Impact of natural hazards on global ecosystems

Master Thesis

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Master’s degree programme in Environmental Sciences

Master’s Thesis

Impact of natural hazards on global ecosystems

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I greatly appreciate the patience of Zélie with my never-ending API requests, the discussions with Chris about CLIMADA and ecosystems and Thomas Röösli, Inga Sauer, Sam Lüthi, Simona Meiler, and Tobias Geiger for providing their hazard datasets. In general, thanks to the entire WCR group for the interesting conversations during coffee breaks and barbecues.
# Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resilience</td>
<td>The ability of an ecosystem to cope with disturbance-driven changes without shifting into another ecological state.</td>
</tr>
<tr>
<td>Ecoregion</td>
<td>Regions representing geographically distinct ecological communities with boundaries representing the required area for key ecological processes. In this study, this term is only used to describe the ecoregions dataset.</td>
</tr>
<tr>
<td>Biome</td>
<td>Large-scale ecological regions according to the predominant vegetation. In this study, this term is only used to describe the ecoregions dataset.</td>
</tr>
<tr>
<td>Realm</td>
<td>Biogeographic division of the world in 8 parts. In this study, this term is only used to describe the ecoregions dataset.</td>
</tr>
<tr>
<td>Habitat</td>
<td>Area used by a particular species community. In this study, this term is only used to describe the terrestrial habitat dataset.</td>
</tr>
<tr>
<td>Disturbance legacy</td>
<td>Long-term (decades to centuries) effects of disturbances on structural and spatial patterns of ecosystems.</td>
</tr>
<tr>
<td>Hazard event</td>
<td>A pulsed climate or weather extreme.</td>
</tr>
<tr>
<td>Hazard regime</td>
<td>Historic patterns (intensity, frequency and extent) of natural hazards.</td>
</tr>
<tr>
<td>Frequency</td>
<td>Occurrence of a hazard event per year.</td>
</tr>
<tr>
<td>Return period</td>
<td>Recurrence intervals of a specific event (= invert of the frequency).</td>
</tr>
</tbody>
</table>
Abstract

Natural hazards are a driver of ecological dynamics as they alter individual species, community structure and entire ecosystems. Their ecological impact can be highly variable over space and time: perceived by some species as disastrous but vital for the survival of others. The ability of a system to cope with such events is called ecological resilience and depends on biotic and abiotic factors, as well as the disturbance legacies. With global climate change, intensity, frequency, and spatial distribution of natural hazards will change. As a result, understanding the ecological resilience is crucial to analyse implications of future changes. So far, studies investigated mainly the impact of one natural hazard on specific species, regions, or ecosystem services but an approach to investigate global patterns is still missing. In this thesis, the impact modelling platform CLIMADA was used to assess the current impact of four natural hazards (tropical cyclones, river floods, wildfires, European winter storms) on ecoregions on a global scale. For each natural hazard type, distinct patterns of a hazard's impact on ecoregions were found with large differences among and within ecological realms and biomes. Based on the current hazard-ecosystem interactions, the relative change of hazard activity over the next 60 years was quantified by comparing current and future hazard patterns. Results indicated global changes in hazard activity with new patterns of tropical cyclone activity and river flood events for most ecoregions. To identify the implications of changing hazard regimes for ecoregions, recovery times of experimental field studies were analysed and linked to local return periods of tropical cyclones. Differences between modelled return periods and measured recovery times were found between the analysed sites, but a global scientific link was difficult to prove because of differences in site and hazard characteristics. The knowledge about hazard-ecosystem interactions combined with the implications of recovery times yields great potential to investigate upcoming changes through climate change for specific regions. Lastly, the findings of this thesis were applied on a set of ecologically important areas. Here again, all regions experienced natural hazards to some extent so far, but future intensities and frequencies will change radically for some areas. Additionally, the statistical tests imply a link between hazard occurrence and ecological status which has great potential for further application.
1 Introduction

Natural hazards are pulsed climate or weather events which play a key role on ecosystem dynamics at the global scale. By influencing local species, a natural hazard affects the structure of the biotic community and the entire ecosystem (Chung Te Chang et al., 2020; T. C. Lin et al., 2020; Mori et al., 2013; Oliver et al., 2015; Smith, 2011). High-intensity tropical cyclones, for example, lead to defoliation and crown damage in forest ecosystems. The reduced leaf area creates canopy gaps which enhance growth of shade-intolerant plant species. The patchiness of the canopy gaps allows a coexistence of shade-tolerant and intolerant species ultimately resulting in increased diversity. Further, the reduced photosynthesis rate decreases the net primary productivity, and the additional biomass through the leaf litter increases soil and stream water nutrient levels. This affects the nutrient cycles of the entire ecosystem. Hence, the common cyclone-related defoliation influences forest ecology on multiple scales (T. C. Lin et al., 2020). This example illustrates how natural hazards strongly influence ecosystems in the short- and long term in a variety of aspects (T. C. Lin et al., 2020; Mori et al., 2013; Seneviratne et al., 2012; Smith, 2011).

In the past, natural hazards were often perceived as disturbance events with disastrous effects on ecosystems. Based on this point of view, management strategies focused on the avoidance of large disturbances which lead to questionable land policies (Hoss et al., 2008; Leverkus et al., 2019; Mori, 2011; Pausas et al., 2008). One well-studied case is the fire management of the past century in the Appalachian mountain range. Until late 19th century, the principal vegetation cover was an oak-dominated forest that experienced area-wide fires every 6-13 years. After intensive logging in the industrial period (1880-1920), the forest ecosystem was destroyed, and the proposed restoration management technique was fire-suppression. Over the next decades, tree density increased but the endemic fire-associated vegetation did not recover. Following studies of historical disturbance patterns, which represent the hazard regime affecting the region, revealed a crucial role of frequent fires for the landscape and for the existence of endemic plant species as a result of its long-term fire history. Consequently, a new management technique was suggested, the reintroduction of frequent fires, to maintain the fire-associated vegetation (Flatley et al., 2013; Hoss et al., 2008). Although such large-scale fire events may be perceived as socially and ecologically disastrous, they may be greatly beneficial for ecological diversity and integrity as a result of increased heterogeneity (Adámek et al., 2016; Flatley et al., 2013; Hoss et al., 2008; Leverkus et al., 2019; Mori, 2011; Pausas et al., 2008).

The long-term impact of a hazard event on an ecosystem is determined by its resilience which is defined as ‘the ability of an ecosystem to cope with disturbance-driven changes’ (Mori, 2011). It describes the capacity of a region to absorb disturbances without shifting into another equilibrium state (Mori, 2011). The level of resilience is affected by changes in the abiotic environment and biotic interactions, as well as the disturbance history and legacies of a region (Mori, 2011; Xi, 2015). Disturbance legacies are defined as long-term (i.e., decades to centuries) effects on structural and spatial patterns of ecosystems (Seidl et al., 2014). An example for such disturbance legacy effects is the canopy height in cyclone-affected tropical broadleaf forests. For instance, because of constant pruning, the highly frequented Fushan Experimental Forest in Taiwan, which experiences about 13 storms per year, has a lower stand height compared to sites that experience no cyclones. Among different sites in cyclone-prone areas, the biotic communities were functionally more stable (e.g. fluctuations in biomass, leaf area, wood density, tree height) in regions with higher numbers of storms per year (Hogan et al., 2018; Ibanez et al., 2019). Hence, the degree of hazard-ecosystem interactions can serve as an indicator for the ecological resilience and the equilibrium state it is returning to (Chung Te Chang et al., 2020; Hogan et al., 2018). The level of adaptation present in the equilibrium state of a region defines the ecological response of a region and the fate of an ecosystem in future (Hogan et al., 2018).
Given the predicted changes of frequency, intensity, and distribution of natural hazards with global climate change, understanding their current patterns is crucial to investigate implications of future changes (Seneviratne et al., 2012; Smith, 2011). For instance, tropical cyclone activity is expected to decrease in frequency (i.e., the occurrence of a hazard per year), but increase in intensity connected with a poleward shift on a global scale (Knutson et al., 2015; Kossin et al., 2016). Flood projections for the late 21st century indicate major changes including increasing frequencies worldwide except for northern America and central and western Eurasia (Hirabayashi et al., 2008). Further, depending on future environmental resources and conditions, a global rearrangement of fire probabilities is likely (Krawchuk et al., 2009). However, changes in hazard patterns are not limited to global hazards, they can also occur locally. For example, maximum wind speeds and the spatial extent of winter storm in Europe are also predicted to increase (Usbeck, Wohlgemuth, Dobbertin, et al., 2010). Future changes in hazard patterns will affect ecosystems on a local and global scale (T. C. Lin et al., 2020). When these novel hazard occurrences exceed a region’s resilience, the ecosystems cannot return to its equilibrium state but might shift to another one with a different ecological structure (T. C. Lin et al., 2020; Mori, 2011).

