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ANTHROPOCENE, THE CHALLENGE FOR *HOMO SAPIENS* TO SET ITS OWN LIMITS

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ABSTRACT. *The Anthropocene as a distinct geological era has been the subject of active discussion within the scientific community. This era includes the notion that Homo sapiens has had a large impact on global planetary processes. Here, we aim at connecting the notion and nature of the Anthropocene with the social-economic success and the unexpected or unplanned environmental impacts of the anthropogenic activity. Some of the main achievements along the history of humankind have been important developmental steps for many human civilisations but they have also had undesired results that we could not foresee, including the rise of greenhouse gases emissions, the shifts in the area of species distributions or the affection of all major biogeochemical cycles. Increasing human life expectancy and health has promoted an exponential population growth, which together with the increased environmental footprint per capita has pushed many core variables for Earth functioning (e.g. biodiversity, nitrogen cycle, climate change) out of their safety limits. We illustrate examples of many ecosystems that have collapsed around the world because we have crossed the limits of their sustainable exploitation. Paradoxically, it is humanity itself who is pushing the Planet to conditions in which our own survival will unlikely be possible. The reason behind such a strong ecological and functional impact on the Planet within a relatively short space of time is an unsustainable economic system based on the assumption that a perpetual economic growth is not only possible but also desirable. Our awakening should lie on a global framework aimed at changing our relationship with the Planet.*

Antropoceno, el reto de* Homo sapiens *para fijar sus propios límites

RESUMEN. *El Antropoceno como era geológica diferenciada ha sido objeto de discusión activa dentro de la comunidad científica. Esta era incluye la noción de que* Homo sapiens *ha tenido un gran impacto en los procesos globales planetarios. Aquí intentamos conectar la noción y naturaleza del*

Antropoceno con el éxito socioeconómico y los impactos no esperados ni planificados de la actividad antropogénica. Algunos de los principales logros a lo largo de la historia de la humanidad han sido pasos importantes para muchas civilizaciones humanas, pero también han dado lugar a consecuencias indeseadas que no se podían prever, incluyendo el incremento de gases de efecto invernadero, los cambios en las áreas de distribución de especies o la afección a los grandes ciclos biogeoquímicos. El aumento de las expectativas de vida humana y la salud han promovido un incremento exponencial de la población, que junto con la mayor huella ambiental per capita han llevado a muchas variables esenciales para el funcionamiento de la Tierra (por ejemplo, la biodiversidad, el ciclo del nitrógeno, el cambio climático) fuera de sus límites de seguridad. Ponemos ejemplos de muchos ecosistemas que han colapsado en el mundo debido a que han cruzado los límites de su explotación sostenible. Paradójicamente, es la propia humanidad la que está empujando al Planeta hacia condiciones en las que su supervivencia no será posible. La razón que está detrás de este fuerte impacto ecológico y funcional en el Planeta en un plazo relativamente corto es un sistema económico insostenible basado en la asunción de que un crecimiento económico permanente es no solo posible sino también deseable. Nuestro despertar debería descansar en un marco global dirigido a cambiar nuestras relaciones con el Planeta.

Key words: Anthropocene, biodiversity, climate change, drought, environmental impact, erosion, biogeochemical cycles, global change, invasive species, planetary limits, sustainable development.

Palabras clave: Antropoceno, biodiversidad, cambio climático, sequía, impacto ambiental, erosion, ciclos biogeoquímicos, cambio global, especies invasoras, límites planetarios, desarrollo sostenible.

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1. The concept of Anthropocene

Anthropocene, our current era, encapsulates the notion that humans are having a huge impact on global planetary processes. The concept of Anthropocene is broadly accepted by the scientific community, with many books, articles and even an entire scientific journal dedicated to it. Anthropocene as a distinct geological era is, however, still pending of validation by the International Commission on Stratigraphy of the International Union of Geological sciences. A synchronous and global signature within geological-forming materials is necessary to formally define the onset of any geological time division. The global peak in atmospheric radiocarbon due to thermonuclear bomb tests during the 1950s and 1960s, which has left recognizable footprints in tree-rings and sediments, provides a potential basis for the onset of the Anthropocene Epoch in 1965 (Turney *et al*., 2018). However, the term and its application to the geological time scales is subjected to intense discussion at the International Union of Geological Sciences (IUGS). In fact, the Holocene has been subdivided very recently (July 2018) into three ages (see IUGS official site www.iugs.org). Following this revision, we are in the Meghalayan Age, the youngest of the three Holocene ages, which runs from 4,200 years ago to the present. It began with a destructive, 200-years drought that severely affected civilisations in Egypt, Greece, Syria, Palestine, Mesopotamia, the Indus Valley, and the Yangtze River Valley. This devastating drought was likely triggered by shifts in ocean and atmospheric circulation. What makes the Meghalayan Age unique among the intervals of the geologic timescale is that it begins with a global cultural event produced by a global climatic event. The new Holocene subdivision has no bearing on the Anthropocene, which remains an undefined unit under active research and discussion by the Anthropocene Working Group of the Subcomission on Quaternary Stratigraphy. However, the Anthropocene remains a useful concept despite its current lack of a precise stratigraphic or temporal definition. When talking about time, the Holocene divisions are unbiased and more appropriate, while when we talk about human impacts it becomes convenient to refer to the notion of Anthropocene.

Homo sapiens and the hominids in general have always had a noticeable environmental impact, but the exact point in time from which we can talk about an era influenced by human-like species is, and probably will always be, a matter of debate. Actually, it could be more insightful to consider the cause rather than the effect to define the Anthropocene, i.e. the human footprint on a given environmental change more than its actual magnitude (Smith and Zeder, 2013). With such a view, the extensive use of fire driving landscape transformation as well as the early extinctions of megafauna by the end of the Pleistocene are seen by some authors as early indicators of the beginning of the Anthropocene (Glikson, 2013; Malhi *et al*., 2016). More consensus on the notion of Anthropocene is found as we approach to the industrial revolution, although some authors still find the atmospheric changes induced by wet rice agriculture and the methane associated with cattle rising some 8000-5000 years before present valid to set the beginning of this era (Smith and Zeder, 2013). Many large-scale changes induced by humans after the Second World War in the so-called Great Acceleration (e.g. mass produced fertilizers, the amount of carbon dioxide in the atmosphere, plastics spread around the globe, invasive animal and plant species, and the growth of megacities, Figs. 1, 2 and 3) are undoubtedly associated with the concept of Anthropocene. In fact, the stratigraphic presence of radionuclides from nuclear bombs, such as long-lived plutonium-239 could well serve the purpose of marking the onset of the exponential phase of the human impact on the Planet.

