Chapter

Introductory Chapter: The Present Global Ecological Crisis in the Light of the Mass Extinctions of Earth History

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1. Introduction

Extinctions usually happen. They are part of the evolutionary processes. Like individuals, species also have a lifespan, which means that they go extinct naturally without any external forces over a period of time. It is called normal or background extinction rate. When the level of extinction is much higher than the background extinction rate, we talk about mass extinctions. Mass extinctions occur at different temporal and spatial scales. We consider both the local disappearances of frog populations and the Late Cretaceous impact event as mass extinctions. Mass extinctions may have different causes, but their dynamics and patterns are similar in many respects. During the Earth's history, several mass extinctions have extirpated species globally from time to time. These global mass extinctions usually have some external causes as number one triggers, such as climate change, volcanic outbursts, or impact events. We refer to the Earth's largest mass extinctions during the Phanerozoic as the "Big Five."

By the twenty-first century, mankind has fallen into the mess of global problems (into a global ecological crisis) which endanger not only its welfare, peace, and development but its survival and mere existence as well. It is the time of uniting and addressing the issues of common concern; however, mankind has reached this era torn to 195 independent national states without having an authorized global organization which would represent common interests of mankind efficiently.

Mankind forms a single family all over the world regarding its origin, and natural processes are basically global, since climate change, overpopulation, contamination of oceans, air pollution, and radioactivity do not know state borders. Science is also a global international activity, the common treasure and work of mankind.

The report *Our Common Future* published in 1987 by the World Commission on Environment and Development of the UNO defines sustainable development as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1]. Sustainable society is a global form of operation of mankind aimed at but not yet realized, which ensures the survival of humanity, the long-lasting preservation of environmental and social living conditions, the protection of human environment (climate, atmosphere, water, soil, and biosphere), the operability of the biosphere and the protection of its biodiversity, the operation of the economy, the reduction of social tensions (inequality, famine, extreme poverty, crime, riots, terrorism, aggression, wars), the scientific and technological development as well as the rise of mankind, and the preservation and development of our natural and cultural heritage long-term (even through hundreds or thousands of years). The establishment of a sustainable society depends on macro-level (law, political will, consensus, public support) and micro-level conditions (affecting the everyday operation of individuals, families, companies and small communities). When scientists make an effort in order to save an endangered species [2, 3], they might not consider the complexity of the whole problem, which would make the work necessary.

The sustainability of the human society is endangered by global problems of our time, which are in close relationship with each other as well. Among global problems, overpopulation (global population explosion) has a central role, since more people have a larger ecological footprint, consume more, pollute more, occupy more space from natural ecosystems, and emit more carbon dioxide through their activities. Overpopulation directly intensifies global climate change, global biodiversity crisis, deterioration of the global state of the environment, and urbanization and reduces the extension of rain forests and natural habitats as well as the nonrenewable energy sources (fossil fuels, natural building materials, stock of water). At the same time, increasing population results in higher population density as well; this directly enhances aggression [4] and the risk of epidemics.

Global environmental crises appear at the macro-level (at the level of the society, mankind, and politics); they relate to each other on a large scale, in an interaction network. Global overpopulation results in biodiversity crisis, this reduces the climate regulation ability of the biosphere, and this results in climate change. At the same time, overpopulation contributes directly to climate change through energy consumption, combustion of fossil fuels, and the change of land use [5]. Climate change results in significant transformation of the biosphere [6, 7]. Besides these, overpopulation directly results in social crisis, increasing aggression, as well as epidemics. Biodiversity crisis (extinction of key species and the reduction of habitats) and climate change induce each other in a positive feedback loop, since through the biosphere, climate-regulating ecosystem services are weakened. Overpopulation and social crisis are in a similar positive feedback loop, since it is proven that poverty and hopelessness increase the number of offspring. People living in poverty have nothing to distribute, nothing to base the future on; that is why many of them change from K- to r-strategy, trusting that some of their offspring will survive. Social crisis and public health crisis as well as social crisis and aggression (violence, crime, terrorism, riots, and civil war) are in a similar feedback loop. These interactions are shown in **Figure 1**.