The description of hazard-ecosystem interactions and the resulting equilibrium state is crucial to investigate current resilience levels. Especially regarding upcoming changes of global hazard patterns and potential shifts of ecological states, resilience is the key to investigate future implications. So far, several studies investigated the impact of one hazard on a specific ecosystem, region or species but an analysis of multiple hazards on a global scale is missing (Chuvieco et al., 2013; Thom & Seidl, 2016; Xu et al., 2015). In this Master Thesis, the goal is a global analysis of the impact of natural hazards on ecosystems. Since there is no yet known general functional relation of a hazard’s impact to ecosystems, the impact is determined here in a categorical approach by the hazard’s intensity and frequency (Smith, 2011; Xi, 2015). Using the platform CLIMADA, current impacts of four natural hazards (Tropical Cyclones, River Flooding, Wildfires, Winter Storms) are analysed in ecological regions. As ecosystems are adapted to the prevalent hazard regime, these computed hazard patterns are assumed to be the state of equilibrium between ecosystems and the hazard regime affecting the system. Based on this equilibrium state, implications of rapid climate change for hazard-ecosystem interactions can be assessed by comparing the future estimates with the current patterns. This allows an analysis of changes in global hazard patterns and local shifts in hazard regimes affecting ecosystems. To identify the implications of these changes for ecosystems, recovery times of experimental field studies are analysed and linked to the local return periods (i.e., recurrence intervals of a specific event). With all this in mind, the ecological role of hazards and the implications of upcoming changes brought upon by climate change is determined for specific regions of ecological importance.

The used datasets for ecosystems and hazard, as well as the impact computation methods are described in Section 3. Resulting outcomes are presented and briefly discussed in Section 4. All figures illustrating hazard impacts shown in this section are visualised in a larger format in the appendix. The last Section 5 contains the conclusion to this thesis including its limitations and future perspectives.
2 Methods

To quantify the impact of extreme weather and climate events on global ecosystems, the open-source software CLIMADA (CLImate ADAptation) was used which is written in Python and available on GitHub (https://github.com/CLIMADA-project/climada_python). This impact modelling platform allows globally consistent impact analysis and is based on three components: exposure, hazard, and vulnerability.

2.1 Exposures

To investigate different aspects of hazard-ecosystem interactions, two ecosystem datasets were used: ecoregions (Ecoregions 2017 ©, 2017) and terrestrial habitats (Jung, Dahal, Butchart, Donald, De Lamo, et al., 2020). Both datasets are globally available on two levels of detail, but they differ in the definition of ecological regions. Ecoregions are locally distinct assemblages of biodiversity and terrestrial habitats represent globally connected vegetation types derived from parametric models. This allows a differentiated evaluation of hazard-ecosystem interactions on local- and regional scales. Due to the lack of information about the influence of hazards on marine ecosystems, mainly terrestrial ecosystems were examined. Further analysis was done with different areas of interest.

2.1.1 Ecoregions

The first map of ecoregions was published in 2001 and is based on more than 100 years of biogeographic knowledge and extensive field studies (Dinerstein et al., 2017). This quantitative approach resulted in geographically distinct ecological communities covering not only vegetal species but all known taxa with boundaries representing the required area for key ecological processes (Dinerstein et al., 2017). Hence the ecoregions present the actual distribution of taxa and therefore, differ from datasets derived from global and regional models (Olson et al., 2001). This first map was largely revised and a new Ecoregions2017 ©RESOLVE map was published in 2017, which is the one used in this study. It is important to note that this dataset does not consider artificial areas. It consists of 847 ecoregions organized in geographic biomes and realms (see Figure 1). The biome concept structures the world into 14 large-scale ecological regions according to the predominant vegetation. Realms are the broadest biogeographic division of the world with 8 categories according to geological history and the resulting distributional patterns of species (Dinerstein et al., 2017; Olson et al., 2001).

Figure 1 Map of the ecoregions grouped by the realms. Every colour illustrates one of the 847 ecoregions. Ecoregions 2017 ©, 2017
The provided dataset includes the geometry data for each ecoregion in the form of polygons, as well as the associated biome, realm, and shape area. While comparing the shape area in the dataset with the published values, some discrepancies were found. As a result, the area of each ecoregion was recomputed with ArcGIS. Since the dataset is given in the geographic coordinate system World Geodetic System 1984 (WGS 1984) and the area calculation in ArcGIS is done with planimetric algorithms, the dataset had to be reprojected to a projected coordinate system (flat, two-dimensional representation of the Earth). Therefore, the equal earth greenwich projection of the WGS 1984 coordinate system (EPSG: 8857) was used which is suitable for analysing precise surface areas (GIS Mapping Software, Location Intelligence & Spatial Analytics | Esri, 2016). After calculating the area, the dataset was reprojected to the geographic coordinate system WGS 1984 (EPSG: 4326). The comparison of the computed and the published ecoregion areas resulted in differences of ±0.65%.

2.1.2 Terrestrial habitats

![Map of the regional level 2 of the terrestrial habitats. Every colour illustrates one of the 79 habitat classes including artificial areas coloured in red.](image)

The terrestrial habitats dataset combines land cover, climate and land use data. Per definition, habitats are areas used by a particular species community (Jung, Dahal, Butchart, Donald, De Lamo, et al., 2020). Based on the habitat classification scheme of the International Union for Conservation of Nature (IUCN), a parametric model was applied to the three components (land cover, climate and land use data) to assess habitat distribution. The final global map of terrestrial habitat types is provided for 2015 with WGS 1984 as Coordinate Reference System and a spatial resolution of approximately 100 m at the equator. Unlike the ecoregion’s dataset, it includes an artificial habitat class covering urban areas, pasturelands, and plantations. The data is designed to be globally consistent for two levels provided that enough information for the classification is available. The legend of Level 1, also called the global level counts 12 classes. The more detailed Level 2 so called regional level consists of 79 classes and reaches a higher level of detail than Level 1 (Figure 2). However, not every site has a level 2 class assigned, since not always enough information is available for the more detailed classification (Jung, Dahal, Butchart, Donald, De Lamo, et al., 2020).

In this analysis, the global composite image at native 100m Copernicus resolution for both levels was used (Jung, Dahal, Butchart, Donald, Lamo, et al., 2020a, 2020b). Since the focus of this analysis lies on terrestrial areas, most marine habitats were excluded except for some coastal areas (coral reefs, intertidal areas, and tidepools). After selecting the habitats of interest, the dataset consists of 7 classes in Level 1 and 58 habitat types in Level 2. As the analysis in CLIMADA is done with a resolution of approximately 4 km, the dataset was resampled by majority to 0.01° with ArcGIS and finally saved as multi-polygon shapefiles.
2.1.3 Areas of interest

Datasets about different regions of ecological interest are listed in Table 1. They cover a variety of aspects that represent ecological importance via species or habitat types, intactness via protection or importance status, or naturalness. All these aspects are important for biodiversity conservation (Allan et al., 2017; Chaplin-Kramer et al., 2020; Parrott, 2010; Ramsar Convention Secretariat, 2014; Spalding et al., 2014).

Table 1 Summary of the datasets with their provided geometry and resolution.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Subject Matter</th>
<th>Geometry</th>
<th>Resolution</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Species Richness</td>
<td>Number of Plant Species</td>
<td>Hexagons (~7792 km²)</td>
<td>95 km</td>
<td>Ellis et al., 2012</td>
</tr>
<tr>
<td>Animal Species Richness</td>
<td>Number of Animal Species</td>
<td>Points</td>
<td>5 km</td>
<td>IUCN, 2021</td>
</tr>
<tr>
<td>Mangroves</td>
<td>Habitat Type</td>
<td>Polygons</td>
<td>1 km</td>
<td>Jung, Dahal, Butchart, Donald, De Lamo, et al., 2020</td>
</tr>
<tr>
<td>Coral Reefs</td>
<td>Habitat Type</td>
<td>Polygons</td>
<td>1 km</td>
<td>Jung, Dahal, Butchart, Donald, De Lamo, et al., 2020</td>
</tr>
<tr>
<td>RAMSAR</td>
<td>Wetlands of International Importance</td>
<td>Polygons, Points</td>
<td>Not defined</td>
<td>Ramsar Convention Secretariat, 2014</td>
</tr>
<tr>
<td>Protected Areas</td>
<td>Terrestrial and Marine Protected Areas</td>
<td>Polygons, Points</td>
<td>Not defined</td>
<td>UNEP-WCMC, 2021</td>
</tr>
<tr>
<td>Last of the Wild</td>
<td>Wilderness areas free of industrial scale activities and other human pressures</td>
<td>Polygons</td>
<td>1 km</td>
<td>Allan et al., 2017</td>
</tr>
</tbody>
</table>

The plant species data is estimated by using the species richness model of Kreft & Jetz (2007) which is based on empirical statistical relationships between species richness patterns and environmental variables (Ellis et al., 2012). The animal species richness data is derived from IUCN and combines raw ranges for amphibians, birds, and mammals. The resulting raster data has not been refined by altitude and landcover and is biased towards vertebrates (IUCN, 2016). Based on these datasets, biodiversity hotspots were calculated from the 10% of the terrestrial surface with highest numbers of species. Mangrove and coral reef habitats were extracted from the second level of the terrestrial habitats data described in Section 2.1.2. The RAMSAR data lists all wetlands with significant value for countries as well as humanity as a whole (Ramsar Convention Secretariat, 2014). Similarly, the protected areas dataset includes all regions of the world with a protection status (UNEP-WCMC, 2021). Both datasets map their sites in polygons or points, where the latter represents the centremost point of the site. Any point was converted into a polygon by applying a circular buffer of 1 km. The last of the wild data divides the world into areas without anthropogenic pressure representing intact habitats globally (Allan et al., 2017).
2.2 Hazards

In CLIMADA, data for four natural hazard types are currently available: tropical cyclones, wildfires, river floods and European winter storms (Table 2). For some of them, future scenarios exist based on the Representative Concentration Pathway (RCP) adopted by the IPCC (IPCC, 2014). In the following, the main characteristics of the used datasets are summarized.