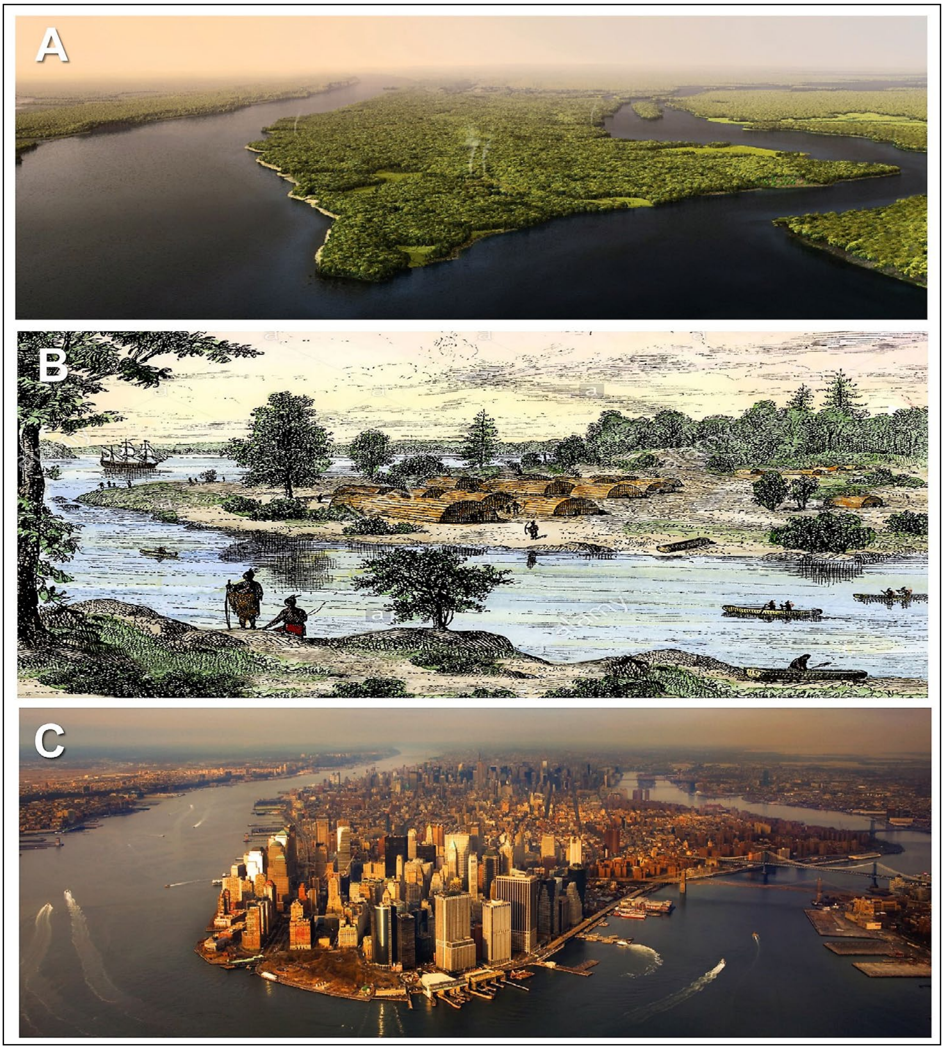

Figure 1. Transformation of the landscape, the case of Manhattan Island. Human settlements are at the centre of big environmental changes in the area that is now Manhattan. It was long inhabited by the Lenape Native Americans, who had a modest initial impact on the landscape (A, reconstruction). Human activity increased over the centuries with Native American building longhouses and deforesting Manhattan Island peaking in the XVI century at the time of the first encounters with Europeans (B, idealized drawing). A few centuries later, in a text-book example of an exponential dynamics, Manhattan Island became the most densely populated area in the United States, with the big city of New York developed in a commercial, financial, and cultural world landmark that has completely transformed the regional landscape with a significant impact on many ecological processes at a global scale (C, aerial photograph).

Although there are divergent opinions from the scientific community regarding the origin of the Anthropocene, most of the studies tend to focus on the negative impacts associated with anthropogenic activities. However, we think that the approaches used constitute a harsh judgement of our past with a skewed point of view, since they often do not include our undoubtedly success as living species on Earth. Likewise, they overlook that the negative environmental impacts driven by our main achievements have in fact been unintentional and unexpected. Thus, we aim here to review not only the main consequences underlying the notion and nature of the Anthropocene, but also its connection with human economy and social evolution. Additionally, we call upon to rethink ourselves and move forward considering the opportunities of change we still have ahead.

2. The nature of the challenge

The capacity of humans to alter the environment is very large and a good example is their role as a geomorphologic agent. To put it in perspective, the amount of earth that people in United States is moving every year would fill Grand Canyon in about 400 years, which is 0.01 percent of the time it has taken the Colorado River to create the canyon (Hooke, 1994). Sand, once a humble and mundane material, is currently the second most demanded natural resource due to an exponential increase in its demand for construction, generating an outstanding global market of severe environmental impacts (Fig. 4, Graviletea, 2017; Fig. 5). Loss of fertile soil is another global challenge associated with human activities. Since the rate of soil that has been removed from farm fields is about ten times the rate at which it is being formed by weathering processes, the very basis of our society might be at risk (Montgomery, 2007). Erosion and loss of fertile soil was, in fact, at the core of the collapse of the Mayan civilization in Central America and contributed to the collapse of the Viking settlements in Greenland and the civilization on Easter Island in the Pacific (Diamond, 2005).

Humans have been able to alter the planet for long time, with many unexpected and mostly undesired effects (see Tables 1 and 2 for examples and references). In fact, humanity itself is pushing the Planet to conditions in which our own survival will unlikely be possible. It is well understood by scientists and well assimilated by society that our emission of greenhouse gases, especially the CO_2 that we release by burning fossil fuels, is behind global warming and the associated climatic changes (Fig. 2). More than 8000 years ago we began to alter atmospheric CO_2 and that early global footprint is detectable and measurable (Smith and Zeder, 2013). Human migrations have already been associated in prehistory with the voluntary or involuntary transport of micro and macro-organisms and their forms of resistance (seeds, spores, eggs, propagules in general). Each large migratory movement and each military campaign of conquest of new territories over the last three millennia was associated with the mobilization not only of wheat, alfalfa, palm, goats or pigs but also of rats, the flu virus, bed bugs, the so-called ‘weeds’, cockroaches and leprosy (Diamond, 2005). Like all processes related to global change, the temporal evolution of these ‘biological invasions’ has been exponential. Today we have several hundreds of exotic species, from Argentine parrots to tiger mosquitoes, acacias, zebra mussels, red crabs, ailanthus or heaven trees, pampas grasses or Florida turtles, which have been established in thousands of areas of the planet by human action and are affecting the functioning of numerous ecosystems and causing significant economic losses and impacts on human health.