Many scholars suggest that we are undergoing a global mass extinction. It is usually referred to it as the sixth mass extinction after the "Big Five." It is debated whether the global mass extinction is approaching [8], it has just begun [9], or it is in a more advanced stage [10]. The current extinction rates are about 1000 times the background extinction rate according to a recent study [8]. Three hundred twenty-two terrestrial vertebrate species have become extinct since 1500 [11]. Ceballos, et al. [10] studied 177 mammals, and they found that they have lost at least 30% of their geographical ranges and more than 40% of the species have experienced a range shrinkage above 80%. Fifteen to thirty-seven percent of species are going to extinct based on mid-range climate change scenarios for 2050 [12].

The current/approaching mass extinction is different from the past mass extinctions, because a single species initiates the biotic crisis. Global population is increasing exponentially mainly because of the economic models based on growth and medical improvements. As a result, the human population is now over 7 billion. Not only the number of people causes environmental issues. Thanks to technical

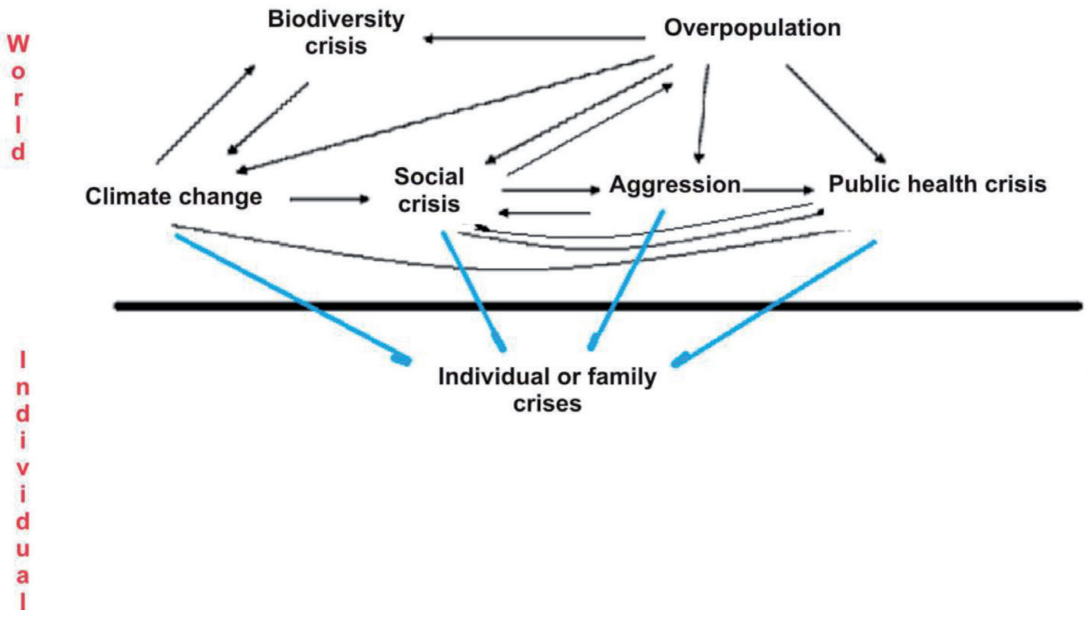

Figure 1.
Interaction network of global crisis phenomena and their relationships with individual crises. Black arrows mean macro-level connections, whereas blue arrows mean direct threats in individuals' life.

improvements and overconsumption, the humans' environmental footprint is continuously increasing, and as a result, it is not sustainable anymore [13]. The Earth has become too small for us. Direct anthropogenic effects (hunting, habitat destruction, pollution) are lowering the diversity and the abundance levels globally. Anthropogenic climate change as an indirect human effect poses challenges to the wildlife. Climatic changes are so rapid that plants and animals may not be able to adapt in the future, and eventually they will collapse. Climate change and direct human effects do not act independently but synergistically reinforcing each other's effects.

We consider the biosphere as an industry providing services for us. We are exploiting the Earth because of our economic thinking. We put ourselves right in the middle of the ecosystem and subordinate everything to our service. The problem is that the biosphere does not work as an industry and, beyond a certain point, it cannot be reproduced. As a result of increasing human pressure, we are reaching the tipping point of a global collapse. However, we cannot predict this tipping point, and we do not know much about the phenomena prior to collapses.