Table 2 Summary of the natural hazards used in this analysis.

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Data</th>
<th>Historical Data Period</th>
<th>Events</th>
<th>Additional Synthetic events</th>
<th>Unit</th>
<th>Resolution</th>
<th>Extent</th>
<th>Future Scenario</th>
<th>Detailed description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical cyclones with future scenarios by Knutson</td>
<td>IB-TrACS</td>
<td>1980 - 2020</td>
<td>Single probabilistic events</td>
<td>50, resp. 10/ year</td>
<td>m/ s</td>
<td>140 arc-sec</td>
<td>Global</td>
<td>RCP 2.6, 4.6, 6.0, 8.5</td>
<td>Aznar-Siguan &amp; Bresch, 2019; Knutson et al., 2015</td>
</tr>
<tr>
<td>Tropical cyclones with future scenarios by Kerry</td>
<td>National Hurricane Centers's best track archive (HURDAT)</td>
<td>1988 - 2012</td>
<td>200 probabilistic years</td>
<td>m/ s</td>
<td>360 arc-sec</td>
<td>Global</td>
<td>RCP 2.6, 6.0</td>
<td>Geiger et al., 2016</td>
<td></td>
</tr>
<tr>
<td>Wildfires</td>
<td>NASA Earthdata acquired by MODIS satellites</td>
<td>2000 - 2020</td>
<td>20 fire seasons</td>
<td>K</td>
<td>120 arc-sec</td>
<td>Global</td>
<td>No</td>
<td>Lüthi et al., 2021</td>
<td></td>
</tr>
<tr>
<td>River floods</td>
<td>Inter-Sectoral Impact Model Intercomparison Project phase 2b (ISIMIP2b)</td>
<td>1971 - 2010</td>
<td>480 probabilistic years</td>
<td>m</td>
<td>150 arc-sec</td>
<td>Global</td>
<td>RCP 2.6, 8.5</td>
<td>Sauer et al., 2021</td>
<td></td>
</tr>
<tr>
<td>European winter storms</td>
<td>Windstorm Information Service (WISC)</td>
<td>1940 - 2014</td>
<td>Single probabilistic events</td>
<td>29/ event</td>
<td>m/ s</td>
<td>140 arc-sec</td>
<td>Europe</td>
<td>No</td>
<td>Röösli et al., 2021</td>
</tr>
</tbody>
</table>
The Tropical Cyclones dataset results from the International Best Track Archive for Climate Stewardship (IB- TrACS) archive (Aznar-Siguan & Bresch, 2019). Since not all recorded tracks contain all the necessary information, especially before 1980, the data between 1980 and 2020 which includes 1796 events as used. Besides historic events, additional synthetic tracks were generated according to the method in Kleppek et al. (2008). With 50 additional events for each historical year, a tropical cyclone dataset covering 2000 years with a total of 56480 events was generated. Based on the IB- TrACS dataset, changes in hazard intensity and frequency were computed according to the method of Knutson et al. (2015) as implemented in CLIMADA. The two scenarios compared in the scope of this thesis are RCP 2.6 for 2020 representing the current state and RCP 6.0 in 2080 as the future scenario with climate-induced changes of tropical cyclones. To reduce the size of datasets and speed up calculations for the scenarios with Knutson's estimates, 10 additional tracks per year were used.

The second implementation of climate change and the corresponding change of tropical cyclones is based on simulated hurricane tracks provided by Kerry Emanuel (Kossin et al., 2016) and the concept of Geiger et al. (2016). This approach generates future projections by artificial ‘seeding’ of a large number of tropical cyclone tracks that are computed by a dynamical hurricane model. In this thesis, two different general circulation models (GCM’s) (MIROC5, GFDL-ESM2M) were used with 100 realisations each for 2020 and 2080. As a result, each dataset consists of 200 years with 946'930 events in 2020 RCP 2.6 and 672'753 events in 2080 RCP6.0. The difference between Knutson’s method and Kerry’s tracks is the definition of the future projections. Knutson’s projections vary only in intensity and frequency whereas Kerry's tracks consist of an entirely different set of events (Geiger et al., 2016; Knutson et al., 2015; Kossin et al., 2016).

The wildfire dataset is produced following the logic described in Lüthi et al. (2021). It is based on the historical data provided by NASA Earthdata and derived from the Fire Information for Resource Management System (FIRMS) (NASA, 2021). The measurements of brightness in Kelvin [K] were acquired by the MODIS instruments on board of different satellites to provide near real-time active fire locations. The FIRMS data is subsequently mapped on a regular raster with a spacing of 120 arcsec using the BallTree nearest-neighbour algorithm (Pedregosa et al., 2011). In the case that two FIRMS data points fall on the same raster grid-point, the maximum intensity was taken. Fires were aggregated to seasons, to establish comparability. Given the start of the MODIS mission, data is available since November 2000, resulting in 20 available fire seasons (2001-2020) (Lüthi et al., 2021).

The river floods dataset is modelled by simulations based on spatially explicit global maps of flooded areas and flood depth (Sauer et al., 2021). The provided hazard object is made of 24 combinations of GCM / global hydrological model, resulting in a total of 20x24=480 probabilistic years (each year being a CLIMADA event). The frequency of each of these years was then set to 1/480. To compare current and future states, the RCP 2.6 scenario in 2020 as today and the RCP 8.5 in 2080 as future climate scenario was used in this thesis.

The European winter storm dataset is based on historic windstorm footprints derived from the Windstorm Information Service (WISC) of the Copernicus Climate Change Service (Röösli et al., 2021). The dataset covers 1940-2014 and contains around 140 European winter windstorm events. To reduce the file size and speed up the impact calculation, events with wind gusts below 20 m/s were excluded. In addition to the historical data, 29 synthetic events were computed for each hazard event according to the method described in Schwierz et al. (2010). Finally, the used dataset contained 4260 storm events for Europe.
2.3 Vulnerability

Besides exposure and hazard data, CLIMADA needs vulnerability in the form of impact functions for calculating a hazard's impact on an exposure. According to the available dataset and after consulting available literature, low, middle, and high-intensity categories for each hazard type were defined, as presented in Table 3. This categorical approach is independent of the exposure type and thus, allows an impact analysis in a globally consistent way among very diverse ecosystems.

Table 3 The defined low-, middle- and high-intensity categories for each natural hazard.

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Category</th>
<th>Low</th>
<th>Middle</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical cyclones</td>
<td></td>
<td>33-50 m/s</td>
<td>50-58 m/s</td>
<td>58-200 m/s</td>
</tr>
<tr>
<td>River floods</td>
<td></td>
<td>0-1 m</td>
<td>1-3 m</td>
<td>3-35 m</td>
</tr>
<tr>
<td>Wildfires</td>
<td></td>
<td>0-60°C</td>
<td>60-150°C</td>
<td>150-240°C</td>
</tr>
<tr>
<td>European winter Storms</td>
<td></td>
<td>20-35 m/s</td>
<td>35-60 m/s</td>
<td>60-80 m/s</td>
</tr>
</tbody>
</table>

The standard categorization for tropical cyclones used to define intensity classes is the Saffir-Simpson scale. It defines five levels according to maximum wind speed (National Hurricane Center, 2021). Events of category 1 or 2 mostly have minor impacts like broken limbs or foliage loss in forests (T. C. Lin et al., 2020; Mabry et al., 1998). A category 3 tropical cyclone has ambiguous effects depending on the location and the ecosystem: records from no impact up to uprooting were found. In contrast, category 4 and 5 events often result in high defoliation and mortality rates (T. C. Lin et al., 2020; Mabry et al., 1998). With this classification, 89.5% of the average annual number of tropical cyclones based on IB- TrACS data in 2020 with 50 additional tracks per year is category 1, 7.3% are middle and 3.16% are high-intensity events.

For defining the categories of river flood events, the Technical Report of the European Commission about global flood depth-damage functions was used as a guideline (Huizinga et al., 2017). It contains a collection of maximum damage values for agricultural sites in different countries and calculations of continental and global damage-functions (Huizinga et al., 2017). In this thesis, flood events up to 1 meter are defined as low-, 1-3 meter as middle-, and above 3 meters as high-intensity events. With this classification, 5.83% of the expected average annual number of events of river floods are of low-category, 24.5% are middle-, and 69.68% are high-intensity events.

The perception of high temperatures varies between the different parts of a plant. Seeds and rhizomes in the soil seem to be less sensitive to heating and their survival depends on the depth distribution (Odion & Davis, 2000). Heating experiments indicated lethal damage to aboveground plant tissue and rhizomes at 60°C whereas seeds were damaged lethally at 170°C (Odion & Davis, 2000; Schimmel & Granström, 2016). Thus, for this thesis fires with a maximum temperature above 333 Kelvin (= 60°C) were defined as middle, and above 420 Kelvin (= 147°C) as high-impact fires. With this classification, 52.53% of the average annual number of wildfire events of the last 20 years are low-severity fires, 46.54% are middle, and 0.93% are high-severity wildfires.

