2021 ERDKUNDE Vol. 75 · No. 3 · 225–244

FORUM: REVIEWS AND COMMENTS

NATURE-BASED SOLUTIONS MUST BE REALIZED - NOT JUST PROCLAIMED - IN FACE OF CLIMATIC EXTREMES

Carl Beierkuhnlein

With 6 figures

Summary: Natural hazards resulting from climate change are increasing in frequency and intensity. As this is not a linear trend but rather by singularities and anomalies including a broad spectrum of climatic and weather extremes with high temporal and spatial uncertainty, focused avoidance strategies are difficult to prepare. However, the effects of climate change are mostly addressed with outdated 'business as usual' approaches by governments and most stakeholders, which are unfit to tackle the complexity of current challenges. Coping action for natural hazards is mostly undertaken during and after such events compensating damage through payments and restoration. In the future, pro-active nature-based solutions are needed for risk mitigation and avoiding severe damage through enhancing all facets of biodiversity from species richness, structural roughness, to spatial heterogeneity of ecosystems. This will not avoid extreme weather events, but it will reduce the damage of increasingly appearing natural hazards. However, this strategy cannot be implemented all of a sudden. Long-term and spatial concepts are needed. For this purpose, currently missing governance structures based on geographical, geoscientific, ecological, meteorological, and societal expertise should be installed. In recent years, a good scientific and knowledge basis for the required solutions has been developed, which now must translate into action. Here, a series of suggestions is compiled for a broad spectrum of extreme events and societal fields, which is far from being complete but should stimulate critically needed creativity and commitment. Nature-based solutions will not deliver a complete protection and cannot be the only kind of action, but we can no longer rely on post-disaster compensation or on the safety illusion of mere engineering and construction works. The efficiency of biodiversity as an insurance for maintaining ecosystem services is well understood. The implementation of nature-based adaptation, coping, and protection measures is less expensive than traditional end-of-the-pipe constructions. It requires an in-depth understanding of interacting processes and trans-disciplinary cooperation based on a broad acceptance in the public. Investments into these solutions would pay off, not tomorrow, but in the future. It is the best sustainable and feasible approach for disaster prevention.

Zusammenfassung: Naturkatastrophen als Folge des Klimawandels nehmen an Häufigkeit und Stärke zu. Da sich diese Entwicklung nicht als linearer Trend abzeichnet, sondern über Singularitäten und Anomalien inklusiver klimatischer und Wetterextreme mit hoher zeitlicher und räumlicher Ungewissheit, ist es schwer geeignete Vermeidungsstrategien vorzubereiten. Allerdings werden die Auswirkungen des Klimawandels durch staatliche Behörden und Praktiker vor Ort zumeist mit überkommenen etablierten Maßnahmen bekämpft. Diese erweisen sich als zunehmend ungeeignet angesichts der Komplexität der aktuellen Herausforderungen. Aktuell werden Gegenmaßnahmen während und nach solchen Ereignissen ergriffen, um entstandene Schäden durch Zahlungen und Maßnahmen auszugleichen. Zukünftig werden proaktive naturbasierte Lösungen (Nature-based solutions) zur Vermeidung schwerer Schäden benötigt, um Risiken einzugrenzen und zu vermeiden. Dies kann durch Förderung verschiedener Aspekte der Biodiversität geschehen, wie der Förderung der Artenvielfalt, Strukturvielfalt, und zeitlicher Vielfalt in Ökosystemen. Extreme Wetterereignisse werden damit nicht vermieden, aber die Schadwirkungen vermehrt auftretender Naturkatastrophen können reduziert werden. Allerdings lässt sich eine derartige Strategie nicht sofort umsetzen. Langfristige und räumliche Konzepte werden benötigt. Umsetzungsstrukturen sollten auf der Grundlage geographischer, geowissenschaftlicher, ökologischer, meteorologischer und gesellschaftlicher Expertise etabliert werden. In den letzten Jahren wurden gute wissenschaftliche Grundlagen und Kenntnisse für die benötigten Lösungsansätze erarbeitet. Diese sollten nun in Handlungen überführt werden. Hier werden verschiedene Vorschläge für ein breites Spektrum von Extremereignissen und gesellschaftlichen Handlungsfeldern präsentiert. Diese Zusammenstellung ist bei Weitem nicht vollständig, sondern soll dazu auffordern kreativ die Herausforderungen anzugehen. Natur-basierte Lösungen

https://doi.org/10.3112/erdkunde.2021.03.06 ISSN 0014-0015 (Print) · ISSN 2702-5985 (Online)

werden keinen kompletten Schutz bieten und repräsentieren auch nicht die einzige Maßnahme, aber wir sollten nicht länger zu sehr auf Nachsorge vertrauen oder auf die Sicherheitsillusion technischer Baumaßnahmen. Die Effizienz der Biodiversität als Versicherung für Ökosystemdienstleistungen ist gut verstanden. Die Umsetzung natur-basierter Anpassungs-, Ausgleichs- und Schutzmaßnahmen benötigt weniger Finanzmittel als traditionelle „End-of-the-pipe" Maßnahmen. Sie erfordern jedoch ein vertieftes Verständnis der wechselwirkenden Prozesse und damit transdisziplinäre Zusammenarbeit, basierend auf einer breiten gesellschaftlichen Akzeptanz. Investitionen in derartige Lösungen werden sich nicht umgehend, sondern in der Zukunft auszahlen. Sie sind ein nachhaltiger und machbarer Ansatz zur Krisenprävention.

Keywords: Green Deal, European Biodiversity Strategy, drought, heavy rain, flooding, natural hazards, heat waves, disasters, biodiversity, ecosystem services, governance, Earth Critical Zone

1 Introduction

Nature-based solutions for tackling the societal challenges in face of climate change are increasingly supported (Nesshover et al. 2017). However, the implementation of this concept is just at its beginning. Approaches are still focused to pilot projects, often superficial in its ecological foundations, and in most cases ignoring widely the possible benefits provided by biodiversity (Mori 2020). Even if the current policy of the European Green Deal (European Commission 2020) is strongly supported by nature conservation (IUCN 2020), this strategy is lacking a comprehensive concept for linking biodiversity governance with disaster prevention related to increasingly emerging climatic extremes.

From a global perspective it is evident that climate change is stronger in the northern hemisphere due to the large surface of land masses, and the effects on the marine realm are also stronger in the north due to the melting of ocean ice and related reduction in albedo (IPCC 2014, 2019, 2021). Additionally, geographic aspects contribute to the particular sensitivity of Europe to climate change. The energy transport of the gulf stream provides a temperate climate in high latitude. European ocean-land interactions are pronounced and controlled by the distance to oceans, and by heterogeneous land structures and mountain ranges. This constellation is creating a situation, where changes in framework conditions of the climatic environment can have enormous implications.