About 200 species extinct every day which is a rate of extinction comparable with past global mass extinctions. According to Newbold et al. [14], the level of natural biodiversity is so low on two-thirds of the world's land surface that it might already jeopardize normal ecosystem functioning and human well-being. We have only a rough estimation for the global number of species which is above 10 million, but we know only 15% of them [15]. Biodiversity loss is also an estimated number. Despite the possible inaccuracies of estimations, researchers agree that global biodiversity loss is significant. However, biodiversity loss cannot tell us how far we are from a possible collapse. The diversity levels before the big mass extinctions did not predict the points of the collapses, either.

High diversity is the sign of a healthy ecosystem; hence, its significant decline indicates an ecological crisis. A great diversity drop preceded the big mass extinctions; however, changes in diversity do not always show the severity of the ecological problem and a more advanced stage of a collapse. Diversity may remain constant before extinctions. This happened during the Early Jurassic (Toarcian) mass extinction according to Harries and Little [16]. Diversity does not necessarily have a nadir at the extinction boundary, for example, when mass extinction occur before the low point of the environmental perturbation or in case of delayed extinction when survivors and opportunistic invaders compose a transient mixed biota. Sometimes, the diversity remains constant during dominance shift when the collapse of the dominant elements does not cause significant structural changes in the ecosystem. It may also happen that the diversity level is still high but important ecosystem elements are already missing; hence, collapse is much closer than the hypothetical point suggested by biodiversity levels. Therefore, diversity values cannot necessarily tell how far we are from a collapse, and mass extinction can happen even in case of higher diversity. Spatial scales and taxonomical levels also affect diversity changes. Towards lower levels and scales, diversity loss is usually greater, though this rule is not set in stone.

The lowest diversity levels are usually at the beginning of the recovery phase [17, 18]. Diversity starts to increase rapidly but gradually after a short gap following a dominance shift [19], except when environmental perturbation is prolonged. For example, after the Late Permian mass extinction, a series of volcanic bursts delayed the recovery for 10 million years [20]. However, a sharp diversity increase after the extinction does not always reflect the level of recovery, but a short-lived opportunist blooms [21]. The environment has a great role both in mass extinctions and recoveries, especially at global level. However, at local spatial scales, biotic factors may be as important as environmental factors.

In summary, diversity is an important indicator of ecological crisis, but it does not necessarily give reliable information on the advancement of a collapse. Because of the complexity of ecosystems, diversity does not always reflect the severity of a crisis.

Past mass extinctions and the recent ecological and biodiversity crisis must have some similarities, common points which can take use closer to understanding collapses. Hence, we should compare and combine our knowledge on recent biotic crisis and collapses with that of past mass extinctions.

The Late Ordovician mass extinction, about 445 million years ago, wiped out 57% of marine genera and 60–70% of marine species [22]. Two pulses of extinctions caused the massive loss of species. The Late Ordovician mass extinction is the only "big" which is explained by purely climatic reasons. The first wave of extinction was caused by glaciation and the second one by subsequent global warming. Glaciation exterminated warm-loving taxa with both small and large ranges. The tropical realm suffered the greatest loss. The global warming event mainly caused the extinction of wide-ranging, cosmopolitan, cold-loving taxa [23]. The Late Ordovician marine mass extinction probably started with no delay right at the beginning of environmental changes [24]. The pertained high temperature after the mass extinction, however, was likely to hinder the recovery at a global scale [23]. This does not mean that quick recoveries could not happen regionally [25]. The Late Ordovician mass extinction, which was the second largest, did not necessarily caused huge structural changes in the ecosystems [26, 27]. It must be noted that Erwin [27] debates the large magnitude of the Late Ordovician event.

The Late Devonian mass extinction began about 380 million years ago. 50% of the genera and at least 70% of species were lost [28]. It includes two events with different dynamics. The Kellwasser event showed the gradual turnover of the marine realm because of the gradual environmental changes presumably caused by tectonic movements [29]. It was not followed by great structural changes, and some researchers do not even consider it as a real mass extinction. The second event was larger and more destructive. The Hangenberg event resulted in a sudden faunal change. It affected all major vertebrate groups. Both the ecology and the environment were lost and caused the restructuring of the vertebrate ecosystems worldwide [29]. The recovery was probably delayed [27], and the fauna was very cosmopolitan at the beginning [30]. The cause of the second event is debated, but it must have been sudden and of large magnitude. Perhaps, the most likely reason for the Late Devonian crisis was the Siberian trap volcanism. De Vleeschouwer et al. [31] suggest that the Late Devonian events were astronomically forced.