Winter storms are measured in the same unit as tropical cyclones, but their wind gusts do not exceed 80 m/s. In boreal forests, wind gusts of 20 m/s could already be linked to treefall, 25-32 m/s resulted in small-scale disturbances of deciduous forests and wind speeds of 32-39 m/s had catastrophic impacts (Quine & Gardiner, 2007). On the contrary, no impact was noted below 30 m/s gusts in Britain and only wind speeds above 40 m/s, respectively 35 m/s in Swiss forests, resulted in widespread damage (Gregow et al., 2017; Quine & Gardiner, 2007; Usbeck, Wohlgemuth, Pfister, et al., 2010). As a result, the categories used in this thesis are 20-35 m/s as low, 35-60 m/s as middle and 60-80 m/s as high impact storms. Using this classification, 97.1% of the expected average annual number of events are low-impact storms, 2.87% are middle-impact storms, and only 0.00004% are high-impact storms.
2.4 Impact calculation

The framework CLIMADA combines exposure, hazard and impact function and returns a hazards impact. To explain the computation of hazard impacts per ecoregion, Figure 3 illustrates a simplified example with four ecosystems, two windstorm events and one hazard category.

In a first step, the polygons of the exposure data (ecoregions, terrestrial habitats, areas of interest) are linked to the geographic hazard (represented as differently coloured points in the toy model). To do so, a global grid of points is assigned to the exposure data which in turn is connected to the centroids of the hazard data. Since a regular grid of the globe inaccurately represents areas far from the poles, a projected equal-area grid that has the same area for each grid cell is used to assign points in a globally consistent way. Therefore, a global grid with a resolution of 4x4 km was created based on the NSIDC EASE-Grid 2.0 Global (EPSG: 6933) projection. The generated global grid was then converted into the hazard’s coordinate reference system (World Geodetic System 84 (WGS 84), EPSG: 4326). These geometry points were then spatially joined to the exposure polygons. The merging of hazard centroids and exposure points was done by using the assign_centroids function of the CLIMADA Python exposures module. This function assigns the closest hazard centroid to each exposure point based on the nearest neighbour interpolation. Points further away than 100 km of the next centroid were ignored. In a next step, for each of these exposure points 1 was set as the ir value. The resulting dataframe with assigned exposure points, hazard centroids and values represents the exposure.

In a second step, a hazard’s impact is computed with this exposure and hazard data. For each hazard event, hazard intensities are analysed at each exposure point. Every time a point experiences a hazard event of one of the defined categories, it is listed as affected. The number of affected exposure points within one region is then summed up per category (left table on the bottom in Figure 3). This represents the affected area per ecoregion by the hazard category. The sum of affected points is then multiplied by the frequency of the event. In a last step, this value is summed up for all events which returns the expected average annual number of events summed over all locations for category 1 (middle table on the bottom in Figure 3). As regions differ in their area size, this absolute value is divided by the area of a region to get a more comparable relative value (right table on the bottom in Figure 3). In the simplified example (Figure 3), the absolute value is highest in shrublands, but in relative terms grasslands are the most affected ecosystem. This method was applied to all four hazard types and their three hazard categories (low, middle, high).

A different viewpoint on a hazard’s impact on specific regions is given by the return period. Since the frequency of a hazard event is given in years, the invert of the frequency is the return period of the event.
Thus, the return period of low-, middle- or high intensity events per exposure point is equal to the invert of the expected average annual number of events per exposure point and category.

2.4.1 Analysis of hazard-habitat linkages

To analyse a potential link between habitat distribution and hazard patterns, each exposure point is designated as affected if it experiences at least one event, independently of the hazard category. Based on the ratio of affected versus unaffected exposure points, the proportion of affected area within a habitat type was calculated. This value highlights the habitat types experiencing hazards in a large part of their area indicating a potential connection between hazard occurrence and habitat distribution.

In addition, statistical correlation tests between habitat and hazard patterns were performed. Therefore, the Kruskal-Wallis test and a point-biserial correlation analysis was performed. The Kruskal-Wallis test compares the median of multiple groups and assumes no difference between them (null hypothesis). Like other statistical tests, it calculates a test statistic (H-value) and compares it to a distribution cut-off point (McKight & Najab, 2010). In this example, it points out if there is a difference between the hazard pattern in the 72 terrestrial habitats. The hazard pattern is assessed through the expected average annual number of events summed over all categories per exposure point. According to this data, it tests the null hypothesis which states that the median of average annual number of events per exposure point is the same for all habitat types. Hence, a p-value lower than 0.05 indicates that depending on the habitat type, the number of hazards statistically significantly differs. However, this test only indicates a significant difference between all habitats but it does not specify which habitats exactly are different (McKight & Najab, 2010). For this reason, the point-biserial correlation analysis which measures the relationship between a dichotomous and a continuous variable was performed (Kornbrot, 2014). It is a special case of Pearson's correlation and tests the probability that there is no effect or relationship between the variables. Here, the dichotomous variable was habitat distribution. For each separate habitat class, 1 was assigned to each exposure point within the habitat and 0 to those points outside of the habitat. The hazard pattern indicated by the expected average annual number of events per exposure point and category was defined as the continuous variable. After computing the correlation for each habitat type and hazard category, the test returns a correlation coefficient for each combination allowing a more in-depth analysis. Since both approaches have certain disadvantages, a comparison of both results (proportion of affected area and statistical correlation coefficients) facilitates a better understanding of potential connections between hazards and habitats. The proportion of affected area overrates small habitat types, as a hazard affects more easily a high percentage of a small habitat than large ones. On the contrary, the correlation coefficient of the point-biserial test is size dependent. Hence, large habitat types can have higher coefficients.

2.4.2 Analysis of hazard-diversity linkages

To investigate the potential link between species richness and hazard patterns, different statistical tests were used. Besides investigating Pearson's correlation coefficients between the two continuous variables (number of species, average annual number of hazard events per exposure point summed over all categories), a second analysis with a categorical approach was done to analyse the influence of multi-hazards on diversity. To do so, the hazard occurrence (point experiences at least one event of any category) was determined for each hazard type and exposure point and then summed up over all hazard types per exposure point. As a result, a total hazard value between 0 and 3 hazards per point was computed on the global scale (tropical cyclones, river floods, wildfires) and a value between 0 and 4 on the European level (additional European winter storms). In addition, species richness was divided into three categories (low, middle, high diversity) based on the number of species per point. The Chi-Square test of independence compares the observed to the expected observations and tests whether a statistical link between the two variables exists. With a significant p-value, the null hypotheses can be rejected assuming that there is no statistical connection between the two variables (Connelly, 2019; Sharpe, 2015). The input data is displayed in crosstabulation tables that represent the distribution and intersection of the two variables. Similar to the Kruskal-Wallis test (see Section 2.4.1), the Chi-Square analysis only indicates a general relation over all categories but does not show further details (Sharpe, 2015). Therefore, the Spearman's correlation coefficient measures the correlation between two ranked variables and was used to determine the magnitude and direction of the connection between the categories (Myers & Sirois, 2014).
3 Results

The results section starts with a general analysis of the impact of global hazard patterns on ecoregions and their link to habitat distribution, and then focuses on specific aspects (climate change, recovery times) and cases (areas of interest) of this hazard-ecosystem interaction.

3.1 Current hazard patterns

This section gives an overview of the current patterns for each natural hazard. First, global patterns are analysed by the value of expected average annual number of events per biome and ecoregion (see section 2.1 and 2.4). The Ecoregions2017©RESOLVE map with its biogeographic units was used to calculate the average annual number of hazard events (Dinerstein et al., 2017). Since the terrestrial habitats data is organized on global and regional levels with the aim to map habitat distribution around the world, regions are categorized based on their vegetation characteristics but not by biogeographic regions (see Section 2.1.2). As a result, regions distributed around the world that are not spatially connected can be in the same habitat class. For instance, the level 2 habitat temperate forest occurs in northern America, Europe and Asia. This leads to abstract results with high tropical cyclone activity in European forests because of the high number of cyclones in Asia (Figure 4).

![Figure 4 The average annual number of middle-intensity tropical cyclones per level 2 habitats. The colour indicates the absolute value per habitat type.](image)

In a second step, potential relations between hazard occurrence and the distribution of a habitat type were investigated. The goal is to find connections between habitats of coarser scale and natural hazards. Hence, the regional level 2 data of the terrestrial habitat dataset which has the advantage of having detailed, but still globally connected regions (as described in Section 2.1.2). With this dataset, the proportion of hazard-affected area was computed and compared to the statistical Kruskal-Wallis and point-biserial test (see section 2.4).
3.1.1 Tropical cyclones

Most tropical cyclones originate in the western North Pacific and have landfall on east and southeast Asia. Central and North America experience mainly low impact hurricanes from the southern Pacific and northern Atlantic (T. C. Lin et al., 2020). Consequently, the global analysis of the impact of tropical cyclones on the realm level (described in Section 2.1.1) resulted in the highest average annual number of events in the Indomalaya for all categories (Figure 5). No other realm has comparable amounts of tropical cyclones on average per year. When considering the relative affected area, the realm Oceania with its many islands experiences the highest rate of tropical cyclones on average per year and km² in all categories.