Biodiversity is known to buffer the effects of climatic fluctuations. If many species are present, it is likely that they exhibit species-specific responses to a changing environment with some species reducing their performance and others taking over. Such kind of compensation can only take place if a broad spectrum of biota is represented. In consequence, biodiversity provides an insurance for the functioning of ecosystems (Yachi and Loreau 1999; Loreau et al. 2003) and contributes to their regulation (Cottingham et al. 2001). Biodiversity has a positive effect on most ecosystem services (Balvanera et al. 2006). Thus, it is in the interest of the society to protect, and even enforce, all facets of biodiversity.

Now, there is a specific restriction to Central European ecosystems, which is their naturally low species richness. This is a consequence of Pleistocene climatic fluctuations combined with the topographic structure and the spatial arrangement of landmasses and oceans. East-West oriented mountain ranges and the Mediterranean Sea acted as biogeographical barriers for migration and caused the loss of previously existing taxa with every glaciation cycle. Although European tree flora shows a comparable functional diversity to the one in North America (Liebergesell et al. 2016), it involves less taxa and, in consequence, the loss of species could easily result in an impact on ecosystem functioning. Many Central European tree genera are represented just by one to three species, whereas in temperate North America or East Asia species richness within tree genera can be higher by one order of magnitude.

This results in the situation that temperate Central Europe features a highly sensitive climatic situation in face of climate change combined with a low level of biodiversity that could contribute towards buffering climate chance impacts. Therefore, special attention should be given to the preservation and management of biodiversity in European landscapes, which is mostly ignored in climate change impact studies (e.g., Marachi et al. 2005; Lindner et al. 2010).

Many temperate forests of Central Europe have been re-established just during the last century after extensive deforestation since medieval times. Partly they are located on degraded soils, or they experienced non-sustainable uses, exploitation, and devastation (Spieker 2003). This has changed since the mid of the 20th century. However, the need for resources rather promoted monocultures of fast-growing conifer species such as Norway spruce (*Picea abies*) or Scots pine (*Pinus sylvestris*). Such stands cover a much larger area than their natural range, and they are more susceptible to storms, droughts, fire, pests, and pathogens than deciduous forests (Wohlgemuth et al. 2019). Besides spruce, also beech (*Fagus sylvatica*) shows significant climatic sensitivity (Kolar et al. 2017) but especially in lower elevation, spruce trees with their shallow roots react stronger to drought (Bolte et al. 2010; Pretzsch et al. 2014). In recent years, storm events, bark beetle outbreaks and drought have caused increased canopy mortality particularly in Central and East European forests (Senf et al. 2021).

Certainly, it is unquestioned that the drivers of climate change, i.e., carbon emissions of various kinds, need to be mitigated. The current and expected near-future climate warming is substantially linked to human activities (IPCC 2014). Climate change has already triggered a series of fundamental repercussions in natural ecosystems ranging from the loss of sea ice, over melting permafrost to destabilized tropical ecosystems (Lenton et al. 2008). Such feed-back mechanisms and tipping points are accelerating climatic change impacts on top of the direct human footprint. Planetary boundaries have been reached and the capacity of the Earth Critical Zone to buffer short-term impacts has been exceeded in many cases.

Climate change is affecting the human sphere not just through a trend in multi-decadal global average temperatures but rather by the regional expression of these trends and their translation into temporal patterns. The general challenge towards a better understanding is to identify links between processes acting at different spatial and temporal scales, which is an intrinsic and vital approach in geography - even if geographers are not sufficiently involved into this research agenda (Thorne 2014; MacDonald 2021). Likewise, the spatial expression of social and community resilience to climate change is an emerging geographical topic (Setten and Lujala 2020).

Species and ecosystems are improbably controlled by long-term average values of climate but rather by short-term climatic events (Jentsch et al. 2007; Jentsch and Beierkuhnlein 2008). These events, in consequence, have a strong influence on species populations, community assemblages and ecosystem structures. In turn, species composition of biotic communities, their diversity, and the spatial organisation of ecosystems can contribute to the control and regulation of such short-term events (Cottingham et al. 2001).

Models on precipitation change with climate warming exhibit a high internal variability. Nevertheless, they are robust in simulating an increasing likelihood of heavy rain events with global warming. But, such an increase was difficult to proof. Heavy rain is still rather rare, often very short, and in addition mostly local to regional. This complicates traditional statistical evaluations and the detection of significant correlations due to an insufficient number of cases. However, recently, the expected increase in such events could be verified due to the increasing availability of observational datasets with high temporal resolution through the application of machine learning techniques (Madakumbura et al. 2021).

The expectation of an increasing probability of 'extreme events' in general (e.g. Münchener Rückversicherungs-Gesellschaft 2003; Field et al. 2012; Petoukhov et al. 2013; Büntgen et al. 2021; IPCC 2021) is leading to a semantic dilemma, which cannot be discussed here in detail. It may be difficult to understand that the same event that was termed 'extreme' cannot be categorized as extreme anymore if extremeness is just defined by the likelihood of occurrence (Hegerl et al. 2011). A higher frequency of a specific event reduces the statistical extremes, whereas at the same time repeated events may even cause a stronger impact. On the other hand, species and ecosystems differ in terms of their sensitivity to a given event.

The drought period in the years 2018 and 2019 had caused a lasting economic damage to Central European forestry and agriculture (Kapsambelis et al. 2019; Senf et al. 2020). This drought was climatically more extreme than the one in 2003 (Schuldt et al. 2020), even if there was a less direct impact on the human society. Based on tree ring proxies, Büntgen et al. (2021) find that a comparable sequence of European summer droughts like the one since 2015 did not occur since more than 2000 years.

The heat wave in the summer of the year 2003 caused more than 40,000 additional cases of death in Central Europe. Mortality rates in Switzerland increased for the time June to August 2003 by 7% (Grize et al. 2005). The economic damages of this drought and heat wave were enormous (Münchener Rückversicherungs-Gesellschaft 2003) and have been estimated beyond the damage that was covered by insurances to more than 10 billion Euros. In 2018, however, the mean growing season air temperature (April to October) was 3.3 °C above the long-term average values, and 1.2 °C warmer than in 2003! Combined with a shortage in precipitation including the year 2019, drought-induced tree mortality became evident all-over Central Europe for both conifers and deciduous tree species (Schuldt et al. 2020). Conifers were strongly affected by bark beetles. As 90% of the Central European forest surface is dominated by only 11 tree species, such periods can strongly threaten the functioning of entire forest landscapes.