The Late Permian event was the most devastating of all mass extinctions about 252 million years ago. More than 80% of genera and 90–95% of species died out [22]. It was probably triggered by a long series of volcanic outbursts of the Siberian Traps [32]. The environmental consequences were severe anoxia and acidification in the oceans, elimination of the ozone layer, and a prolonged greenhouse effect [33, 34]. In the terrestrial ecosystems, the physical environment deteriorated: the erosion increased, the sediments and soils altered [32]. The authors suggest that the Late Permian mass extinction was not sudden and simultaneous [30, 35]. In the oceans, it was relatively faster. On the landmasses, plants and herbivores extinct later in time [32]. The recovery was considerably delayed: it took about 10 million years because of the constant environmental perturbation. However, it could be quicker locally in case of more favorable environmental conditions, for example, in well-oxygenated marine environment or under locally favorable climate [36, 37]. The recovery was selective in terms of geographic location, as well. Higher altitudes, perhaps, recovered earlier than the tropical realm also because of quicker environmental improvements [36, 38]. After the mass extinction, the marine community reorganized to a large extent, probably, because of the loss of dominant elements [27, 32].

The Late Triassic mass extinction happened about 201 million years ago and extirpated 48% of genera and 70–75% of species [22]. It was triggered by the sudden volcanism of the Pangaean Atlantic rifting. The volcanic outburst caused significant geochemical changes: it elevated atmospheric CO_2, SO_2, and PAH levels. The marine and terrestrial ecosystems collapsed immediately and simultaneously [39]. The Late Triassic event was quick and not as massive as the previous mass extinctions at genus level. The major elements of the ecosystem structures were preserved [27]. Boucot [30] debates this and suggests that the level-bottom marine ecosystems thoroughly reorganized. The extinction of competitors gave the opportunity for the dinosaurs to rise and dominate in the next period.

The youngest and publicly most well-known “Big Five” is the Late Cretaceous mass extinction which eliminated about 48% of genera and 70–75% of species 66 million years ago [22]. It belongs to less massive extinctions at genus level. An impact event was likely to initiate the global crisis with regional differences. Probably, widespread fire, sun-blocking dust cloud, perhaps climatic cooling, increased SO_2 level, and the related acidification were the main consequences of the asteroid collision. The collapse was larger and more serious closer to the impact area with greater drop in diversity [40, 41]. The extinction was sudden and simultaneous among diverse taxa, which refers to a common great and abrupt impact [42]. It was selective affecting specialized species and terrestrial plants more seriously [43, 44]. The recovery of the environment and the ecosystems was quick but gradual after the crisis [45, 46]. The diversity increased rapidly [47]. Most ecosystems did not go through thorough restructuring (e.g., [30]). The smaller magnitude of the event and the quick recovery might explain this [27]. The fire and the lack of sunlight hit the flora harder than most ecosystems, especially in regions closer to the impact zone. As a result, the flora became quite different from the one prior to the collapse at a regional scale [45]. After the extinction, mammals, birds, and flowering plants became dominant and long-term successful survivors.

Mass extinctions give the impression as if they had their own unique stories with some similarities and more differences. Similarities of mass extinctions are very important because they make collapses more predictable. Research questions related to similarities bring us closer to understanding the current global crisis. For example, is it possible that different causes of extinctions result in similar extinction mechanisms? Do events of different magnitudes lead to recoveries of different dynamics?