![Figure 5: Average annual number of tropical cyclones per ecological realm for all three categories. A) illustrates the absolute values and B) the relative values per realm area [km²].](image)

On the biome level, the impact analysis showed the highest average annual number of tropical cyclones in the tropical & subtropical moist broadleaf forests in all categories (Figure 6). This biome predominantly occurs in tropical regions of central and southern America, central Africa and south and southeast Asia. The second-most affected biome is the temperate broadleaf & mixed forest which experiences mainly low- and middle-intensity hazards. This type of forest covers primarily the eastern US coast, eastern Asia, and Europe. However, European temperate forests are less affected than the American and Asian part of the biome as illustrated in Figure 5. In relation to the size of the biome, tropical & subtropical coniferous forests experience the highest average annual number of low and middle-intensity but the mangroves have the highest number in high-category cyclones. Coniferous forests are mainly found in the Neotropical and the Indomalaya realm with part of the Philippines and Caribbean islands as most affected ecoregions. Highly-affected mangroves are located at the eastern and western coast of central America and in southeast Asia.
Since tropical cyclones originate almost exclusively over tropical seas, tropics are naturally highly affected, but the final analysis on the ecoregion level reveals differences between and within the realms. Within the highly affected basin Northwest Pacific, cyclone-prone ecoregions are located at the eastern coast of the Indomalaya and the Palearctic. Especially tropical & subtropical moist broadleaf forests in China, Taiwan, and the Philippines, as well as temperate broadleaf & mixed forests in the Japanese archipelago are affected (Figure 7). Cyclone-prone ecoregions in the other realms are the Pilbara shrublands in Australasia, Southeast US conifer savannas in the Nearctic, Cuban dry forests in the Neotropics, and Madagascar humid forests in the Afrotropic. In comparison to the highly affected ecoregions of the other realms, ecoregions in the Indomalayan and the Palearctic experience up to 10 times higher values of the average annual number of all category tropical cyclones in absolute and relative values (Table 4).

Figure 6 Average annual number of tropical cyclones per ecological biome for all three categories. A) illustrates the absolute values and B) the relative values per biome area (km²).
A) Low-Intensity (33-50 m/s)
B) Middle-Intensity (50-58 m/s)
C) High-Intensity (58-200 m/s)
D) Expected average annual number of tropical cyclones per ecoregion [km$^2$] for all categories

Figure 7 Map of the Indomalaya with coloured ecoregions according to their average annual number of tropical cyclones in relative numbers. A)-C) show the different categories and D) lists the values of the most affected ecoregions per category (1 = low-intensity, 2 = middle-intensity, 3 = high-intensity).

Table 4 List of ecoregions with highest numbers of tropical cyclones on average per year listed by realm.

<table>
<thead>
<tr>
<th>Realm</th>
<th>Biome</th>
<th>Ecoregion</th>
<th>Average annual number of tropical cyclones summed over all categories</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Absolute per area</td>
</tr>
<tr>
<td>Australasia</td>
<td>Deserts &amp; Xeric Shrublands</td>
<td>Pilbara shrublands</td>
<td>870.33</td>
</tr>
<tr>
<td>Nearctic</td>
<td>Temperate Grasslands, Savannas &amp; Shrublands</td>
<td>Southeast US conifer savannas</td>
<td>1041.38</td>
</tr>
<tr>
<td>Neotrop</td>
<td>Tropical &amp; Subtropical Dry Broadleaf Forest</td>
<td>Cuban dry forests</td>
<td>243.422</td>
</tr>
<tr>
<td>Afrotrop</td>
<td>Tropical &amp; Subtropical Moist Broadleaf Forest</td>
<td>Madagascar humid forest</td>
<td>234.53</td>
</tr>
<tr>
<td>Palearctic</td>
<td>Temperate Broadleaf &amp; Mixed Forest</td>
<td>Taiheiyo evergreen forest</td>
<td>2097.24</td>
</tr>
<tr>
<td>Indomalaya</td>
<td>Tropical &amp; Subtropical Moist Broadleaf Forest</td>
<td>Luzon rain forest</td>
<td>2286.67</td>
</tr>
<tr>
<td>Oceania</td>
<td>Tropical &amp; Subtropical Moist Broadleaf Forest</td>
<td>Fiji tropical moist forest</td>
<td>63.7</td>
</tr>
</tbody>
</table>
In a next step, the assessment whether a statistical relation between hazard occurrence and habitat distribution exists is presented (see Section 2.4). Here, the focus is no longer set on the geographically distinct ecological communities of the ecoregion’s dataset but on the regional level 2 habitats of the terrestrial habitat dataset (see Section 2.1.2). Since the p-value of the Kruskal-Wallis test is lower than 0.05, a significant difference between habitat type and the prevalent hazard pattern, indicated through the expected average annual number of events summed over all categories per exposure point, is revealed (H-value = 689178.3, p = 0.0). To identify the differences between the habitat types, the point-biserial analysis was used to quantify the relationship between each habitat and tropical cyclone category. The strongest positive and significant coefficients resulted between coral reefs and middle-intensity events with a point-biserial correlation coefficient \( r_{pb} \) of 0.118 (\( p = 0.0 \)). Correlation coefficients were also high for the other two hazard categories (\( r_{pb} = 0.116 \) for low-, and \( r_{pb} = 0.11 \) for high-intensity cyclones, \( p = 0.0 \)). Other habitats positively correlated to all three tropical cyclone categories are tropical/subtropical moist montane forests (\( r_{pb1} = 0.075, r_{pb2} = 0.076, r_{pb3} = 0.072, \) all with \( p = 0.0 \)) and tropical/subtropical moist shrublands (\( r_{pb1} = 0.066, r_{pb2} = 0.076, r_{pb3} = 0.074, \) all with \( p = 0.0 \)). Negative correlations imply that a region experiences significantly less events compared to all others. The highest negative numbers in combination with all categories are with hot deserts (\( r_{pb1} = -0.05, r_{pb2} = -0.034, r_{pb3} = -0.025, \) all with \( p = 0.0 \)). Other negative coefficients were found for low-intensity events and several habitats dominant in the northern hemisphere (boreal forests, temperate grasslands and tundra grasslands). Figure 8 shows the proportion of the total area of each habitat that experienced at least one tropical cyclone of any category. According to this quantitative analysis, coral reefs are highly affected with almost 80% of its area experiencing cyclones. Second highest values (over 50%) appear in other marine habitats, namely tidepools, mangrove submerged roots, and other intertidal areas. The only terrestrial habitat with over 50% of its area affected are mangroves.

To sum up, tropical cyclones affect ecoregions of every realm but large differences exist between and within them. Globally, tropical and subtropical forests are the most affected ecoregions but highest numbers occur in the Indomalaya, especially on tropical islands in front of the pacific coast. The connection between different tropical/subtropical ecosystems and tropical cyclones was also found in the statistical analysis. Besides terrestrial habitats in the tropics, intertidal areas such as mangroves or coral reefs are highly affected by tropical cyclones.

![Figure 8 Proportion of the total area of each habitat that experiences at least one tropical cyclone event (of any category). Not affected habitat types are not shown in this graph.](image-url)
3.1.2 Wildfires

Wildfires are a global phenomenon that can occur everywhere if there is biomass to burn, a promoting environmental condition and an ignitor (Krawchuk et al., 2009). The analysis of the impact of wildfires on the biome level (see Figure 9) showed that out of the 14 biomes described in Section 2.1.1, tropical & subtropical grasslands, savannas & shrublands are the biome that experiences the highest number of wildfires on average per year, in each impact category (1-3). Interestingly, the biome experiences more events of middle- than of low- intensity. When considering the relative affected area, the biome flooded grasslands & savannas instead has the most wildfire events on average per year in the middle- and high-intensity category. Again, this biome experiences more middle- than low-intensity events. In general, all tropical & subtropical biomes are more affected than temperate, Mediterranean, or montane biomes as shown in Figure 9.

Figure 9 Expected average annual number of wildfires per ecological biome for all three categories. A) illustrates the absolute values and B) the relative values per biome area [km$^2$].

The analysis of the more detailed ecoregions leads to a clear pattern in global wildfire distribution as shown in Figure 10. All of the 10 most affected ecoregions over all categories are located in the Afrotropic realm, or more precisely in savannas and steppes of the western African coast, and central and eastern Africa. Within the realms Palearctic, Antarctica, Australasia, and Nearctic, the ecoregions with highest numbers of wildfire events on average per year over all categories (1-3) are shrublands, grasslands and savannas. On the other hand, tropical/subtropical broadleaf forests are the most affected ecoregions in the Indomalaya, Neotropics, and Oceania. In the global comparison of the relative values per area, ecoregions in the northern hemisphere are less affected. But the ecoregions in the north of the Palearctic and Nearctic realm belong to the largest of the world. Hence, the impact analysis in absolute values shows a different pattern. The total number of wildfires on average per ecoregion and year is highest in the east Siberian taiga, neotropical grasslands and broadleaf forests and in Australian deserts (Figure A5–A7, Appendix A.2).
Figure 10 Map of the ecoregions coloured according to their average annual number of wildfires in relative numbers. A)-C) show the different categories and D) lists the values of the most affected ecoregions per category (1 = low-intensity, 2 = middle-intensity, 3 = high-intensity).

Since the wildfire data is based on the current century (2000-2020), the focus of wildfires close to the equator might be a result of the increasing anthropogenic pressure in these regions. As Cochrane (2003) highlights in his paper, many regions of wet tropical rainforest rarely experienced wildfires in the past but now burn regularly as a result of increasing human activity (Cochrane, 2003; Kim et al., 2018; Krawchuk et al., 2009). Therefore, the analysis was redone with the same dataset but without all artificial areas (urban areas, pasturelands, plantations) (see Figure 2). After excluding all exposure points within these regions, African steppes, the Eurasian pontic steppe, and Brazilian grasslands and broadleaf forests have been shown to experience the biggest absolute decrease in fire activity. The relative change is highest in the heavily threatened regions of the world which are not necessarily heavily-affected by wildfires: central and eastern Europe, eastern Asia and India, and the midwest of the USA. Still, the African savannas and steppes remain the ecoregions with the highest expected average annual numbers of events in both absolute and relative terms.