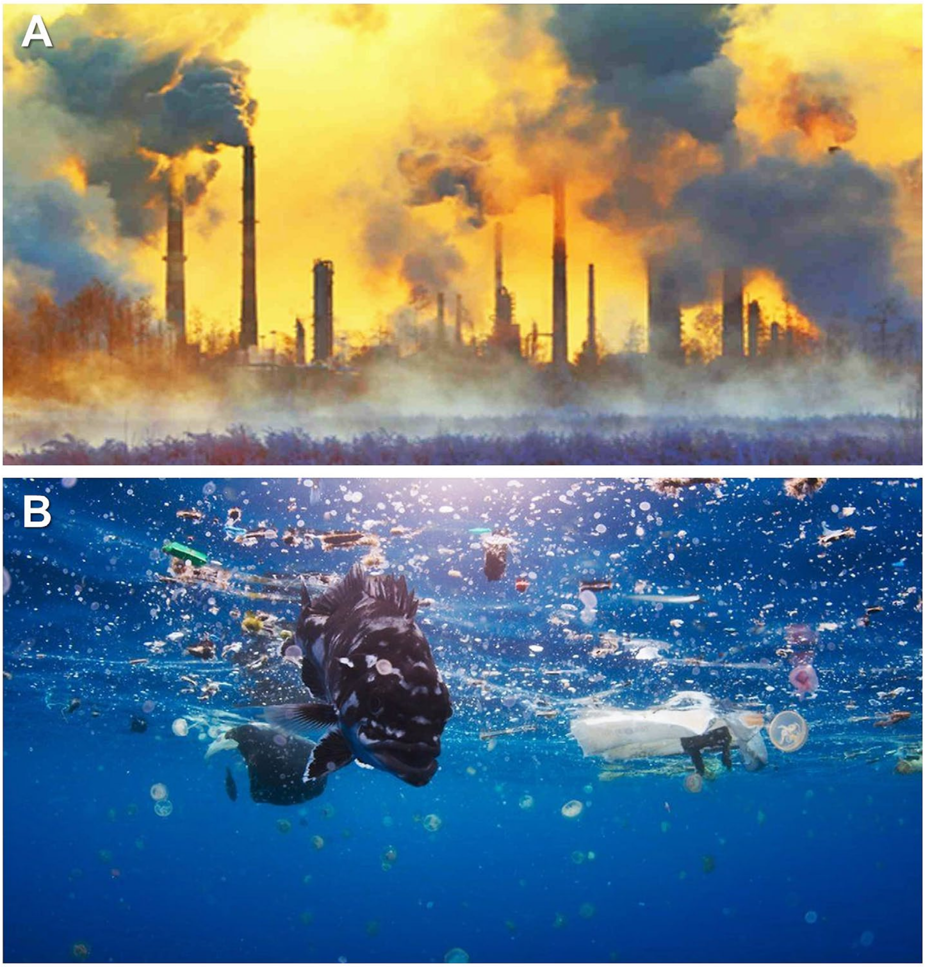

Figure 2. The human footprint in the planet follows an exponential increase, accelerating its impact over the last decades. A) Carbon footprint and the greenhouse effect. A greenhouse gas is a gas in the atmosphere that absorbs and emits radiant energy within the thermal infrared range. The major greenhouse gases in Earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide, and ozone. Without these gases, the average temperature of Earth's surface would be about −18 °C, rather than the present average of 15 °C. The recent rise in CO_2 levels in the atmosphere is mainly due to human activity, with the burning of fossil fuels as the leading cause and deforestation as the second major cause. In 2010, 9.14 gigatonnes of carbon were released from fossil fuels and cement production worldwide, compared to 6.15 GtC in 1990. B) Plastic footprint is becoming as environmentally dangerous as the carbon footprint, with marine plastic pollution as one of the most serious emerging threats to the health of oceans and a major hazard to marine biodiversity. More than eight million tons of plastics leak into the ocean every year, an amount set to quadruple by 2050. More than 268,940 tons of litter is estimated to be floating in the Earth's oceans. Most marine debris (80%) comes from trash and rubbish in urban runoff with plastic bags, food containers and packaging being the largest components of this plastic litter. Plastic debris in the Central Pacific Gyre exhibited a five-fold increase between 1997 and 2007, with the baseline in 1997 for plastic pieces outnumbering plankton on the ocean surface 6:1.

Climate change driven by human activities (especially the burning of fossil fuels) has been gaining greater prominence in planetary transformations becoming a key factor of global environmental change (IPCC 2014). Nowadays, the human incidence on the global hydrological cycle is very high because its interference by the direct consumption of water and its alteration of the surface runoff is combined through all kinds of infrastructures with human alteration of the climate of the planet. This double action has generated extensive areas where the change in water availability will be between 30 and 50% compared to the reference period 1970-2000 when two more degrees of average global temperature are reached (Figs. 2 and 3).

By extracting phosphorus from the soil (Fig. 6) and nitrogen from the air to make fertilizers and taking advantage of the carbon-based energy that was stored for hundreds of millions of years, human beings are increasing the productivity of the planet and accelerating certain parts of the cycles of matter and energy well above the natural levels. Human beings are breaking planetary records with unusual ease and speed. Perhaps one of the most surprising is that of being the only species capable of appropriating approximately a quarter of all the net primary biological production on Earth.

3. Unexpected results

> "Let us not, however, flatter ourselves overmuch on account of our human victories over nature. For each such victory nature takes its revenge on us. Each victory, it is true, in the first place brings about the results we expected, but in the second and third places it has quite different, unforeseen effects which only too often cancel the first".
>
> Friedrich Engels (Marx and Engels, 1987, vol. 25, 460-461).

Although the development of new technologies has allowed humanity to overcome the restrictions imposed by nature and environmental conditions and consequently increase their wellbeing, it has also had unexpected outcomes (Tables 1 and 2). Technology has not only been employed with good intentions (e.g. to create nuclear bombs and invest in military weapons). Likewise, although globalization has favored international trade and human global movement, it has also rippled effects among nations. A collapse in a remote region can have important consequences globally. Medicine advances have substantially increased human life expectancy; therefore, human population has grown disproportionally, reaching the biophysical limit of the planet and surpassing the biosphere's regenerative capacity (Meadows *et al*., 1972, Wackernagel *et al*., 2002). In this scenario, management of limited natural resources has become more difficult. Due to the lack of long-term planning of anthropogenic actions, the magnitude of these unexpected negative results is so that they are threatening the resilience of the Earth system. Among these unexpected results, of especial importance are: climate change, biodiversity loss, land-use change, alteration of biogeochemical cycles, stratospheric ozone depletion, ocean acidification, freshwater use, atmospheric aerosol loading and chemical pollution (Steffen *et al*., 2015).

Table 1. Early signals of the Anthropocene, facts, achievements and unexpected results. Key references are provided for each case.