Besides the "Big Five," some smaller mass extinctions also provide valuable information on the characteristics of collapses. Less researched mass extinctions which were presumably caused by climate change (or climate change was an important contributor in the event) should get more attention. For example, during the Early Jurassic (Early Toarcian) mass extinction and the Paleocene-Eocene thermal maximum, increased CO_2 level and temperature, acidification, and anoxia were typical accompanying phenomena of the global biotic crisis just like today; therefore, they could be used as an analogy. The Middle Permian (Capitanian) event which is a newly recognized major mass extinction and probably related to the large Late Permian mass extinction can also be linked to marine anoxia and acidification caused by volcanic eruptions. We have poor knowledge and inadequate data on periods before mass extinctions. It would be important to reveal more phenomena and patterns that preceded global past collapses to be able to create scenarios for the possible future biotic crisis.

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References

[1] Gro Harlem B. et al. Our Common Future - Report of the World Commission on Environment and Development, United Nations (Transmitted to the General Assembly as an Annex to document A/42/427 - Development and International Cooperation: Environment). 1987. Available from: https://www.are.admin.ch/are/en/home/sustainable-development/international-cooperation/2030agenda/un-_-milestones-in-sustainable-development/1987--brundtland-report.html

[2] Gilián LD, Bódis J, Eszéki E, Illyés Z, Biró É, Nagy JG. Germination traits of adriatic lizard orchid (*Himantoglossum adriaticum*) in Hungary. Applied Ecology and Environmental Research. 2018;**16**(2):1155-1171

[3] Suel H, Mert A, Yalcinkaya B. Changing potential distribution of gray wolf under climate change in lake district, Turkey. Applied Ecology and Environmental Research. 2018;**16**(5):7129-7137

[4] Konrad L. Die acht Todsünden der zivilisierten Menschheit. Serie Piper, Auflage, München 1973;34. Auflage, München; 2009. ISBN 3-492-20050-8 (im Verlag Auditorium-Netzwerk auch als Hörbuch erschienen)

[5] Rüstemoğlu H, Uğural S. CO_2 emissions in Iran for 1990-2010: A decomposition analysis. Applied Ecology and Environmental Research. 2017;**15**(4):1833-1846

[6] Garamvölgyi Á, Hufnagel L. Impacts of climate change on vegetation distribution No. 1. Climate change induced vegetation shifts in the Paleartic region. Applied Ecology and Environmental Research. 2013;**11**(1):79-122

[7] Hufnagel L, Garamvölgyi Á. Impacts of climate change on vegetation distribution No. 2, climate change induced vegetation shifts in the New World. Applied Ecology and Environmental Research. 2014;**12**(2):255-422

[8] Pimm S, Jenkins CN, Abell R, Brooks TM, Gittleman JL, Joppa LN, et al. The biodiversity of species and their rates of extinction, distribution, and protection. Science. 2015;**344**(6187). DOI: 10.1126/science.1246752

[9] Barnosky AD, Matzke N, Tomiya S, Wogan GOU, Swartz B, Quental TB, et al. Has the Earth's sixth mass extinction already arrived? Nature. 2011;**471**(7336):51-57. DOI: 10.1038/nature09678

[10] Ceballos G, Ehrlich PR, Dirzo R. Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. Proceedings of the National Academy of Sciences of the United States of America. 2017;**114**(30):6089-6096. DOI: 10.1073/pnas.1704949114

[11] Dirzo R, Young HS, Galetti M, Ceballos G, Isaac NJB, Collen B. Defaunation in the Anthropocene. Science. 2014;**345**(6195)

[12] Thomas CD, Cameron A, Green RE, Bakkenes M, Beaumont LJ, Collingham YC, et al. Extinction risk from climate change. Nature. 2004;**427**(6970):145-148. DOI: 10.1038/nature02121

[13] Hoekstra AY, Wiedmann TO. Humanity's unsustainable environmental footprint. Science. 2014;**344**(6188): 1114-1117. DOI: 10.1126/science.1248365

[14] Newbold T, Hudson LN, Arnell AP, Contu S, De Palma A, Ferrier S, et al. Has land use pushed terrestrial

biodiversity beyond the planetary boundary? A global assessment. Science. 2016;**353**(6296):288-291

[15] Chapman AD. Numbers of Living Species in Australia and the World—A Report for the Australian Biological Resources Study. 2nd ed. Toowoomba, Australia; 2009. Available at: http://www.environment.gov.au/system/files/pages/2ee3f4a1-f130-465b-9c7a-79373680a067/files/nlsaw-2nd-complete.pdf. ISBN 978 0 642 56861 8