The following paragraph investigates potential relationships between the distribution of habitats and wildfires (see Section 2.1.2 and 2.4). The Kruskal-Wallis Test indicates a statistically significant difference between habitat type and expected average annual number of wildfires summed over all categories (H-value = 430122.1, p = 0.0). This makes the point-biserial analysis necessary to determine the specific habitat types related to wildfires. According to this correlation test, the strongest coefficients are obtained for middle-intensity events and dry savannas ($r_{pb} = 0.41$, p = 0.0), subtropical/tropical dry forests ($r_{pb} = 0.25$, p = 0.0), and moist savannas ($r_{pb} = 0.13$, p = 0.0). These habitats experience significantly more middle-intensity wildfires than others. On the other hand, negative coefficients were found for low-intensity events and hot deserts ($r_{pb} = -0.16$, p = 0.0) and boreal forests ($r_{pb} = -0.11$, p = 0.0), which indicates that these habitats experience less wildfires on average than other habitats.
In Figure 11, the proportion of the total area of each habitat that experienced at least one wildfire (of any category) in the last 20 years is shown. Highly affected habitats (>70% of area) are dry and moist savannas, subtropical/tropical dry forests, subtropical/tropical moist shrublands, and subtropical/tropical seasonally wet/flooded grasslands. In comparison to the point-biserial test results, similar habitats indicate a link between habitat distribution and hazard patterns. Only the seasonally wet or flooded grasslands and moist shrublands are additionally listed as heavily affected.

Altogether, a connection between fire activity and specific ecosystems was found (savannas, grasslands, shrublands, and some tropical forests). Especially the tropical ecoregions of Africa are highly affected in absolute, and relative numbers. The prevailing habitat types in these regions also indicate a spatial link with hazard occurrence. The fact that regions experience more middle- than low-intensity events indicates that either such events are more common, or the defined threshold was set too low with 60°C. However, such repeatedly burning regions are considered as highly resilient by structural adaptation over decades. A special aspect of wildfires is the human influence. Increasing anthropogenic pressure through out of control slash-and-burn farming, human fire accidents or artificially altered ecoregions with increased sensitivity rapidly changes the fire activity of a region (Pausas et al., 2008; Stevens-Rumann & Morgan, 2016). Hence, the described current hazard patterns might not actually represent the equilibrium state of hazard-ecosystem interactions.
3.1.3 European winter storms

In Europe, the predominantly occurring biomes are boreal forests in the northern part (55% of Europe’s surface) and temperate broadleaf & mixed forests in central Europe (30% of the surface of Europe). Since winter storms arise on the Atlantic and have landfall on the European west coast, temperate broadleaf & mixed forests are the main affected biome in the low and middle storm categories. In relation to biome size, temperate broadleaf & mixed forests experience the highest average annual numbers of low- and middle-intensity winter storms together with temperate conifer forests and Mediterranean forests, woodlands & scrub. Exceptional high-intensity wind speeds were rare events between 1940-2014 and occurred so far in temperate conifer forests and boreal forests/taiga (Figure 12).

The more detailed analysis with the 62 European ecoregions illustrates the distribution of winter storms across Europe in relative numbers (Figure 13). Especially broadleaf and mixed forests in northwestern Europe (British Isles, Iceland, and the western coast) are affected by high intensities of wind. The few high-impact storms occur in conifer and mixed forests in the Alps and in boreal birch forests and alpine tundra in Iceland.
The low p-value resulting of the Kruskal-Wallis test indicates a significant difference between the terrestrial habitat type and the average annual number of winter storms summed over all categories (H-value = 722676, p = 0.0). To specify these differences, a point-biserial analysis between all habitat types and the average annual number of the three hazard categories was done. The result indicates a significant positive connection between low-intensity events and temperate shrublands located on the European mainland and the British Isles \( (r_{pb} = 0.28, p = 0.0) \) and between middle-intensity events and Icelandic cold deserts \( (r_{pb} = 0.32, p = 0.0) \). Negative coefficients were obtained for boreal forests and low-intensity storms \( (r_{pb} = -0.33, p = 0.0) \) meaning they are significantly less affected habitats compared to all others. The proportion of affected habitat area results in no informative outcome since winter storms affect 92% of all exposure points in Europe.

In summary, it could be shown that there is a difference between different habitats and their number of winter storms, indicating a statistical relation between some habitats. However, the exposure on European scale is rather coarse with only 62 ecoregions all over Europe. To address this problem, a more detailed dataset could be used to reveal deeper insight into potential relations between habitat distribution and storm events. In addition, the low number of high-intensity winter storms since 1940 might indicate a low resilience all over Europe. Hence, increasing intensities as a result of the changing climate might affect regions which never experienced similar wind speeds before (Usbeck, Wohlgemuth, Dobbertin, et al., 2010). Another important characteristic of Europe is its high anthropogenic influence. Especially since artificially altered forest structures are more susceptible to hazard events (Milad 2011).
3.1.4 River floods

In contrast to the previously investigated hazards which all have defined characteristics, river floods present themselves in a variety of forms: from regular seasonal large-scale events in floodplains to unpredictable, irregular high-energy pulses in upland streams. Depending on the location, their impact is characterised by their long duration or the increased water flow together with rising flow rate. Hence, adaptation strategies depend on the site characteristics and type of flooding event (Kozlowski, 2002; Lake et al., 2006).

According to the impact analysis per biome, the highest average annual number of high-intensity river flood events occurs in tropical & subtropical moist broadleaf forests and tropical & subtropical grasslands, savannas & shrublands. Unlike the other hazard types, regions experience more high-intensity flooding events (additional water levels of at least 3 m) than low- or middle-intense ones. One explanation might be that a large proportion of the predicted events are seasonal large-scale floodings with high water level rises. In relative numbers per biome size, flooded grasslands & savannas experience by far the most events: six times more than the second most affected biome tropical & subtropical moist broadleaf forests (Figure 14).

![Figure 14: Average annual number of river floods per ecological biome for all three categories. A) illustrates the absolute values and B) the relative values per biome are [km²].](image)

In relation to size, most of the ecoregions with highest average annual numbers of floodings are areas of small size compared to the other ecoregions. For instance, the eastern African halophytics (0.015 events on average / year & km²) with a size of 3775 km² or the Lake Chad flooded savanna (0.006 events on average / year & km²) with a size of 32'000 km². This complicates global visualizations of river flood impacts as the highly-affected ecoregions are not visible (Figure A11-A13, Appendix A.2). As a result, the following description of river flood patterns and impacts is based on the absolute values of river flood events on average per year as illustrated in Figure 15.
On the ecoregion level, the highest absolute number of river floods on average per year for low- and middle-category occurs in the Sahelian Acacia savanna. High-intensity events affect the same area in Africa, but highest values appear in the Sudd flooded grassland in central and western Africa. Within the Palearctic, the central Asian southern desert, Kazakh and Pontic steppe and Mongolian-Manchurian grasslands experience flooding events. Other affected regions are the Cerrado grassland in Brazil in the Neotropic and the eastern Siberian Taiga in the Nearctic. The relatively to their area size highly affected flooded grassland & savanna ecoregions are located in central Africa and southeast Asia (Figure A11-A13, Appendix A.2).

Figure 15 Map of the ecoregions coloured according to their average annual number of river floods in absolute numbers. A)-C) show the different categories and D) lists the values of the most affected ecoregions per category (1 = low-intensity, 2 = middle-intensity, 3 = high-intensity).
Further, an assessment of a statistical relation between flooding occurrence and habitat distribution was made (see Section 2.1.2 and 2.4). The low p-value of the Kruskal-Wallis test between the expected average annual number of flood events of all categories and terrestrial habitat type indicates a significant connection (H-value = 114689.34, p = 0.0). Especially between high-intensity river floods and dry savannas ($r_{pb} = 0.09$, p-value 0.0), subtropical/tropical swamps ($r_{pb} = 0.07$, p-value 0.0), and hot deserts ($r_{pb} = -0.048$, p-value 0.0) a significant relation exists according to the point-biserial analysis. Since the point-biserial correlation analysis returns smaller values for small regions, the rather low correlation coefficients might be the result of the habitats size. Hence, the proportion of affected habitat area was used to achieve further insight. Over 55% of total tropical/subtropical swamp area and seasonally wet/flooded grasslands experience river floods. In the larger habitat type 'Dry Savannas', only 25% of the area is affected (Figure 16).

Once again, a connection between hazard activity and specific ecosystems was found. Especially the tropical ecoregions in the Afrotropic are highly affected in absolute, and relative numbers. Further, a connection between distinct habitat types (dry savanna, tropical/subtropical swamps, seasonally wet/flooded grasslands) and the expected average annual number of events could be found. Two of the heavily affected habitat types, the tropical/subtropical swamps and seasonally wet/flooded grasslands, experience flooding events on a regular or seasonal basis by definition of their biome. Hence, the long duration of the events is more important than the increased velocity of water bodies. In this analysis, there is no distinction between the characteristic of the event, but it might be an interesting subject for further investigation.