'Centennial flooding' events from large rivers have partly increased to a decadal or even sub-decadal frequency (Thorne 2014), which is in line with modelling projections (Hattermann et al. 2016). In August 2002, Danube and Elbe flooded large landscapes with 21 deaths in Germany and more than 9 billion Euros of economic damage. During May and June 2013, many water gauges at these rivers recorded even higher flood peaks (Thieken et al. 2016). Local and regional extreme precipitation events have caused additional disasters in recent years. Flooding events in summer 2021 caused more than 100 fatalities in Germany. Economic consequences are huge as infrastructure and buildings are destroyed. Monetary damage is estimated to several billion euro. After repeated flooding disasters in the UK, the perception of responsibilities in the public was divided between i) failure in planning and governmental management and investment, ii) inappropriate farming through over-intense land-use in upstream catchments and iii) poor judgement of victims in choosing to live, work, or farm in vulnerable areas such as valleys (Thorne 2014). However, decisions for investments, farming practice, or settlements are not made within a few years but are rather a legacy of long-term experience, made under historical climatic conditions. Now, what has been thought to be reliable, became elusive. Historic villages on former safe sites may have to be abandoned. Sensitive infrastructure may have to be relocated.

The IPCC expected in 2012 for Europe "increased damages from rivers and coastal floods", "increased water restrictions", and "increased damages from extreme heat events and wildfires". The expectation of increasing risks related to extreme events is confirmed in the current IPCC report (IPCC 2021). It is highly likely, that the above-described events were not singularities but will be followed by repeated, and maybe even more severe hazards as a consequence of climate change. The catastrophic recent climatic extremes in Central Europe ask for consequences to avoid or at least reduce future climate change related casualties and economic damage.

The protective services for human lives, infrastructure and economic activities provided through the conservation and restoration of ecosystems for instance in terms of mitigating erosion, reducing the risk of landslides and mud avalanches, maintaining slope stability, cooling air masses, reducing windspeed, and improving flood control are evident (Sudmeier-Rieux et al. 2006). But this knowledge is not sufficiently taken up in land use planning and management although findings have been compiled for years, for instance in a comprehensive special report of the IPCC (Field et al. 2012). Research has provided concepts for identifying potential impacts and reducing risks related to extreme climatic events in Central Europe (e.g., Beierkuhnlein and Jentsch 2013; Beierkuhnlein et al. 2014). Obviously, such guidelines have not passed the science / policy barrier. An interface between research and the society is a long time required desideratum, but obviously the produced knowledge is not practically executed, yet.

On the one hand, calls have been released by funding agencies for years, and research projects yielded results, respectively. On the other hand, policy and application tend to respond not before projected hazards and human catastrophes have come true. There is no excuse for not acting, besides avoiding conflicts with land users or landowners. It is frustrating for researchers to understand that their findings, which have been supported by public funding and whose transfer into practice could have contributed to reduce impacts and maybe even avoid losses of human lives, were not taken up in decision making processes, planning, policy, and governance during the last decade!

The speed of climate change and correlated climatic anomalies, and the rapid increase of knowledge in the scientific community, are obviously facing rigid inertia in the minds and processes in administration and politics. Short-term interests of stakeholder communities such as industry, agriculture, tourism, or transport are prioritized and pro-active risk reduction through nature-based solutions (see Essl and Beierkuhnlein 2013) is neglected. Obviously, expenses and conflicts are not accepted in the society until human disasters become reality.

Here, suggestions for pro-active nature-based solutions aiming to reduce the negative impact of climatic extremes are compiled. There is no general solution due to the significantly different quality, intensity, duration, and frequency of climatic extremes. Also, the related effects to ecosystems and the society differ substantially. However, many ecological concepts for disaster mitigation through nature-based solutions have been made in recent years. Applying such concepts needs to keep in mind that it is not about returning to a historic reference state of nature (Chiarucci et al. 2010). Climate change is expressed by a combination of trends and events. Negative effects of this rapidly moving target can best be approached through the management of functional biodiversity.

2 Challenges through extreme climatic events and nature-based solutions

2.1 Heavy rain events and flooding

Hilly and mountain regions with large agricultural fields must be focused on, where topographic energy comes together with low surface roughness and large areas with compacted soils and surface run-off. Here, large pieces of land should be subdivided by hedgerows, woodlands, wetlands to create barriers for run-off and spaces where water can be stored. Current agricultural fields of this kind must be restored for the purpose of disaster mitigation.

It is not just the size of agricultural fields (Fig. 1) and their topographic position; it is also the kind of land use that can promote or mitigate runoff (Cossart et al 2020). One major problem during the German flood disaster in Summer 2021 was the huge amount of mud that was deposited in villages. Evidently, this was due to soil erosion from agricultural fields and vineyards that are not protected by a permanent vegetation formed by perennial plants and respective rooting. In upstream catchments open soil should be reduced to small pieces of land with low inclination.

Permanent cultures such as grassland play an immanent role in erosion control. Soil loss from grassland is very low to neglectable (Fullen and Booth 2006). Biodiversity of grasslands is correlated with rooting depth and rooting architecture in the soil, which is crucial for soil stability (Mueller et al. 2012). The stability of soil aggregates was also found to increase with plant species diversity (Pérès et al. 2013). Körner (2021) shows slope stability to increase with biodiversity in high mountains. The co-occurrence of different root types contributes to the protection of soil surfaces under heavy rain.

Kennel (2004) calculated the contribution of forests to water retention in comparison with technical water management. In particular, floodplain forests ('Auwald') were estimated with a monetary advantage of 20 000 Euro per hectare, and also forests on slopes provided a substantial benefit.

A modified future water management must begin in the long-time neglected headwaters, small brooks and ditches (Křeček and Haigh 2019). Runoff and discharge during and after periods of heavy rain accumulate downstream where coping measures are limited, and where valuable infrastructure and cities are often located at rivers. During the 20th century, water management was focused or even restricted to large rivers (BMU 2010). The upper catchments were not included in planning. Agricultural soils were frequently drained, small rivers were straightened and regulated, natural meanders were removed and residence time of waters in catchments was reduced, resulting in rapidly peaking flood pulses downstream. These were thought to be controlled by dikes, dams, and flood walls.