Date	Era	Facts	Achievements	Unexpected effects	References
350000 to 110000 BCE	Palaeolithic	Early quarrying	Provisioning of raw materials and stones to create tools for food processing and hunting	Landscape transformation	Dakaris *et al.*, 1964
		Human hunting activities	Protein nutrition enables the development of human brain	Massive extinction of megafauna	Bailey, 1983
		Fire discovering and management	Warming technology, cook and hunting activities support. Changes in diet and parasite killing	Landscape transformation, deforestation	Bellomo, 1994
		Early gold mining	Tool creation that enable communities to cut animal fur for dressing or better hunting	Landscape transformation	McGeehan-Liritzis, 1983
11000 to 6800 BCE	Mesolithic	Gathering wild plant and animal husbandry	Improving diet by the domestication of species	Changes in biodiversity and species selection	Halstead, 1987
		First form of agriculture and human settlements	Seven founder crops were domesticated. Farming activities started with the domestication of several livestock species. Food supply was under control	Populations grew drastically, involving an increase in the dependence on and the intensification of agriculture and farming. Changes in land use. Deforestation. Biological invasions.	Lev-Yadun *et al.*, 2000
		Fishing	Improve diet by including fish protein and a source of phosphorus	Woodland transformation through logging for ship construction	Stiner and Munro, 2011
6800 to 3200 BCE	Neolithic	Agricultural revolution	Permanent settlements, diet improvement and the increase of human population	Landscape transformation through woodland cutting and burning, changes in biodiversity due to species selection and propagation	Johnson 1996
		Invention of wheel	Wheeled vehicles that facilitated terrestrial transport. Wagons	Breakdown of biogeographical barriers. Transport of living material beyond their area of original distribution. Biological invasions.	Anthony, 2010
3200 to 1300 BCE	Bronze Age	Bronze production	More durable materials and technological advance	Landscape transformation by mining activities and the development of the first anthropogenic material	O'Brien, 1997
		Big constructions as Egypt pyramids or the great wall	Development of human culture and the improvements of connections	Ecosystem transformation and the origins of cultural landscapes	Bloxam and Heldal, 2007
56 BCE – 400 CE	Roman Empire	Development of coastal settlements	Marine trade	Changes in marine food-webs and biodiversity	Lotze *et al.*, 2011
		Increase in raw materials demand	Bigger cities, first infrastructures and constructions	Changes in landscapes, vegetation and climate	Reale and Dirmeyer, 2000
5th to 15th century	Middle Ages	The age of discovery	Global exploration	Consequences in human demography, agriculture expansion, and trade and industrial intensification. Species introduction and biological invasions. Land use changes and cultural landscapes. Flow of wild organisms around the planet	National Geographic Society, 1991
16th century	First industrial Revolution	Watt steam engine	The steam engine replaced the water wheel and horses as the main sources of power for British industry. It became one of the main drivers in the Industrial Revolution. Machine tools and factory system of production	Emergence of the modern capitalist economy. Massive urbanisation and rural exodus. The growth in coal consumption gave rise to an unprecedented level of air pollution. Flow of wild organisms around the planet	Wrigley, 2013
19th century	Second industrial revolution	Steel, automotive industry	Horseless carriage, safer, faster and more efficient	Pollution. Increase of CO_2 release. SO_2 release and acid rain. Flow of wild organisms around the planet	Unruh, 2000
		World's first antibiotics	Paul Ehrlich (synthetic antibiotic chemotherapy) Alexander Fleming (penicillin). Control of bacterial infections, increase human health	Increase life expectancy, increase of human population	Chain, 1979
20th century	Third industrial revolution	Haber-Bosch Cycle invention	Chemical synthesis of nitrogen and ammonia. Explosive and fertilizers manufacturing	Nitrogen emissions to the atmosphere have been multiplied by 20. Water eutrophication. Nitrogen cycle degradation with unexpected consequences. Tropospheric ozone synthesis	Erisman *et al.*, 2008

Table 2. The most relevant anthropogenic activities for the functioning of planet Earth and their associated achievements for the humankind and unexpected results. Key references are provided for each case.

Date	Facts	Achievements	Unexpected effects	References
1950	Nuclear weapons	Increase of weapon power	Release and dissemination of radioactive isotopes to the atmosphere and marine environment	Prăvălie, 2014
1950	Green revolution	Increase in food production and the nutrition possibilities for the poorest people with the consequent increase of human population	Natural ecosystem destruction, genetic pollution, secondary chemical pollution derived from fertilizers and pesticides	Tilman *et al*., 2001
1960	Big water infrastructures (ie. Aswan High Dam)	Water availability for household consumption, agricultural uses, power production and recreational uses	River dynamics and ecosystem degradation with upstream erosion and sediment accumulation. Blockage of migratory routes for fishes and other species, and delta salinization among others	Shalash, 1982
1960	Mega mining industry	Mineral extraction for industrial development	Earth movement with the subsequent change in landscape geomorphology and erosion rates. Water and air pollution	Bury, 2005
1960 - 1970	Rare earth industry took off	Technological advance in clean energy and smart-phone and camera technologies	Ecosystem degradation and habitat destruction, water poisoning and chemical pollution derived from the secondary products used to extract and purify the rare minerals	Alonso *et al.,* 2012
1960 - 1970	Nuclear power- energy	Cheap, clean and highly efficient energy production	Emission of radioactive gases and effluents with health consequences	Nuclear Regulatory Commission, 1991
1980 - 1990	Spreading of megacities	Increase in population and per-capita consumption. Migration from rural areas	Greenhouse gases emission, high water and energy consumption and waste production	Newman, 2006
1988	First fiber optic cable	Global connectivity and information exchange around the world at very high speed	Anthropogenic noise, heat dissipation, electromagnetic field creation, alteration of seabed with direct consequences to flora and fauna	Meißner *et al.,* 2006
1990	Intense commercial flights	Democratization of traveling around the world, reducing trip times and costs	Release of huge amounts of CO_2 and CH_4 to the atmosphere and the acceleration of the effects of global warming	Brouwer *et al*., 2008
1990	Massive oil exploitation	Increase in transportation demand and industrial development	Hazardous waste and oil spills with dramatic consequences to biodiversity and ecosystems, pollution of surface and subsurface water and the atmosphere. Greenhouse gases emission and global warming acceleration	Karl, 2007
1990 - 2000	Artificial islands	Increase in residential and commercial infrastructure with touristic and economic interest	Degradation of abyssal ecosystems. Change in sea currents with the subsequent erosion of coast lines. Changes in fish migration. Increase in flood risk, eutrophication and water turbidity	De Groot, 1979
2000	Deep-sea tailing placement	Eliminate construction and industrial wastes from above ground with a very low cost	Sea bed degradation. Massive inputs of fine sediment, enriched in heavy metals derived from terrestrial ore deposit	Hughes *et al.,* 2015

Climate change refers to the global warming occurring in the planet with current average global temperatures 1.5ºC above pre-industrial temperatures (IPCC, 2014). This is partly due to the human-caused rise on emissions of greenhouse gasses such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), which atmospheric concentrations have increased 40%, 150% and 20%, respectively since the industrial revolution (IPCC 2014). As a consequence of emissions from fossil fuel combustion and industrial processes the atmospheric CO_2 concentrations have overpassed 350 parts per million (actually, it has recently reached 410ppm; Mauna Loa Observatory, Earth System Research Laboratory (ESRL) - National Oceanic and Atmospheric Administration (NOAA) 2017), triggering a rise in sea temperatures and a largescale coral bleaching and mortality (Veron *et al.*, 2009). For example, in the Great Barrier Reef as well as in the Coral Sea and the Caribbean Sea, the ocean acidity has reached risky levels (Hoegh-Guldberg *et al.*, 2007) and coral communities have been unable to recover afterwards (Pandolfy *et al.*, 2003; Mumby *et al.* 2007). Global warming is also enhancing drought periods at regional scale, which have increased in turn forest fire risk and desertification.