In summary in section 3.1 the current impact of each natural hazard on ecoregions was quantified and spatial hazard-habitat interactions were described. The results illustrated distinct patterns of affected ecoregions and indicated hazard-habitat links for each natural hazard type. As mentioned in the introduction (Section 1), the present hazard pattern can serve as an indicator for the ecological resilience and its equilibrium state it will return to (Chung Te Chang et al., 2020; Hogan et al., 2018). For the further analysis, the described outputs of sections 3.1.1-3.1.4 are assumed as the current equilibrium state to which an ecoregion is adapted to. By doing so, future scenarios can be compared to the current states and upcoming changes for each ecoregion can be analysed.
3.2 Future hazard patterns

Based on the described global hazard patterns and resulting equilibrium states of ecoregions in the Sections 3.1.1-3.1.4, the next section analyses the changes of future hazard patterns. Currently available are scenarios for tropical cyclones and river floods. As the focus of this section is set on the global changes of hazard patterns and differences for specific local regions, the ecoregions were used as exposure dataset. On this scale the expected average annual number of events was calculated for each ecoregion in 2020 and 2080 for all three hazard categories. These calculated values were then compared in absolute and relative numbers and illustrated on a global scale. This allows an analysis of changes in global hazard patterns and local shifts in hazard regimes affecting ecoregions.

3.2.1 Tropical cyclones 2080 RCP 6.0

The RCP scenario of 6.0 additional watt/m² is one of the moderate-forcing stabilization scenarios with a high greenhouse gas emission rate (IPCC, 2014). To estimate future hazard intensities and frequencies, two different approaches were considered. Knutson’s scenarios consider changing hazard intensities and frequencies of a fixed set of tracks whereas Kerry Emmanuel generates a new set of tracks with changes in physical forcing (see section 2.2).

3.2.1.1 Estimates by Knutson

According to the study by Knutson et al. (2015), cyclone frequencies will decrease in the late 21st century but intensity is predicted to increase. However, this pattern is not necessarily present in each cyclone basin (Knutson et al., 2015). A comparison of the average annual numbers of tropical cyclones per realm in 2020 and 2080 in absolute terms and their relative change is shown in Table 5.

For low intensity events, the average annual number of tropical cyclones will remain approximately constant with changes of at most ±6% for the Indomalaya, the Afrotropic, Australasia and the Palearctic. The other realms (Nearctic, Neotropic, Oceania) have expected increases of up to +60%. Middle- and high-intensity cyclones are predicted to increase in every realm between 20 and 60%, whereby the lower numbers of increase occur in the same realms which also experience less changes in the low-intensity category (Australasia, Afrotropic and Indomalaya). In comparison to the results of the study by Knutson et al. (2015), decreasing cyclone frequencies are only detected in two realms (Indomalaya, Afrotropic) and to a very small extent (-2.74%, resp. -1.92%). Increasing intensities, however, are expected in every realm according to the results of this study.

<table>
<thead>
<tr>
<th>Realm</th>
<th>Low-Intensity</th>
<th>Middle-Intensity</th>
<th>High-Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2020</td>
<td>2080</td>
<td>2020</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>2080</td>
<td>2020</td>
</tr>
<tr>
<td></td>
<td>Relative</td>
<td>Relative</td>
<td>Relative</td>
</tr>
<tr>
<td></td>
<td>Change [%]</td>
<td>Change [%]</td>
<td>Change [%]</td>
</tr>
<tr>
<td>Nearctic</td>
<td>3390.32</td>
<td>6054.66</td>
<td>44.0</td>
</tr>
<tr>
<td>Palearctic</td>
<td>3882.09</td>
<td>4129.06</td>
<td>5.98</td>
</tr>
<tr>
<td>Indomalaya</td>
<td>7121.22</td>
<td>6931.15</td>
<td>-2.74</td>
</tr>
<tr>
<td>Neotropic</td>
<td>2181.79</td>
<td>3919.79</td>
<td>44.34</td>
</tr>
<tr>
<td>Oceania</td>
<td>29.22</td>
<td>70.74</td>
<td>58.7</td>
</tr>
<tr>
<td>Afrotropic</td>
<td>1618.55</td>
<td>1587.99</td>
<td>-1.92</td>
</tr>
<tr>
<td>Australasia</td>
<td>2004.58</td>
<td>2028.82</td>
<td>1.19</td>
</tr>
</tbody>
</table>

Table 5 Average annual number of tropical cyclones in absolute values for 2020 and 2080 with an RCP 6.0 scenario and the relative change per realm for all categories.
Figure 17 Relative change of tropical cyclone activity by Knutson between 2020 and 2080 (RCP 6.0) per ecoregion for each category (A-C). The scale is logarithmic with blue as negative and red as positive values in percent. Purple areas are newly affected by such hazard intensities. Grey areas are not affected by tropical cyclones.
The relative change of cyclone activity illustrated in Figure 17 indicates decreasing numbers only in the low category for a few specific ecoregions. Some regions in Australasia are slightly less affected, as well as ecoregions in the Indomalaya and the eastern coast of Africa. However, no region has a higher relative decrease than -35%. On the contrary, many ecoregions experience an increasing number of tropical cyclones. Australia, eastern Asia, the eastern African coast, and central and northern America show increasing numbers in all categories. Some ecoregions are exposed to events with categories never seen before. Examples for ecoregions with new high-intensity category hazards are the eastern Canadian forest, the Tamaulipan Mezquital desert, and the north Saharan Xeric steppe with absolute increases of +0.6, +0.1, respectively +0.05 average annual tropical cyclones. All these regions currently experience low- and middle-intensity cyclones but no high-intensity events.

### 3.2.1.2 Estimates by Kerry

Similar to Knutson et al. (2015), estimates of Kerry expects decreasing frequency and increasing intensity of tropical cyclones in a warmer climate. In addition, predictions include a poleward migration in hazard distribution (Kossin et al., 2016). As a result of the basin-wide tropical cyclone frequency decrease and the poleward shift, decreases of -50% or more are expected in some regions (Kossin et al., 2016). The comparison of the expected average annual number per realm in 2020 and 2080 and their relative change is shown in Table 6. With these estimates, cyclone activity is expected to decrease in every realm, for every intensity category. Especially in the Nearctic, the Indomalaya, the Neotropic and Australasia cyclone activity is expected to decrease with values up to -36%.

**Table 6 Average annual number of tropical cyclones in absolute values for 2020 and 2080 with an RCP 6.0 scenario and the relative change per realm for all categories.**

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Low-Intensity</th>
<th>Middle-Intensity</th>
<th>High-Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Realm</td>
<td>2020</td>
<td>2080</td>
<td>Change [%]</td>
</tr>
<tr>
<td>Nearctic</td>
<td>3.49*10^05</td>
<td>2.94*10^05</td>
<td>-18.88</td>
</tr>
<tr>
<td>Palearctic</td>
<td>1.79*10^05</td>
<td>1.63*10^05</td>
<td>-10.07</td>
</tr>
<tr>
<td>Indomalaya</td>
<td>1.25*10^05</td>
<td>1.02*10^06</td>
<td>-22.66</td>
</tr>
<tr>
<td>Neotropic</td>
<td>5.41*10^05</td>
<td>4.39*10^05</td>
<td>-23.12</td>
</tr>
<tr>
<td>Oceania</td>
<td>4.05*10^04</td>
<td>3.49*10^04</td>
<td>-15.94</td>
</tr>
<tr>
<td>Afrotrropic</td>
<td>3.12*10^05</td>
<td>2.75*10^05</td>
<td>-13.39</td>
</tr>
</tbody>
</table>

Illustrated in Figure 18 are the estimates of relative change of tropical cyclones per ecoregion. It can be seen that many ecoregions will experience less or even no more cyclones and only few are exposed to an increasing number of events. Especially ecoregions on the eastern coast of Africa, central and south America, and parts of Australia and the Indomalaya experience more middle- and high-intensity cyclones. Important to mention are newly affected ecoregions of the world, flooded grasslands in Florida, the Guianan savanna and the Angolan scarp savanna/woodland are currently not affected by high-intensity cyclones but will be in 2080 (absolute increase of +9.22, +3.2 and +7.06 expected average annual tropical cyclones respectively). In more detail, each of these ecoregions will experience more high-intensity events but the patterns for the other hazard categories differ. The flooded grasslands in Florida already experience low- and middle intensity hazards but in 2080 these numbers will decrease by up to -10%. Hence, less hazards of low and middle intensity but increasing extreme events are expected. The Guianan savanna in Africa currently experiences only low-intensity hazards, in future however, it will be newly affected by middle- and high-intensity events. The Angolan scarp savanna and woodland will have decreasing numbers of low-intensity (-3.25%) and increasing middle-intensity hazards (+1500%).
A) Low-Intensity (33-50 m/s)

B) Middle-Intensity (50-58 m/s)

C) High-Intensity (58-200 m/s)

Figure 18 Relative change of tropical cyclone activity by Kerry between 2020 and 2080 (RCP 6.0) per ecoregion for each category (A-C). The scale is logarithmic with blue as negative and red as positive values in percent. Purple areas are newly affected by such hazard intensities. Grey areas are not affected by tropical cyclones.
Similar to the predictions published in Kossin et al. (2016), in the work presented in this thesis, decreasing frequencies of tropical cyclones in all realms and categories were detected. The afore mentioned increases in intensities was not detectable on the realm level, but on the ecoregion level. Further, a poleward shift was not evident on the global scale in this thesis, but in the study of Kossin et al. (2016) a shift of 1.2° until 2080 was modelled which might be too little to detect based on the impact calculation presented in this thesis. However, the presented results clearly demonstrate the predicted decreases of 50% or more in some regions.