However, it is evident that it is more beneficial to keep water in an area as long as possible and not to pass it through as fast as possible. Rivers need space to extend during and after periods of heavy rain. This does not apply only to large rivers (Klijn et al. 2018). After the small catchments upstream, floodplains are the second most important spaces, where peaks of discharge can be mitigated to avoid subsequent hazards downstream. If flooding of valley bottoms is not allowed, this will necessarily happen in settlements and industrial areas. As it shows in summer 2021, bridges that were built under the terms of past climate cannot resist modern flood waves

Fig. 1: Different grain sizes of agricultural fields in two German landscapes. Flerzheim, North Rhine-Westphalia (left), and Mittelpöllnitz, Thuringia (right). In combination with slope, patch size of agricultural fields has a strong influence on runoff during extreme heavy rain events. Sources: www.geoportal.nrw; www.geoportal-th.de/

that accumulate when heavy precipitation events are focused to a landscape. In consequence, valleys and floodplains need to be seen increasingly as buffers during discharge events. Even if the colluvial soils in valleys are very fertile, agricultural land use is not the best option as it does not reduce the flow velocity. Forest mires, mountain fens and lowland wetlands are better performing in terms of holding back floods (Jansky and Kocum 2008; Bredemeier 2011; Streich et al. 2020).

Examples for nature-based solutions:

- Agriculture: Reduce soil compaction; Increase biodiversity of grasslands; Reduce field sizes; Establish or restore hedgerows and field margins; Reduce mowing frequency; Avoid ploughing fields on slopes, Plant additional meadow-orchards on slopes and in valleys to reduce speed of surface run-off.
- Forestry: Establish forests in valleys with the main purpose of the retention of floods; Create small woodlands in agricultural land use matrices; Plant stripes of woodlands along river margins to prevent lateral erosion.
- Water management: Restore small rivers and headwaters; Establish polders for short-term water storage in large valleys with diverse, permanent vegetation; Remove or close underground pipes and concrete ditches and trenches to avoid rapid discharge and replace by local swamps.
- Settlements: Replace settlements in continuously risky valleys by natural ecosystems; Create natural spaces within cities to hold back and store heavy rain precipitation; Reduce land sealing of parking lots and industrial areas; Encourage roof greening to withhold rainwater on the spot.

2.2 Periods of drought

Since the beginning of this century, Central Europe was affected by at least two phases of extreme drought (2003, 2018-2019) (Schär et al. 2004; Schuldt et al. 2020) (Fig. 2) and additional years came along with regional or temporal drought impacts. In Eastern Europe, the year 2010 was characterized by a centennial drought with burning bogs and related huge amounts of carbon emission (Konovalov et al. 2011). European carbon sequestration was substantially reduced in years of drought (Ciais et al. 2005).

Buras et al. (2020) found an even stronger impact on ecosystems caused by the 2018 drought compared to the year 2003. Surprisingly, the effect of changes in the water balance were significantly more pronounced in pastures and arable land compared to forests. However, European forests tend to show long-term responses to drought, reflected in excess mortality (Senf et al. 2020). Senescent canopies can be well detected via remote sensing (Fig. 3), mainly through canopy mortality and related repercussions on the demographic structure of tree populations (Senf et al. 2021).

van Ruijven and Berendse (2010) demonstrated that higher species richness is accompanied by faster recovery of vegetation after drought. An increased resistance towards drought with biodiversity has also been shown for Swiss grasslands, starting already from low levels of diversity (Pfisterer and Schmid 2002). This does not assert that drought would have no effect, but the decline in growth during drought is compensated faster if biodiversity is high. The timing of drought evidently matters and can influence the role of

Fig. 2: Drought damage in August 2003 on forest trees (*Acer pseudoplatanus*, left; *Sorbus aucuparia*, right) in the understory of deciduous forest close to Bayreuth

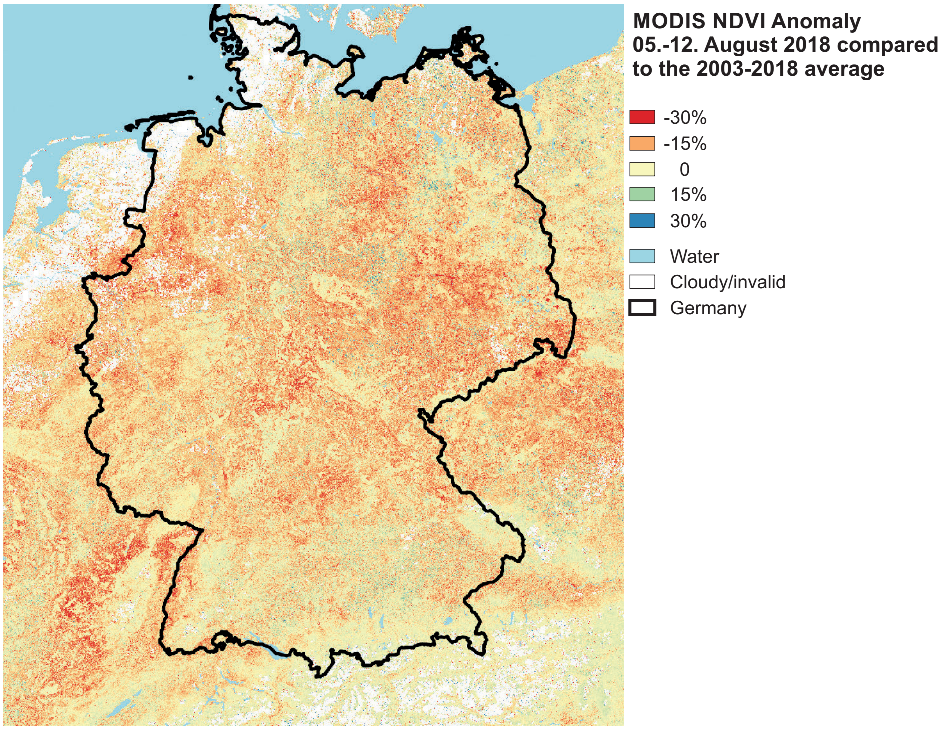

Fig. 3: Drought damage to Central European ecosystem in summer 2018 reflected through NDVI change detection comparing the pre-drought average with the situation in 2018 for early August. Sensor MODIS. Data Source: Global Inventory Modeling and Mapping Studies (GIMMS).

biodiversity for ecosystem functioning (Kahmen et al. 2005). Additionally, the management regime can modify the interaction between drought and biodiversity. However, species rich grassland was found to perform better under drought in comparison with species poor vegetation (Pfisterer and Schmid 2002; Vogel et al. 2012).

Examples for nature-based solutions:

- Agriculture: Increase biodiversity in grasslands to compensate decline of drought sensitive species by less sensitive drought-resistant species; Enhance crop-rotation systems and diversity patterns of crops within landscapes; Establish agro-forestry-like approaches such as meadow orchards to utilize different levels of soil- and groundwater during periods of drought.
- Forestry: Manage understory natural regeneration; Reduce fire risks by replacing conifers by deciduous tree species; Avoid litter accumulation through improving soil fertility.
- Water management: Provide discharge during drought periods for rivers from wetlands, mires, fens, and bogs; Restore depleted aquifers during precipitation periods and winters.