[16] Harries PJ, Little CTS. The early Toarcian (early Jurassic) and the Cenomanian-Turonian (late cretaceous) mass extinctions: Similarities and contrasts. Palaeogeography, Palaeoclimatology, Palaeoecology. 1999;**154**(1):39-66

[17] Foster WJ, Twitchett RJ. Functional diversity of marine ecosystems after the late Permian mass extinction event. Nature Geoscience. 2014;**7**(3):233-238. DOI: 10.1038/NGEO2079

[18] Lowery CM, Bralower TJ, Owens JD, Rodríguez-tovar FJ, Jones H, Smit J, et al. Rapid recovery of life at ground zero of the end-cretaceous mass extinction. Nature. 2018;**558**(7709):288-291. DOI: 10.1038/s41586-018-0163-6

[19] Cooper RA, Sadler PM, Munnecke A, Crampton JS. Graptoloid evolutionary rates track Ordovician-Silurian global climate change. Geological Magazine. 2014;**151**(2):349-364. DOI: 10.1017/S0016756813000198

[20] Hochuli PA, Sanson-Barrera A, Schneebeli-Hermann E, Bucher H. Severest crisis overlooked—Worst disruption of terrestrial environments postdates the Permian–Triassic mass extinction. Scientific Reports. 2016;**6**(28372):1-8. DOI: 10.1038/srep28372

[21] Looy CV, Twitchett RJ, Dilcher DL, Cittert JHAVK, Visscher H. Life in the end-Permian dead zone. Proceedings of the National Academy of Sciences. 2001;**98**(14):7879-7883. DOI: 10.1073/pnas.131218098

[22] Benton MJ. When Life Nearly Died: The Greatest Mass Extinction of all Time. Thames and Hudson; 2003

[23] Darroch SAF, Wagner PJ. Responses of beta diversity to pulses of Ordovician-Silurian mass extinction. Ecology. 2015;**96**(2):532-549

[24] Sheehan PM, Coorough PJ, Fastovsky DE. Biotic selectivity during the K/T and late Ordovician extinction events. Geological Society of America Special Paper. 1996;**307**:477-489

[25] Krug AZ, Patzkowsky ME. Geographic variation in turnover and recovery from the late ordovician mass extinction. Paleobiology. 2007;**33**(3):435-454

[26] Brenchley PJ, Marshall JD, Underwood CJ. Do all mass extinctions represent an ecological crisis? Evidence from the late Ordovician. Geological Journal. 2001;**36**(3-4):329-340

[27] Erwin DH. The end and the beginning: Recoveries from mass extinctions. Trends in Ecology and Evolution. 1998;**13**(9):344-349

[28] Briggs D, Crowther PR. Palaeobiology II. John Wiley & Sons; 2008. p. 223 ISBN: 978-0-470-99928-8

[29] Friedman M, Sallan LC. Five hundred million years of extinction and recovery: A phanerozoic survey of large-scale diversity patterns in fishes. Palaeontology. 2012;**55**(4):707-742. DOI: 10.1111/j.1475-4983.2012.01165.x

[30] Boucot AJ. Phanerozoic extinctions: How similar are they to each other? In: Kauffman E, Walliser O, editors. Extinction Events in Earth History. Berlin: Springer Berlin; 1990. pp. 5-30

[31] De Vleeschouwer D, Da Silva A-C, Sinnesael M, Chen D, Day JE, Whalen MT, et al. Timing and pacing of the late Devonian mass extinction event regulated by eccentricity and obliquity. Nature Communications. 2017;**8**(1):1-11. DOI: 10.1038/s41467-017-02407-1

[32] Benton MJ, Twitchett RJ. How to kill (almost) all life: The end-Permian extinction event. Trends in Ecology and Evolution. 2003;**18**(7):358-365. DOI: 10.1016/S0169-5347(03)00093-4

[33] Lau KV, Maher K, Altiner D, Kelley BM, Kump LR, Lehrmann DJ, et al. Marine anoxia and delayed earth system recovery after the end-Permian extinction. Proceedings of the National Academy of Sciences of the United States of America. 2016;**113**(9):2360-2365. DOI: 10.1073/pnas.1515080113

