboration of Quaternary palaeoecologists, forestry experts, and decision-makers, by estimating the biomass potential of pristine forests and address the future forest succession (Leverett et al., 2021). Proforestation is much more effective than planting new tree individuals (Zastrtow, 2019). It could reconcile nature-based biological carbon sequestration and an array of ecosystem services such as biodiversity enhancement, water and air quality, flood and erosion control, public health benefits, low impact recreation, and scenic beauty. But actions like proforestation must become a global effort, much more aggressive than the impact that the pandemic forced over the reduction to global CO_2 emissions.

The terminology recently used to distinguish ecosystems based on the degree of human interaction ("novel ecosystems," "impacted ecosystems," or "designed ecosystems") suggests that societies would most efficiently invest time, effort, and financial resources if they focus on managing novel ecosystems for the ecosystem services that they can provide, rather than attempting to restore them to their previous states (Morse et al., 2014). Viewing "novel ecosystems" in this way and recognizing the trade-offs between their positive and negative aspects will allow managers the pragmatic flexibility needed to make informed and sensible decisions concerning resource use and ecosystem maintenance (Morse et al., 2014). However, addressing these questions requires to plan adequate monitoring programs for the data collection and an accurate knowledge of the dynamics, structure, and longevity of past biodiversity to fully depict the influence of human impact and ecosystem response over time.

In conclusion, we need scientists with different expertise such as naturalists, biologists, oceanographers, limnologists, geologists, climatologists, historical ecologists, archaeologists, soil scientists, possibly interacting with economists and local stakeholders endowed with specific skills to evaluate environmental sustainability and to propose effective and long-term solutions to address global environmental crises and human responses (Fig. 5). We need to face a deep change in perspective: from the post-event emergency response and assistance to risk forecast and prevention.

The Quaternary record allows our knowledge to stretch beyond the present and to collect insights into the Earth ecosystems future scenarios through lessons from the past. Although not all the solutions pertain to the expertise pertaining of Quaternary scientists, knowing Quaternary helps understanding causes and dynamic processes to propose suitable and sustainable interventions.

AUTHOR CONTRIBUTIONS

L.C. conceived of the presented idea and took the lead in writing the manuscript with input from all authors. C.R. focused on paragraph 2 and 8, M.P. and A.Z. on paragraph 3, MR. P. on paragraph 4; E.F., PP. and S.F. on paragraph 5, A.B. on paragraph 6, and I.M. on paragraph 7. G.M. provided critical feedback. L.C. C.R., P.P. and I.M. drew the figures. All authors commented on the manuscript.

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