As a consequence of global warming, glaciers and ice sheets on polar and mountain land have started melting, which has caused a sea-level rise (~3.90 ± 0.4 mm/year over the past 40 years; Kench *et al.*, 2018) accentuated by the expansion of sea water due to ocean warming (Nicholls and Cazenave, 2010). In fact, sea-level rise is expected to reach between 0.6 and 1 m by 2100 (Lowe *et al.*, 2009; Melillo *et al.*, 2014), which has raised global concern about heavily populated coastal zones. Of especial concern are nations settled in small islands (Barnett and Campbell, 2010; Hubbard *et al.*, 2014; Weiss, 2015). Five low-lying reef islands from the Solomon Archipelago have already vanished due to sea level rise (Albert *et al.*, 2016).

Humans have drastically transformed the original landscapes over history and more than 40% of the Earth surface has suffered land-use changes mainly for urbanization and intensive agriculture. Anthropogenic activities such as mining, agriculture and construction of road networks have moved large amounts of soil and sediments (Wilkinson, 2005; Tarolli and Sofia, 2016), with increasing levels of soil erosion triggered by intensification of agricultural practices (García-Ruiz *et al.*, 2015). This intensification of agriculture has allowed humans to appropriate more than 40% of the net primary production of terrestrial ecosystems (Zhou *et al.*, 2018). Intensification of agriculture and human appropriation of the Earth surface have been possible partly through deforestation and clearcutting practices, which is well known to negatively impact biodiversity and key ecosystem services (MacDougall *et al.*, 2013; Lindenmayer *et al.*, 2016). An alarming case is the deforestation of the 17% of the Amazon rainforest surface to grow soya mainly for biofuel, almost reaching the Amazon tipping point (~20%) in which the hydrological cycle of the rainforest will be unable to support this ecosystem any longer (Lovejoy and Nobre, 2018). Increases in human pressures together with direct forest loss are threatening 90% of the Natural World Heritage Sites, recognized as some of the Earth's most valuable natural assets (Allen *et al.*, 2017).

The rate of species extinction has increased over the past centuries because of anthropogenic activities, being more intense for large-bodied vertebrates (Malhi *et al*., 2016). Species declines disrupt interactions and have effects on other species to which they are connected affecting the trophic chain and ultimately affecting the ecosystem (Mace *et al*., 2012; Johnson *et al*., 2017). Therefore, ecosystem services provided by species in the upper trophic levels will be lost on a first stage, and subsequently services provided by species lower in the food chain will also be affected (Dobson *et al*., 2006).

Anthropogenic activity has also led to human-mediated transit of organisms leading to profound habitat alterations due to a redistribution of species pools on the Earth at large spatial scales (Guerin *et al*., 2014; Martín-Forés *et al*., 2017). This global species redistribution has important economic, ecological and cultural impacts (Vitousek *et al*., 1996; Pimentel *et al*., 2005; Sala *et al*., 2000). Biological invasions have accelerated biodiversity loss affecting ecosystem structure (Vitousek *et al*., 1996), function and services (Hooper *et al*., 2012), and, eventually, human wellbeing (Mace *et al*., 2012).

Homo sapiens has largely affected all major biogeochemical cycles of the planet. As a result of the burning of fossil fuels and carbon emissions due to land-use change, atmospheric CO_2 levels have increased more than 30% above those of pre-industrial times, profoundly impacting on the global carbon cycle. Nitrogen and phosphorus biogeochemical cycles have been modified primarily due to the intensification of agriculture (Foley *et al*., 2005). Since the implementation of the Haber-Bosh process, atmospheric N_2 has been industrially fixed to produce fertilizers. Ultimately, fixed nitrogen turns out into reactive forms that pollute the environment, and cause eutrophication. Nitrous oxide, N_2O, is one of the most important greenhouse gases released to the atmosphere (Gruber *et al*., 2008; Rockström *et al*., 2009) and the main ozone-depleting substance (Ravishankara *et al*., 2009) contributing to exacerbate the ozone hole. Phosphorus has been extracted in large amounts to produce fertilizers (Fig. 6), which have flown to freshwater systems and ultimately into the ocean generating eutrophication (Steffen *et al*., 2015). When a critical threshold is crossed, accumulation of phosphorus in the ocean can cause anoxic events (Carpenter and Bennett, 2011). Anthropogenic activities such as coal burning releases large amounts of mercury into the environment, which is bio-accumulated in the trophic chain through methylation and have toxic effects (Beckers and Rinklebe, 2017). Human-mediated emissions of previously deposited mercury to the atmosphere as a result of industrial practices (Pirrone *et al*., 2010) are having global consequences of widespread contamination due to long-distance mercury atmospheric transport and deposition (Wang *et al*., 2016).

Two recent examples of ecosystem collapse are the Colorado River delta and the desiccation of the Aral Sea. One of the advantages of the ability to control and divert water fluxes is that humans have been able to settle even in areas where resources were scarce; such is the case of Los Angeles, the second city with greater number of inhabitants of the United States. In the 1930s, the diversion of the

Colorado River by dams and irrigation projects started taking place and associated with it disputes between the United States and Mexico for its control. More than 80 major diversions have moved water out from the Colorado River for agricultural and urban purposes in the United States and Mexico (e.g. major impoundments and water supply to big cities located nearby such as Los Angeles, Denver, Albuquerque, San Diego and Las Vegas; Parrish, 2003, Ward, 2017). The main problem was an over-allocation of the freshwater by which more water from the river was legally apportioned to both countries than the amount that normally flows (Gleick *et al*., 2002). Consequently, the Colorado River desiccated over time before reaching the sea, resulting in a pronounced decrease of nutrient and sediment flowing into the delta (Fradklin, 1981). Thus, the river channel got straightened, and the hydrogeology of the system changed drastically. This led to endemic biodiversity extinction and a rise in salinity, and triggered the collapse of the Colorado River delta ecosystem (Kowalewski *et al*., 2000), which constituted a key stopover in the migration routes of birds and supported high levels of marine biodiversity.