[34] Petsios E, Thompson JR, Pietsch C, David J. Biotic impacts of temperature before, during, and after the end-Permian extinction: A multi-metric and multi-scale approach to modeling extinction and recovery dynamics. Palaeogeography, Palaeoclimatology, Palaeoecology. 2019;**513**:86-99. DOI: 10.1016/j.palaeo.2017.08.038

[35] Shu-zhong AS, Shi GR. Paleobiogeographical extinction patterns of permian brachiopods in the Asian-Western Pacific region. Paleobiology. 2014;**28**(4):449-463

[36] Kidder DL, Worsley TR. Causes and consequences of extreme Permo-Triassic warming to globally equable climate and relation to the Permo-Triassic extinction and recovery. Palaeogeography, Palaeoclimatology, Palaeoecology. 2004;**203**(3):207-237. DOI: 10.1016/S0031-0182(03)00667-9

[37] Twitchett RJ, Krystyn L, Baud A, Wheeley JR, Richoz S. Rapid marine recovery after the end-Permian mass-extinction event in the absence of marine anoxia. Geology. 2004;**32**(9):805-808. DOI: 10.1130/G20585.1

[38] Wei H, Shen J, Schoepfer SD, Krystyn L, Richoz S, Algeo TJ. Environmental controls on marine ecosystem recovery following mass extinctions, with an example from the early Triassic. Earth Science Reviews. 2015;**149**(October):108-135. DOI: 10.1016/j.earscirev.2014.10.007

[39] Götz AE, Ruckwied K, Pálfy J, Haas J. Palynological evidence of synchronous changes within the terrestrial and marine realm at the Triassic/Jurassic boundary (Csővár section, Hungary). Review of Palaeobotany and Palynology. 2009;**156**(3):401-409. DOI: 10.1016/j.revpalbo.2009.04.002

[40] Barreda VD, Cúneo NR, Wilf P, Currano ED, Scasso RA. Cretaceous/paleogene floral turnover in Patagonia: Drop in diversity, low extinction, and a classopollis spike. PLoS One. 2012;**7**(12):1-8. DOI: 10.1371/journal.pone.0052455

[41] Schueth JD, Bralower TJ, Jiang S, Patzkowsky ME. The role of regional survivor incumbency in the evolutionary recovery of calcareous nannoplankton from the cretaceous/Paleogene (K/Pg) mass extinction. Paleobiology. 2015;**41**(4):661-679. DOI: 10.1017/pab.2015.28

[42] Harries PJ, Kauffman EG. Patterns of survival and recovery following the Cenomanian-Turonian (late cretaceous) mass extinction in the Western Interior Basin, United States. In: Kauffman E, Walliser O, editors. Extinction Events in Earth History. Berlin: Springer Berlin; 1990. pp. 277-298

[43] Harries PJ, Kauffman EG, Hansen TA. Models for biotic survival following mass extinction. Geological Society London Special Publications.

1996;**102**(1):41-60. DOI: 10.1144/GSL.SP.1996.001.01.03

[44] Longrich NR, Scriberas J, Wills MA. Severe extinction and rapid recovery of mammals across the cretaceous–Palaeogene boundary, and the effects of rarity on patterns of extinction and recovery. Journal of Evolutionary Biology. 2016;**29**(8):1495-1512. DOI: 10.1111/jeb.12882

[45] Tschudy R, Pillmore C, Orth C, Gilmore J, Knight J. Disruption of the terrestrial plant ecosystem at the cretaceous-tertiary boundary, western interior. Science. 1984;**225**(4666):1030-1032

[46] Ksepka DT, Stidham TA, Williamson TE. Early Paleocene landbird supports rapid phylogenetic and morphological diversification of crown birds after the K–Pg mass extinction. Proceedings of the National Academy of Sciences of the United States of America. 2017;**114**(30):1-6. DOI: 10.1073/pnas.1700188114

[47] Field DJ, Bercovici A, Berv JS, Lyson TR, Vajda V, Gauthier JA, et al. Early evolution of modern birds structured by global forest collapse at the end-cretaceous mass extinction. Current Biology. 2018;**28**(11):1825-1831. DOI: 10.1016/j.cub.2018.04.062