2.3 Heat waves

Heat is often correlated with drought. Therefore, the direct heat impact can often not be clearly disentangled from shortage in water supply. Extreme heat waves are rare (2003, 2019) and can be short (see Fig. 4). Most terrestrial species tend to tolerate these phases. Mobile organisms need shelters during these periods that are provided through diverse surface structures. Also, water bodies are crucial for cooling. Natural mechanisms of vegetation recovery after stressful extreme events should be supported as it is unlikely that the extreme events themselves can be completely avoided. Reassembly after an extreme heat wave was found to be strongly stochastic in aquatic (Seifert et al. 2015) and terrestrial communities (Kreyling et al. 2011). Losing species during such an event is more likely to have negative consequences for species-poor compared to highly diverse ecosystems.

Direct temperature impact on plants has been confirmed in coordinated experiments, but effects were species-specific (Penuelas et al. 2007). Site conditions and the biogeographical context matters. There are indications for the relevance of the insur-

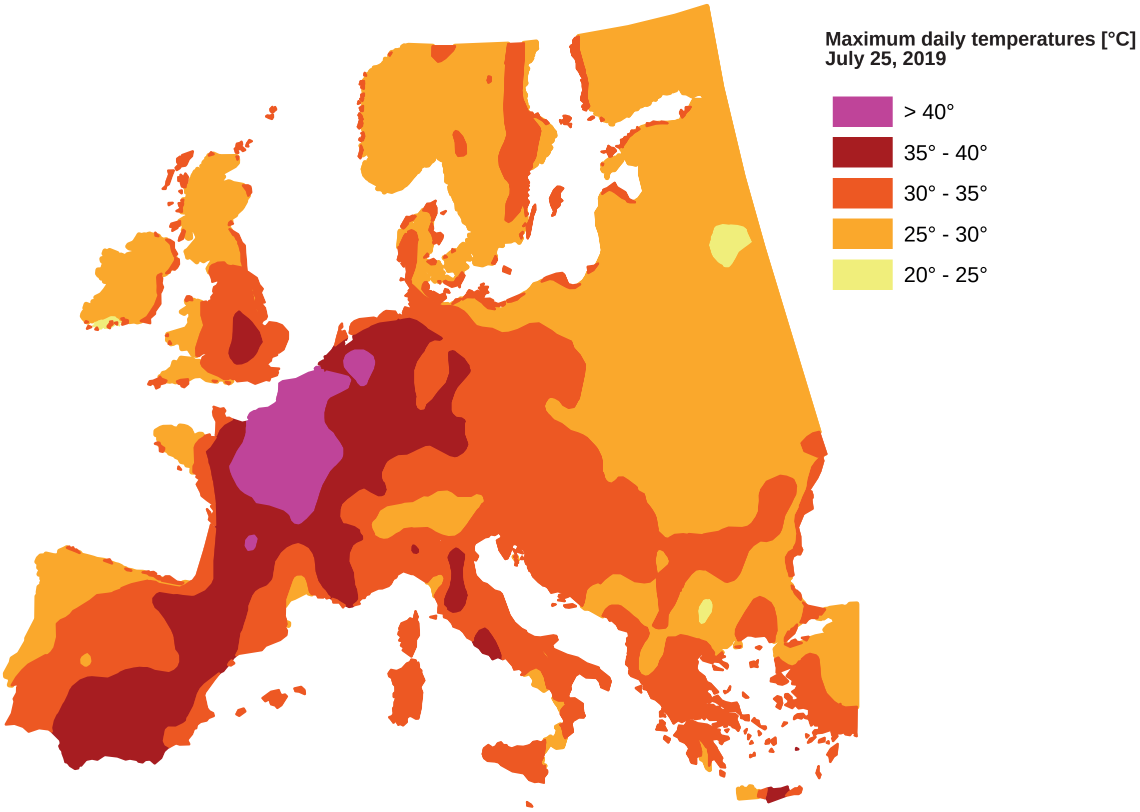

Fig. 4: Maximum temperatures in Central Europe during 25th July 2019. This heat wave represented an event of continental dimension. Based on data from Joint Agricultural Weather Facility (JAWF), NOAA Center for Weather and Climate Prediction, Maryland, USA.

ance theory, as species exhibit different thresholds of heat tolerance. Individual species may be impacted by heat, others by drought, or wind. Species rich communities with redundant members of plant functional types may compensate the decreasing importance of individually affected species. Species richness that seems to be redundant during regular climatic conditions, may come into play in such periods of stress and maintain the community and the entire ecosystem.

European forest disturbance regimes have been found to intensify in general, as reflected in windthrows, bark beetle outbreaks, and wildfires (Seidl et al. 2011). Most studies on heat-related forest fires are focused on the Mediterranean. However, these risks will also increase in Central European conifer forests. Extensive Scots pine forests (*Pinus sylvestris*) in regions with continental climate and on sandy soils are particularly sensitive. Vegetation in general is most responding if drought and heat waves are combined (Abeli et al. 2014).

Ecological warming and heat effects are best studied for aquatic ecosystems with particular emphasis on the marine realm (e.g., Belkin 2009; Smale et al. 2019). However, there are also some limnological studies. Trimmel et al. (2018) simulated the impact of a heat wave to an Austrian river concluding on temperature increases that would completely change aquatic biodiversity. The shading effect of riparian vegetation was assessed to contribute to a cooling of 1 to 2 °C. This highlights the importance of the maintenance and restoration of vegetation structures at river margins.

The urban heat island effect is likely to be enhanced during heat waves. Against the background of warming climate this will create ever more heat stress and health risks to the urban population. Urban vegetation can reduce these risks substantially (Armson et al. 2012). Managing vegetation within the urban environment ('urban greening') is increasingly seen as a mitigation strategy against excessive heat. In dependence on topography, tree cover is more correlated with decreasing air temperatures than other vegetation structures are (Armson et al. 2012; Adams and Smith 2014). Especially large green spaces such as parks have a strong cooling effect. However, the cooling effect on the wider urban area beyond the individual green spaces is under debate and may differ according to the position within the urban matrix (Bowler et al. 2010).

Examples for nature-based solutions:

- Agriculture: Mitigate risks for livestock through shading trees and vegetation structures on pastures.
- Forestry: Reduce risks of wildfires through replacing conifer monocultures by mixed forests; Avoid clearcuts.
- Water management: Re-establish riparian vegetation, trees, and shrubs at brooksides to provide shading and cooling for small rivers and ponds; Promote turbulence and oxygen uptake through natural barriers such as dead wood; Restore channelled rivers in cities.
- Settlements: Promote air cooling through greened house walls; Enlarge green spaces within big cities as cooling islands; Ensure vegetation to survive short-term heat periods.