The Aral Sea (Fig. 3) was formerly the fourth inland water surface in the world and received inflows from the rivers Amu and Syr. The Aral Sea was located within several nations, including Uzbekistan, Turkmenistan, Kazakhstan, Afghanistan, Tajikistan, and Iran. Changes in its water level before 1960 were almost in constant equilibrium. From the early 1960s, human beings have misused the freshwater resources from which the Aral Sea depends. Due to over diversion for irrigation purposes in this rapidly industrializing agricultural region, there was a reduced inflow from the two rivers (Micklin, 1988). This occasioned dramatic changes in the water balance, morphology, and ecology of the Aral Sea. As a result, a human-induced desiccation of the Aral Sea started in which flow to the Aral Sea decreased, its salinity and pollution increased, and its surface diminished. The desiccation of the Aral Sea and the subsequent desertification processes in the region reduced the vegetation and the water bodies of the area, leading to the extinction of indigenous fishes such as *Salmo trutta aralensis* and having important consequences for the fisheries and the food supply of human population located nearby (Micklin, 2007). Additionally, dust and salt storms are currently common in the area, which increases aerosol concentrations in the atmosphere (Indoitu et al. 2015) and favors extreme temperatures (Small *et al*., 2001); thus, a complete desiccation of the Aral Sea would exacerbate regional climate change (McDermid and Winter, 2017).

Another example of ongoing ecological collapse enhanced by anthropogenic activity that is of major concern nowadays is the threat to honeybee colonies that are negatively affected by pesticides, pathogens and climate change (Dennis and Kemp, 2018).

The anthropogenic impacts on Earth functioning are causing political confrontations among countries. The existence of human-made barriers, fences and walls to impede human movements across countries and regions all over the world (Fig. 7) is an expression of these tensions. Human dependence on non-renewable sources of energy has led to the nuclear disasters of Chernobyl (Ukraine, 1986) and Fukushima (Japan, 2011). Likewise, dependence on fossil fuels has derived in warfare among nations worldwide over the past decades with important consequences for humanity. Many wars and diplomatic clashes are due to water conflicts exacerbated by climate change, which is becoming a real security problem (Barnet and Adger, 2007).

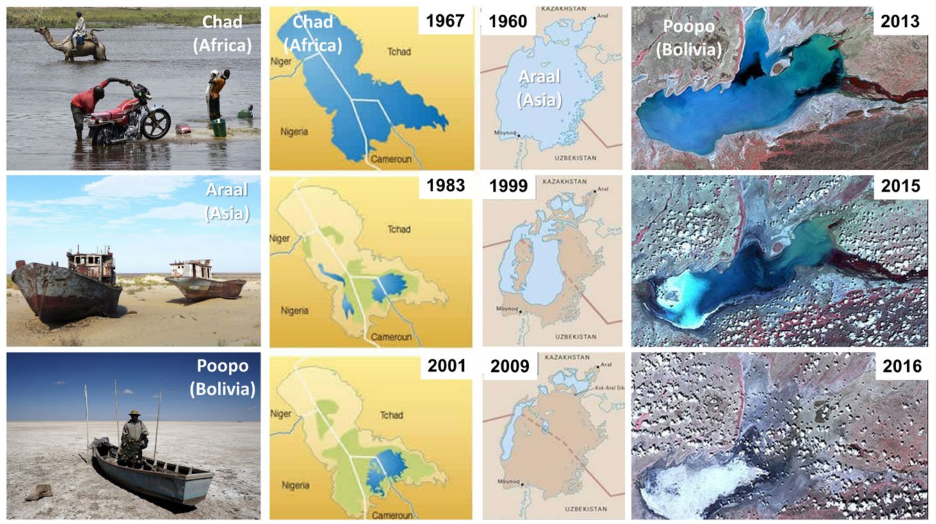

Figure 3. Vanishing lakes and seas, the result of an increasing pressure on freshwater resources. Lake Chad is a historically large, shallow, endorheic lake in Africa, naturally variable in size but showing an unprecedented shrinkage over the last decades. Lake Chad provides water to more than 30 million people living in the four countries surrounding it (e.g. Chad, Niger, Nigeria and Cameroon). In the 1960s it had an area of more than 26,000 km^2 (the fourth largest lake in Africa). An increased demand on the lake's water from the local population has likely accelerated its shrinkage over the past 40 years. United Nations Environment Programme has quantified that Lake Chad has shrank by as much as 95% from about 1963 to 1998. However, more recent satellite studies have shown modest improvement over previous years. The Aral Sea was another endorheic lake, lying between Kazakhstan and Uzbekistan. The shrinking of the Aral Sea has been called "one of the planet's worst environmental disasters". The region's once-prosperous fishing industry has been essentially destroyed, bringing unemployment and economic hardship. Formerly one of the four largest lakes in the world with an area of 68,000 km^2, the Aral Sea has been shrinking since the 1960s after the rivers that fed it were diverted by Soviet irrigation projects. By 1997, it had declined to 10% of its original size, splitting into four small lakes. NASA satellite images (August 2014) revealed that for the first time in modern history the eastern basin of the Aral Sea had completely dried up becoming now the so-called Aralkum Desert. In an ongoing effort in Kazakhstan to restore the North Aral Sea, a dam was completed in 2005 with the water level rising by 12 m over the 2003 level in 3 years, and salinity dropping to values compatible with some fishing. Lake Poopó is a large saline lake located in a shallow depression in the Altiplano Mountains in Bolivia, at 3,700 m a.s.l. The permanent part of the lake body covered approximately 1,000 km^2 and it was the second-largest lake in the country. In 2002 the lake was designated as a site for conservation under the Ramsar Convention, but 3 years later the lake had completely dried up, leaving only a few marshy areas. Although the lake has dried up completely a couple of times in the past, it does not appear that it will recover this time due to a combination of factors: the shrinkage of the Andes glaciers, the increased drought associated to climate change, and the continued diversion of water for mining and agriculture in the area.

4. The main driver of global change: the non-sustainable economy

One hypothesis that has been largely accepted in economy is the environmental Kuznets curve hypothesis: economic growth would not constitute a threat to ecological sustainability when further and higher levels of development and technology are reached by society (Kuznets, 1995). However, Kuznets hypothesis did not take into account the existing feedback between economy and ecology, and the effect that environmental degradation can exert on industrial productivity, trade and politics as well as on many other aspects of human societies (Stern *et al*., 1996). Nowadays we know that economic growth alone is not enough to improve environmental quality (das Neves *et al*., 2017), in fact, as a consequence of the bubble of population growth and economy, degradation of environmental resources has increased, with a direct relationship between economic income and CO_2 due to energy consumption (Kaika and Zervas, 2013).

In current capitalist societies, modern economies are driven towards perpetual economic growth. Market economies mainly rely on technological efficiency and improvements that allow driving down costs and producing more with less investment; consequently, fewer people are needed to produce the same goods, what leads to unemployment. This in turn leads to diminished spending power, a loss of consumer confidence and further reduces consumption demand. Therefore incomes fall and the economy falls into a spiral of recession or depression (i.e. unsustainable degrowth) that ultimately deteriorates social conditions (Jackson, 2009). The underlying problem is that human beings have understood prosperity as an ever-expanding economic paradise, in which financial incomes, goods consumption and growth rate must necessarily increase in order to enhance human well-being. This traditional idea of prosperity generally ignored environmental concerns and, in the cases where they were considered, they were always subordinated to economic growth (Schneider *et al*., 2010). In fact, Moore (2017, 2018) even proposed the term Capitalocene to refer to capitalism and patterns of power, capital and social inequality as the main cause driving ecological impacts. The traditional dynamics of economic growth in capitalist societies push it towards one of two states, either expansion or collapse. Thereby, economic growth is unsustainable in its current form, while economic degrowth appeared as a socially unstable alternative.