2.4 Storms and wind impact

Also, the frequency and intensity of storms seems to be increasing during the last decades. The stochasticity and rarity of such events impede a significant proof, even if trends in increasing frequency and intensity of extreme wind speeds were already detected some years ago (Leckebusch et al. 2006) and an increase of severe autumn storms is projected for Western Europe because of the warming Atlantic Ocean (Baatsen et al. 2015). The disturbance patterns in Central European forests are strongly influenced by storm impact (Pettit et al. 2021). Windthrow in forests has caused enormous economic losses to forestry. Uprooted trees have caused fatalities in settlements. In consequence, forest structures are required that are more resistant to wind impact, and tree species and vegetation structures that are less prone to windfall need to be managed in settlements.

During late February 1990 the centennial storms 'Vivian' and 'Wiebke' devastated large parts of Central Europe with 46 fatalities and large economic impact. Most prominent was the storm 'Kyrill' during January 2007 with more than 2 billion Euro of economic damage. However, this happened less than 10 years after 'Lothar' affected France, Switzerland and south-western Germany in 2002 with more than 100 deaths. There have been other important storm events in between and since then. Such storm events can no longer be seen as occurring just once in a lifetime.

Strongest economic and ecological damages were recorded in uniform conifer forests at hill slopes. Topography together with vegetation structure creates an enhanced risk of impact during these events. The likelihood of being affected by storms is dependent on topography and aspect, soil depth, forest management, vegetation structures, and plant functional traits (Fig. 5). In particular, the canopy structure and heterogeneity is of importance (Seidl et al. 2014).

Examples of nature-based solutions:

- Agriculture: Establish wind shields such as hedgerows to reduce wind-speed close to the ground.
- Forestry: Avoid uniform structure of canopy and avoid individual trees as leftover of a former closed canopy; Aim for more site-adapted forest stands with diverse composition of plant functional types.
- Settlements: Replace less storm resistant tree species by hardwood species such as oak; Reduce velocity of wind through vegetation roughness; Establish tree-rows and hedges as windshields in the vicinity of small settlements.

Fig. 5: Windthrow of a single Norway spruce tree in Frankenwald, Germany. Due to anoxic conditions in the subsoil, this specimen developed a shallow root system at this site in a floodplain. The shallow roots did not provide the required fixing of the tree.

2.5 Changes in frost regimes and snow cover

Not only new qualities of extreme weather conditions, but also lacking or reduced climatic pressures and stressors can cause problems in ecosystems. Central European winter was once characterized by continuous snow cover and high likelihood of frost over weeks and even months. This has changed in recent decades where frost periods melted down to short intervals (Kreyling 2010). As frost was a main component of climate for centuries and millennia, biota and ecosystems are adapted to it and rely on the physical control and regulation of pests and diseases. This applies mainly to permanent vegetation in forests, as agricultural practice in crop production mostly avoids this period.

Reduced frost control of pathogens and pests may result in repeated outbreaks and the replacement of dominance patterns. If low diverse Central European ecosystems are under continuous threat of collapse due to cascading effects of a modified frost regime, the options for nature-based solutions are limited if no active management is allowed and the spectrum of potential key species is small. In protected areas, collapsed ecosystems are rarely restored, but rather left to natural succession albeit climate change is adding uncertainty to the evaluation of future trajectories (Fig. 6).

Late frost events during early summer have occurred regularly in the past. Their appearance is also expected in the future, without a substantial change in timing. In a warmer climate with earlier phenological development, such frost events will become more extreme in terms of impact, even if their absolute intensity does not change, because they will hit organisms that are far more developed (Augspurger 2013; Liu et al. 2018). Satellite imagery allows to detect short-term impacts such as the extreme Central European late frost damage in 2011 (Kreyling et al. 2012a). Besides forests, where late frost impact is clearly visible, late frost events do also negatively influence the biomass production in grasslands (Kreyling et al. 2012b). Furthermore, invasion processes by non-native weeds can be controlled by late frost. At Central European grasslands sites with frequent late frost events, Lupin (*Lupinus polyphyllus*) invasion is unlikely to happen (Vetter et al. 2019). Also black locust (*Robinia pseudacacia*) invasion seems to be climatically limited by late frost events (Vitkova et al. 2017).

Examples for nature-based solutions:

- Agriculture: Diversify the varieties and sorts of fruit trees to avoid synchronized flowering and the complete loss of fruit harvests; as late frost also reduces the productivity of grasslands, a higher diversity of grasses and herbs with different capacities to tolerate late frost events needs to be established.
- Forestry: Enhance the diversity in tree species and forest structures, replacing monocultures by polycultures to reduce the intensity of pest calamities.

Fig. 6: Forest decline in high elevation natural Norway spruce forest after bark beetle outbreaks in the Nationalpark Bavarian Forest. The naturally monodominant stands of *Picea abies* have been affected by *Ips typographus* in consequence of dry weather conditions combined with less severe deep winter frost, that would control bark beetle populations.

3 Discussion

In the face of climate change, complex emergencies are no longer a syndrome that is restricted to developing countries. In the recent past, more than 1200 local governments have declared climate emergencies (Davidson et al. 2020), and very likely this number is already outdated. Concepts and suggestions for nature-based coping strategies have been published years ago (e.g. Beierkuhnlein et al. 2008), but the uptake of this knowledge in practice is scarce.

Central Europe is characterized by an equilibrated seasonal climate, where extreme events are naturally rare, high temperatures and moisture deficits are less important due to the vicinity to the ocean. And the seasonality is driven by the annual cycle of solar radiation together with the westerly circulation patterns powered by the jet stream. Now, and increasingly in the future, several of these drivers are becoming less reliable with the consequence of longer periods with stable weather conditions, either wet or dry (Coumou et al. 2015, Pfleiderer et al. 2019).

The geographic position of Central Europe creates a specific vulnerability to an increasing frequency and intensity of climatic extremes. The temperate biome of Central Europe appears more and more fragile in times of climate change. Central Europe is situated in comparably high latitude. The distinctive temperate climate is owed to the energy support of the gulf stream. Evidently, there is less solar energy input in this high latitude compared with the temperate zone on other continents.

Humans in temperate Central Europe are increasingly affected by climate change through a series of weather regimes including heat waves, flooding, and drought. Interactions and translations of the increase in physical energy in the atmosphere are manifold. This includes changes in global circulation patterns (Petoukhov et al. 2013; Mann et al. 2017) and changes in humidity, cloudiness, and precipitation regimes and events (Field et al. 2012).