The financial crisis that took place in 2008 led the world to the brink of economic and social disaster shaking the traditional growth model to its foundations and forced us to rethink about alternatives and imagine a sustainable economy beyond growth (Rockström and Klum, 2012; Johnsen *et al*., 2017). As a response to this financial crisis that fell into economic, social and environmental crisis, the 'sustainable degrowth movement' has emerged (Martínez-Alier, 2009, Schneider *et al*., 2010, Demaria *et al*., 2013). This movement is defined as an "equitable downscaling of production and consumption that increases human wellbeing and enhances ecological conditions at the local and global level". The traditional gross domestic product (GDP) as an indicator of national success has failed to value everything that is not in the market. Thus, 'green GDP' which considers some of the environmental consequences of growth, the genuine progress indicator (GPI) that considers income distribution or the gross national happiness index used in Bhutan have been alternatively proposed (Robert *et al.*, 2014).

Figure 4. Sand, the second most demanded natural resource after water. The rapid urban growth of the planet has turned this humble material into a scarce commodity extracted and transported over large distances (A-E). Its overexploitation has devastating environmental effects. Everything around us contains sand: cement, glass, asphalt and even plastic. United Arab Emirates is one of the largest importers of sand, despite living surrounded by a sand desert: as a result of wind erosion, this sand is not suitable for cement. In recent decades, Dubai has imported huge amounts of sand from Australia for the construction of complexes and buildings. China has built seven artificial islands in the Spratly archipelago but at the head of the countries that are artificially increasing their territory is Singapore, which is also the largest importer per capita of sand in the world (D). In the last 40 years, it has grown 130 square kilometers on land (20%), using some 637 million tons of sand. And it still intends to extend 100 square kilometers more before 2030. The main suppliers are neighbouring countries: Indonesia, the Philippines, Vietnam, Myanmar (formerly Burma) and Cambodia. In the summer of 2017, the Government of Vietnam announced that if the pace of demand continued as before, by 2020 it would run out of sand. For countries like Spain (E), which live on tourism, the erosion of beaches can wreak havoc on the economy. The problem is that the formation of sand is a slow natural process, which requires years, and the demand is greater than the natural regeneration and supply capacity of ecosystems. The sand business is so lucrative that it has become a worldwide phenomenon, expanding at the same speed as urbanization. What a quarter of a century ago was a mundane raw material, abundant and cheap, is today a scarce resource (Gavriletea, 2017).

Reaching an alternative sustainable development paradigm that integrates social, environmental and economic goals together within the biophysical limits of planet Earth seems crucial. However, without a profound change in the political institutions and in the society as a whole, the current capitalist model has no easy route to a steady-state position.

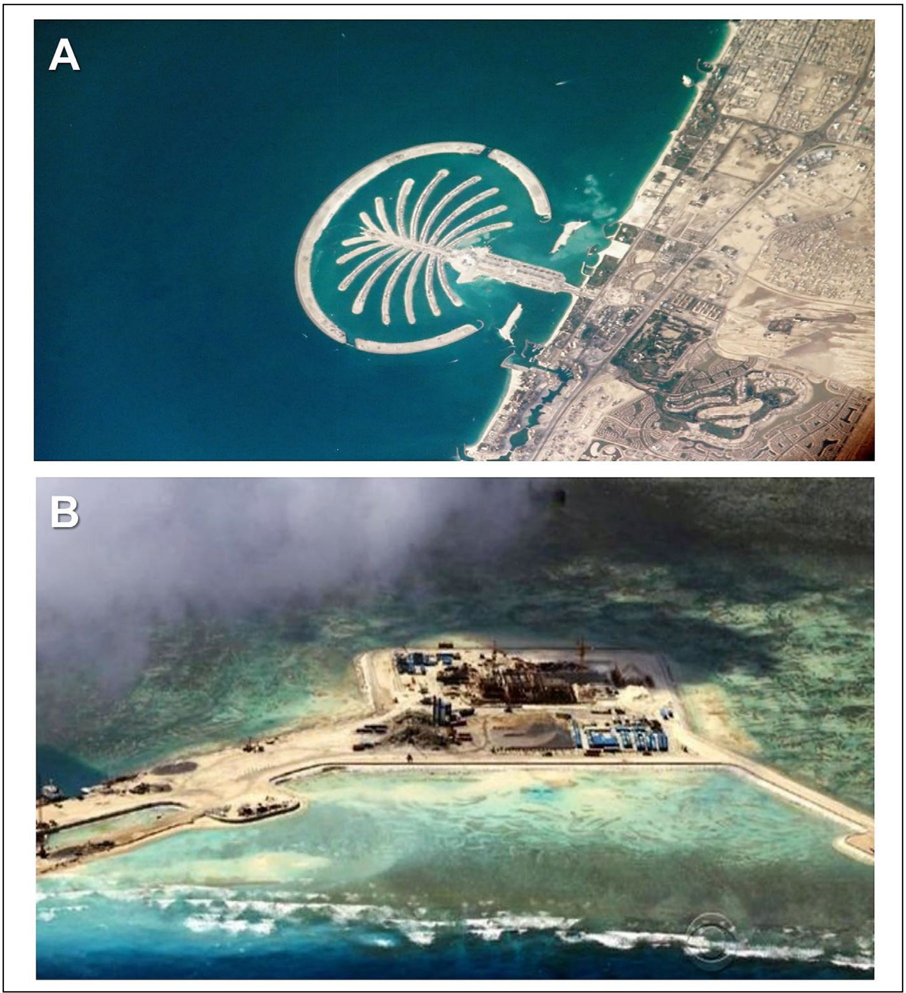

Figure 5. Artificial islands. A) The resort Palm Jumeirah, Dubai, United Arab Emirates, is under construction on reclaimed land on the waters of Dubai's Persian Gulf coast. This human-made palm-shaped structure displays 16 large fronds framed by a 12-kilometer protective barrier. When completed, the resort will sport 2000 villas, 40 luxury hotels, shopping centers, cinemas, and other facilities, and support a population of approximately 500,000 people. B) China claims nearly all of the South China Sea, installing military facilities on artificial islands built on the Spratly and Paracel reefs. Over the first year, the country has built 290,000 square meters of facilities, including underground storage, administrative buildings and large radar installations.