Several responses of marine and terrestrial surfaces and ecosystems are accelerating the processes such as the declining polar sea ice and its albedo together with the energy that is taken up by now open ocean surfaces. Such developments are well monitored through earth observation (e.g., through the European Copernicus program), and have been a main motivation for cost-intense scientific in-situ explorations, proofing the dimension of change and projecting future trends (e.g., Mirtl et al. 2018).

It is a paradox that agricultural land use is on one side responsible for the loss of species (e.g., Bundesamt für Naturschutz 2009) when, on the other side, biodiversity has been found to be beneficial to agro-ecosystems in face of climate change (Schaller et al. 2010). Positive contributions of biodiversity to agriculture are shown for pest regulation (Bianchi et al. 2006; Scherber et al. 2010), carbon sequestration (Fornara and Tilman 2008; Steinbeiss et al. 2008; Adair et al. 2009), and agricultural production in general (Bullock et al. 2001). These positive effects of biodiversity are strongly dependent on the complexity of landscape structures. Homogenized landscapes are not able to provide beneficial contributions of biodiversity (Bianchi et al. 2006). Some believe that climate change should promote intensified agricultural land use in Central Europe because of the warming climate (Bindi and Olesen 2011). Counting on a more industrialized land use including drainage systems, irrigation, fertilization, and land allocation is probably not providing solutions but rather illusions in the face of climatic extremes.

The future effects of extreme climatic events have been mainly investigated through experiments simulating such conditions (e.g., Jentsch and Beierkuhnlein 2010), whereas biodiversity research in general is more and more extending beyond seminal experimental studies (e.g., Hector et al. 1999) and observational studies (Mollenhauer et al. 2018) to modelling (e.g., Bellard et al. 2012), with an increasing focus on remote sensing-based monitoring (Martinez et al. 2010; Rocchini et al. 2018). In perspective, this entire spectrum of approaches should be applied to transdisciplinary studies on the interaction between biodiversity and extreme climatic events. Still, earth observation for emergency management is operated regardless of earth observation for biodiversity and ecological conditions (e.g., Denis et al. 2016). And the same divergence applies to most run-off models in hydrology (e.g., Mokrech et al. 2015).

Besides the spatial context, temporal trajectories should be understood in times of change. Life cycles of organisms differ considerably between ecosystems. Whereas most agricultural species have a rather short lifespan, tree specimen that germinated in the 19th century did this under very different climatic conditions.

In consequence of the normal duration of research projects, most research on the temporal interaction between biodiversity and climatic impacts is focused on grassland. Considering the time associated with establishing forests, and the efficiency of forests and woodlands in mitigating negative impacts of extreme climatic events together with their capacity in sequestering carbon, it is timely to start with the establishment of diverse and multifunctional forests, woodlands, and hedgerows (Messier et al. 2021).

Important categories of Central European land use such as agricultural grasslands were found to maintain stability and promote the resistance of plant communities to extreme weather conditions if biodiversity was high (Hector et al. 2010; Isbell et al. 2015). The stabilizing effect of plant diversity on productivity is explained inter alia by the plant's temporal emergence and the asynchrony of their phenological performance (Hector et al. 2010). Stabilizing effects of biodiversity were found to range across different aspects of ecosystem organization (Proulx et al. 2010). Due to the complexity of ecological systems and their individual differences, such findings and related theoretical concepts cannot be generalized, yet. For drought, there are still contrasting findings according to the role of biodiversity to buffer shortage in soil moisture (van Ruijven and Berendse 2010; Isbell et al. 2015). Resilience was found to be positively correlated with biodiversity in case of drought impact, but negatively in case of heavy rain (Isbell et al. 2015). In consequence, losing biodiversity can mean losing a multitude of functional protection mechanisms.

Current agricultural practice is still mainly built on subsidies for the management of area. The larger the managed area is, the higher the payments in the frame of European Common Agricultural Policy (CAP) (European Commission 2021b). Besides food production, groundwater protection, avoidance of outgassing pollutants, carbon sequestration, provision of slope stability, erosion control, and other important services of high societal importance are not, or not yet sufficiently, considered in agricultural economy. In consequence, there is no incentive for farmers to deliver these services and to protect natural goods.

As far as biodiversity is concerned, farmers receive support for the establishment of short-lived flower belts, managed like agricultural fields, when at the same time on the predominant area of grasslands biodiversity has been reduced to a few clonal grass species through frequent mowing, fertilization, and soil compaction, with the consequence of no flowers, no pollinators, and in this context also no resistance to surface runoff. Such grasslands act almost like a homogeneous plastic layer conducting heavy rain precipitation over large areas rapidly to the next river.

The large amounts of mud that were deposited during the summer 2021 flood in Western Germany clearly indicate, where runoff was produced. The heavy rain even affected a landscape with a large proportion of agricultural fields and vineyards with no plant cover on the soil surface. Such erosion and sedimentation events could be avoided, but at the expense of less crop production. In consequence, subsidies should no longer be granted just for the managed agricultural space, but rather for the kind of land use.

A pronounced topography as it is given in mountain regions is representing critical and positive traits in face of climate change. On one hand, the spatial heterogeneity of site conditions provides in close proximity safe sites and refugia for threatened species and impacted ecosystems (Lawrence et al. 2021). On the other hand, the topographic energy can enhance surface runoff and add risks to catchments with large agricultural fields. In other words, the orography of a landscape needs to be seen in different contexts when future climate change adaptation strategies are discussed.

In forestry, warmer temperatures are increasing the risk of bark beetle outbreak in Central European mountains. Wind damage can promote first bark beetle infestation. If such an impact is followed by dry conditions, large scale forest decline can be ignited. Further on, pathogens such as fungal diseases affecting conifer roots are stimulated by plant stress.

The interplay of warmer temperatures, reduced frost control of pests, increased likelihood of pathogen infection, modified precipitation and moisture regimes, and wind impact may cause cascading effects and can then threaten forest ecosystem biodiversity, integrity, productivity, and services (Pires et al. 2020). It is rarely one impact alone that causes functional decline of ecosystems.

Nature-based solutions are reaching their limits in cases where species-poor natural ecosystems tend to collapse. In these cases, assisted colonization or managed translocation of previously absent species has been discussed but there is no general consensus (Albrecht et al. 2013; Gallagher 2015). Evaluating the risks and benefits of such active management is possible, if geographical or environmental distances to natural sites are close. In the case of the establishment of exotic tree species, caution should be exercised even if good performance in growth and carbon sequestration is conceivable. Such an intervention would mean the design of a ‘novel ecosystems’ because the ecological components of an ecosystem do not act in isolation. There is an open debate about the approach of novel or designed ecosystems (Morse et al. 2014; Higgs 2017). Although the concept of novel ecosystems is linked with biodiversity and ecosystem services (Evers et al. 2018), there is no clear linkage yet developed towards mitigation of extreme climatic events. The scientific basis seems insufficiently solid to suggest assisted migration or the design of novel ecosystems for practical application.

European states have dedicated large surfaces to protected areas (PAs) for instance through the Natura 2000 network. PAs are considered to be a major tool for preserving biodiversity. In addition, they are of paramount importance for a broad spectrum of ecosystem services. As a matter of fact, the current network of PAs is also affected by climate change (Araujo et al. 2011; Nila et al. 2019).

The IUCN defines, “A protected area is a clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values” (Dudley and Stolton 2008). It is in the very nature of PAs that their area and boundaries are defined clearly. However, in consequence, PAs are static and cannot adapt to a changing environment through shifting their designated space. PAs may consequently lose biodiversity and conservation value under climate change. Investing into areas for nature conservation also means to safeguard societal interests (Essl and Beierkuhnlein 2013). If the conservation of habitats and ecosystems is hampered, negative consequences for human societies are likely to follow.

Nevertheless, there is a promising strategy to preserve and even improve the contribution of PAs to the functioning of landscapes, which is the extension of the PA network. The EU has the goal to protect 30 % of both its land and sea cover by 2030. 10 % of this are expected to be strictly protected (https://biodiversity.europa.eu/; European Commission 2021a). Translating the goal of an extended network of protected areas into practice is a chance to safeguard the species and ecosystems in existing PAs, but even more to establish areas for risk reduction such as retention spaces in upstream catchments and in floodplains aiming to reduce surface run-off during heavy rain events. Hoffmann et al. (2019) found that protected areas in the temperate zone are above average threatened by climate change, which is not a consequence of the intensity of warming, but of the small sizes of these reserves. Thus, it makes sense to enlarge individual protected areas in combination with improving the network through stepping-stones. Priority for multi-purpose protected areas and their respective services should be given to landscapes where climatic extremes are most likely to impact human lives. The European Commission (2021a) postulates that biodiversity and climate values should be linked in this process of enlarging protected areas.

The societal syndrome of urbanization is a main driver of land use changes. Cities have become the major arena of human life, hosting specific biota and many plants and animals. Human well-being is strongly related to urban biodiversity and its services (Kowarik et al. 2020). As adaptation and mitigation to climatic extremes is most important in the urban heat islands with high population density, there is still backlog in gaining significant advantages from biodiversity. In European cities up to now, most nature-based solutions that are related to biodiversity are focused on mere vegetation structures and ecosystems (e.g., rivers, ponds, parks) and less on species and genetic diversity (Kabisch et al. 2016; Xie et al. 2020). However, it is inevitable to consider these levels of biodiversity in addition, together with stress-tolerant key species, to ensure the functioning of green spaces during periods of extreme conditions.

Combining biodiversity policy and governance with climate change policy and governance is reflecting a new perception and awareness. For a long time, biodiversity loss and climate change were seen as two fields of societal concern, with low overlap. International conferences of the parties (COPs) were focused either on one or on the other topic. Now it is the time to acknowledge the need for measures that are linking these global syndromes.

However, this is not yet realized at regional and local scales, in municipalities or districts. There, the current political strategy towards extreme climatic events is either focused on technical engineering and protective constructions or on a posteriori compensation of actually incurred damage. In the future, pro-active action and measures are needed and payments should rather be directed to avoid or reduce damage (e.g., by separating large agricultural fields through hedgerows, creating small wetlands all over landscapes, replacing monocultures by diverse stands, or replacing industrial areas in floodplains by swamps and forests). It would be an illusion to rely only on outdated technological approaches which will not withstand the extreme impacts that are likely to occur. In addition, improper installations such as drainage systems or river regulations must be reversed as they are not solving problems but are a main cause of problems, we have these days.

Positions for trained experts from geosciences, environmental sciences, and ecology should be organized at different levels of governance ranging from large municipalities to districts, regions, and states. The emerging threats necessitate the use and interpretation of big data in real time combined with knowledge on ecosystems and biodiversity. It can be questioned, if established administrative structures and educational directions are still appropriate to tackle these challenges. No longer, civil protection and disaster control can be seen as a matter of lower authorities. The management and development of landscape scale concepts for nature-based solutions can hardly be designed by administrative lawyers. The modern state of scientific knowledge and its rapid progress needs be considered.

Even if the understanding about the responses of ecosystems, species and landscapes to climatic extremes has been improved in recent years, there is still considerable uncertainty due to the novel quality, the speed and the extent of changes that are ranging beyond the evolutionary experience of many biota. Surprises must be taken into account (Beierkuhnlein 2008), stochastic behaviour of ecosystems can be launched (Kreyling et al. 2011), but it is likely that pitfalls for planning can be reduced if biodiversity is promoted. Biodiversity, however, reaches beyond a pure number of species. The composition of communities controls the performance and functioning of ecosystems during and after extreme conditions (Kreyling et al. 2008). Additionally, it is crucial to maintain and develop heterogeneity and asynchrony of community patterns and ecosystems at the landscape scale (Wang et al. 2020). In many cases, spatio-temporal heterogeneity should be re-enforced again!

Adaptation to the expected future impacts of extreme weather events appears inevitable. Coping strategies are urgently required. The here suggested actions will not avoid climatic extremes. These are likely to occur with higher frequency and intensity. By their nature, they cannot be predicted for defined areas or times. However, nature-based solutions can reduce negative effects of climatic extremes, and in some cases combine even carbon sequestration with risk reduction for human lives and goods.

Embracing biodiversity at the entire scale of catchments across ecosystems and land use into disaster prevention should be seen as paramount for cost effective and efficient protection of the society. The examples for nature-based solutions given in this article do not aim to be complete or comprehensive. The given suggestions can easily be complemented by additional concepts. The diversity of species, habitats, and ecosystems comes along with a variety of options for nature-based solutions asking for target-oriented and creative implementation.

Acknowledgements

Thanks to Anne Mare Lux for proofreading this manuscript and to Frank Weiser and Reinhold Stahlmann for cartography. This review was established in the framework of the project Aquaklif in the Bayklif network funded by the state of Bavaria for investigation of regional climate change.

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Author

Prof. Dr. Carl Beierkuhnlein
Department of Biogeography
University of Bayreuth
Universitätsstr. 30
95440 Bayreuth
Germany
carl.beierkuhnlein@uni-bayreuth.de