5. The awakening: realizing the consequences and searching for solutions

Despite all these evidences on the environmental impacts directly and indirectly induced by *Homo sapiens*, we keep denying their importance, their causes and their consequences (McCraight and Dunlap, 2011). The idea of unlimited growth that has been promoted by the economic sector crashes with the scientific knowledge about the existence of planetary boundaries (Rockström *et al*., 2009). These boundaries are primarily thermodynamic or biophysical (Steffen *et al*., 2015) and are characterized by simple variables as nitrogen concentration or the increase of sea level rise, so it is possible to estimate when one of these limits has been overcome. A limit represents a tipping point after which the system behaves differently and recovery is unlikely. Most estimations show that we are very close to trespassing or have already passed these limits, particularly regarding biodiversity loss and global biogeochemical cycles such as that of nitrogen. Unfortunately, the scenario is complicated by interactions among drivers and factors determining these limits. For example, global warming due to the accumulation of anthropogenic CO_2 in the atmosphere increases temperature and decreases seawater pH and carbonate accretion (Hoegh-Guldberg *et al*., 2007). This triggers a decarbonation process with the subsequent CO_2 emissions to the atmosphere, which exacerbates climate change and its effects. These cascade effects and pitfall loop add a new level of complexity clouding our judgement and our capacity to slow down the processes involved and to return to a safe operating space. It could be argued that the notion of planetary boundaries is recent and that our society has strong inertias so we are currently unable to reverse our impacts. However, the truth is that the ecological signal for these impacts has been there in front of us for many years so we cannot turn a blind eye.

Many ecosystems have collapsed around the world because we have crossed the limits of sustainable exploitation. Good examples of this ecological pandemic are the global disappearance of lakes and inner seas (Fig. 3) and the increased frequency of earthquakes because we have squeezed the very last drop of many underground aquifers. The consequences of this 'toxic relationship' that we have maintained with the Earth for many centuries are visible now with the tensions generated by human migration: it is expected that 150-300 million people will be displaced by climate and global change related issues by mid XXI century (Gemenne 2011). Thus, the environmental problem has turned back into economic and social matters; in this context, physical barriers to stop migrations seem unlikely to be a solution (Fig. 7). It is time for action and the faster we are able to plan the transition to a more sustainable development the cheaper will be the exchange (Stern, 2006).

As a global society, we have shown that we can work together, modify our production models and be committed to the care of the common house, once we have the right information readily available. The application of the Montreal Protocol to compensate for the hole in the ozone layer (Velders *et al*., 2007) as well as the signature of the Paris agreement are good examples of this global stewardship (Schellnhuber *et al*., 2016). However, the long term agenda needed for big changes is complicated by issues like the adoption of these commitments, which has been led by industrialized countries, diluting the responsibilities of all those who do not identify themselves as world powers. There is a need to generate global frameworks from which to work in more sustainable development models, where economic growth is compatible with the care of ecosystems and with our quality of life. In this sense, the 2030 Agenda proposed by the United Nations, allows each country to design its environmental and economic strategies, pursuing global objectives, but from a local perspective (Biermann *et al*., 2017). Sustainability becomes transversal and permeates aspects such as education, innovation and global alliances, which are essential to a true change in our relationship with the planet.

Figure 6. Intensive mining: unsustainable, dangerously polluting and at the origin of many minor to moderate earthquakes. A) Copper mining in Pima County Arizona - The mine is more than 3.5 kms long by 2.2 kms wide and 400 m deep with benches of 15 m high. Copper mining wastes constitute the largest quantity of metal mining and processing wastes in the United States. 99 tons of waste are generated per ton of copper, with even higher ratios in gold mining, because only 5.3 g of gold is extracted per ton of ore so a ton of gold produces 200,000 tons of tailings. B) Togo phosphates mining. Processed phosphates pose a serious threat to our environment. Substantial phosphate reserves are known to exist, but fears over future supply still remain. Nowadays, phosphorus is mostly derived from phosphate rock mining. Around 170 million tons (Mt) of phosphate rock is mined every year and the majority of this goes to the agriculture industry. Most phosphorus comes from North Africa (Morocco and Tunisia) and the Middle East (Egypt and Jordan), producing around 75% of the world's phosphate. There are well-established geopolitical concerns about the location of the majority of phosphorus reserves.

At the same time that we change the development model, other multidisciplinary initiatives emerge around the world to amend the impacts generated so far while facing future changes. For instance, the Aichi Targets, the Bonn Challenge, 20 x 20 initiative and the AFR 100 aim at the restoration of large-scale ecosystems and at the adaptation to climate change (Aronson and Alexander, 2013; Chazdon *et al*., 2017). These same initiatives have reached purely human ecosystems such as cities, where most of the population concentrates. Here, sustainable development goes hand in hand with the recovery of green infrastructures and the implementation of nature based solutions that provide not only key ecosystem services such as water or air purification, but also safer and more resilient urban environments linked to green entrepreneurship environments (Maes and Jacobs, 2017).

Figure 7. Walls and barriers in the world have many direct impacts and impose difficulties for demographic adjustments and migrations. A) The Great Wall of China is the largest and one of the oldest walls in the world, built primarily along an east-to-west line across the historical northern borders of China to protect the Chinese states and empires against invasions of many nomadic groups of the Eurasian Steppe. The entire wall with all of its branches is 21,196 km long. Many countries have gone on a massive barrier-building campaign after the World War II, and particularly after the Berlin Wall fell in 1989, with the number of walls increasing from 15 then to about 70 now (H). Important examples of recent walls and barriers are: B) Mexico-US border, C) Kuwait-Irak barrier, started by Saddam Hussein, D) the Israel–Gaza security barrier constructed by Israel in 1994 between the Gaza Strip and Israel, E) the peace lines or peace walls in Northern Ireland that separate predominantly Republican and Nationalist Catholic neighbourhoods from predominantly Loyalist and Unionist Protestant neighbourhoods, F) Melilla border fence between the African Spanish colony and Morocco, and G) the Kolomoyskyi Wall at Ukraine-Russian border. Important triggers to build walls have been the wake of the Arab Spring and the Syrian refugee crisis, terrorist threats after September 11, 2001, and the fear of Russian invasions. Many important walls and barriers have been built in all main continents except Oceania (I).

6. Final remarks

We live as extraterrestrials on planet Earth. We think about conquering Mars, desperately seeking a way out of the ecological-social ravages that we cause on Earth. However, this exit does not solve the basic problems that humanity has created, so we are bound to make the same mistakes repeatedly. We must move forward with the basic ecological literacy of society. Our ultimate goal cannot be to 'improve the welfare of humanity' (however important it may seem to us), but the sustainable functioning of a planet that makes our existence possible within a rich and diverse biosphere. Our fantasy about human exceptionalism, considering ourselves apart and above nature without being subject to its laws, makes us pay little attention to the destruction that we are causing of the plot of life. As Nate Hagens and Richard Heindberg (in Heindberg, 2011) have developed extensively, we do not have a problem of scarcity of resources, but rather of excess of expectations. The goal of the new model of human wellbeing that is emerging in the Anthropocene must be fitting our way of life to the ecological limits imposed by the planet. This new model is based on the notion that wellbeing depends on enabling a life of dignity and opportunity to every human being but protecting at the same time the integrity of Earth's life-supporting systems. The conceptual framework, which is visualized as a 'Doughnut' with inner social boundaries and outer planetary boundaries (Raworth, 2017), may provide a much-needed bearing for humanity's 21st century progress.

Acknowledgements

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