Where Knutson described higher increases in most parts of the world and categories, Kerry’s estimates predicted cyclones to completely disappear in many ecoregions (Knutson et al., 2015; Kossin et al., 2016). Taking a closer look at regions experiencing new levels of hazard intensities allows for further analyses. The mentioned regions newly affected by Kerry's tracks all experience higher levels of high intensities but the patterns for low- and middle-intensities are different for each region. Some are already affected but the frequencies can both decrease and increase in future. Hence, the changes in combination of hazard frequencies and intensities leads to completely new hazard patterns which differ between the regions and implies locally specific adaptation strategies. The contrasting results of Kerry's and Knutson's data show the importance of model assumptions and the high uncertainties of future predictions. Nevertheless, hazard patterns will change in any case and ecosystems have to adapt to new tropical cyclone activity. In both predictions, some ecoregions will be affected newly or more frequently by middle- and high intensity events, whereas the implications of such changes for ecosystems are unknown. High-intensity cyclones in coral reefs, for example, resulted in severe ecological damage as a result of extreme coral cover loss (68%) and declines in associated fish communities (Cheal et al., 2017). However, in tropical & subtropical forests, cyclones increase habitat diversity by creating canopy gaps and speed up forest regeneration (T. C. Lin et al., 2020). Furthermore, as we have seen for wildfires (see section 1), natural hazards can be necessary for a habitat type to exist (Flatley et al., 2013; Hoss et al., 2008). Hence, ecosystems are adapted to current tropical cyclone patterns and increases in intensity can have both positive and negative implications for a habitat but the exact outcome is unclear (Feller et al., 2015; T. C. Lin et al., 2020).
3.2.2 River floods 2080 RCP 8.5

River floods predictions are based on the RCP 8.5 which represents the business-as-usual scenario with increasing greenhouse gas emissions over time (IPCC, 2014). Based on the models of Hirabayashi et al. (2008), flood projections for late 21st century indicate major changes with worldwide increasing frequencies except for northern America and central and western Eurasia. The expected average annual numbers of flooding events per realm in 2020 and 2080 and their relative change is shown in the Table 7. On the realm level, flooding frequencies are increasing for all intensities. The heavily affected Afro tropic with highest estimates over all categories in 2020 and 2080 experiences increasing frequencies to a lesser extent than the other realms in low- and middle-intensities. Since Oceania has no recorded high-intensity flooding events in the historical data, the model simulations for 2080 also result in no events.

Table 7 Average annual number of river floods in absolute values for 2020 and 2080 with an RCP 8.5 scenario and the relative change per realm for all categories.

<table>
<thead>
<tr>
<th>Realm</th>
<th>Low-Intensity</th>
<th>Middle-Intensity</th>
<th>High-Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2020</td>
<td>2080</td>
<td>Relative Change [%]</td>
</tr>
<tr>
<td>Nearctic</td>
<td>42.24</td>
<td>67.98</td>
<td>37.87</td>
</tr>
<tr>
<td>Palearctic</td>
<td>692.04</td>
<td>945.77</td>
<td>26.83</td>
</tr>
<tr>
<td>Indomalayan</td>
<td>71.21</td>
<td>115.87</td>
<td>38.54</td>
</tr>
<tr>
<td>Neotropic</td>
<td>199.37</td>
<td>301.72</td>
<td>33.92</td>
</tr>
<tr>
<td>Oceania</td>
<td>0.242</td>
<td>0.58</td>
<td>58.18</td>
</tr>
<tr>
<td>Afro tropic</td>
<td>1027.05</td>
<td>1123.56</td>
<td>8.59</td>
</tr>
<tr>
<td>Australasia</td>
<td>60.46</td>
<td>94.92</td>
<td>36.31</td>
</tr>
</tbody>
</table>

The relative change of average annual river floods between 2020 and 2080 illustrated in Figure 19 indicates increasing frequencies all over the world except in northern Africa for low category events, and northern America and central and western Eurasia for all three categories. Some of the ecoregions in North America experiencing less events in 2080 belong to the biome of flooded grasslands and savannas. This biome is defined through the existence of frequent flooding events. For instance, the Saharan halophytics will experience 35% less low- and middle-intensity floods on average per year and the inner Niger delta flooded savanna -26% of low-intensity and -24% of middle-intensity events on average per year. Newly affected ecoregions are the xeric bushlands at the horn of Africa (+0.15) and the Great Sandy-Tanami desert in Australia (+0.000004 expected average annual river floods). Great Sandy-Tanami desert in Australia already experiences low- and middle intensity events to some extent (7.28, resp. 0.94 expected average annual events) but their frequencies will increase in future by 25% for low-intensity and 82% for middle-intensity events. Similarly, the bushlands in Africa which experience 7.06 of low- and 1.5 average annual number of middle-intensity events will experience increasing frequencies in future by 62% for low-intensity and 646% for middle-intensity events.
A) Low-Intensity (0-1 m)

B) Middle-Intensity (1-3 m)

C) High-Intensity (3-35 m)

Figure 19 Relative change of river floods between 2020 and 2080 (RCP 8.5) per ecoregion for each category (A-C). The scale is logarithmic with blue as negative and red as positive values in percent. Purple areas are newly affected by such hazard intensities. Grey areas are not affected by tropical cyclones.
To sum up, river flooding patterns in 2080 will change almost everywhere in the world with most ecoregions experiencing higher levels. Within the less affected areas of the world, particular attention is required for one biome: flooded grasslands and savanna. This ecosystem is defined by regular or seasonal flooding events which play a crucial role for its ecology (Lake et al., 2006). During floods, the entire floodplain is temporarily transformed and connected to the river channel resulting in an exchange of biota, organic matter, nutrients and sediments. Decreasing numbers of floods may result in dramatic changes of floodplain integrity (Lake et al., 2006; Suchara, 2019). Further, the study of Hirabayashi et al. (2008) detected shifts in the time period of flood seasons: away from springtime to the summer period. The timing throughout the year plays an important role in determining the impact on ecosystems as the ecological resilience depends on the organism’s life cycle. For instance, flood events before or after salmon spawning directly influence the number of returned adult salmons (Milner et al., 2018).

All in all, hazard activity will change in the upcoming years leading to new global patterns of tropical cyclone activity and river flood events. Consequently, many ecoregions of different types and locations must cope with decreasing or increasing intensities and frequencies. The question that is raised now is what the ecological implications of these changes for the ecosystem are.
3.3 Relation between hazard return periods & recovery times

So far, the current hazard patterns affecting ecosystems were described and compared to future scenarios in order to assess the relative change of hazard activity. Still unclear however, is the connection of hazard activity to ecosystem resilience. The goal of this section is to investigate the reaction of an ecosystem in response to a natural hazard. To do so, the return periods of low-, middle- and high-intensity tropical cyclones were computed which quantify the time period in years between two events of the same category. These values were then compared to actual ecological recovery times measured in field studies. This procedure makes it possible to compare the time available for recovery before the next hazard occurs with the actual time needed to recover. For this analysis, two well studied areas that experience tropical cyclones on a regular basis were looked at: the Luquillo Experimental Forest (LEF) in Puerto Rico and the Fushan Experimental Forest (FEF) in Taiwan (T. C. Lin et al., 2020). Both are located on islands belonging to the ecological biome tropical & subtropical moist broadleaf forests and are placed in the northern tropics. To compare the cyclone activity of both sites, the hazard frequencies per exposure point over all events per category were summed up. In order to get the return periods per category and point, the resulting value was inverted (see Section 2.4). Illustrated in Figure 20, we see a consistent pattern of lower return periods for each hazard category in Taiwan compared to Puerto Rico. The mean return period of a category 3 hazard in Taiwan is 24 years compared to 55 years in Puerto Rico. For the high-intensity categories 4 & 5, mean return periods in Taiwan are 45 years and 118 years in Puerto Rico, respectively. Hence, Taiwan experiences about double the amount of middle and high-intensity events within a year.

![Figure 20 Boxplot of the return period in years per exposure point for the Fushan Experimental Forest in Taiwan (red) and the Luquillo Experimental Forest in Puerto Rico (blue).]
Table 8 Summary of the experimental field studies that measured recovery times of different indices grouped by site (FEF in Taiwan, LEF in Puerto Rico).

<table>
<thead>
<tr>
<th>Saffir-Simpson Category</th>
<th>Site</th>
<th>Index</th>
<th>Recovery Time [years]</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>FEF, Taiwan</td>
<td>Total Litterfall</td>
<td>2</td>
<td>K. C. Lin et al., 2017</td>
</tr>
<tr>
<td>4</td>
<td>FEF, Taiwan</td>
<td>Leaf Litter Mass</td>
<td>5</td>
<td>K. C. Lin et al., 2017</td>
</tr>
<tr>
<td>3</td>
<td>FEF, Taiwan</td>
<td>Litterfall &amp; LAI</td>
<td>1</td>
<td>T. C. Lin et al., 2011</td>
</tr>
<tr>
<td>3</td>
<td>FEF, Taiwan</td>
<td>Normalized Difference Vegetation Index (NDVI)</td>
<td>1</td>
<td>Peereman et al., 2020</td>
</tr>
<tr>
<td>3</td>
<td>FEF, Taiwan</td>
<td>Normalized Difference Vegetation Index (NDVI)</td>
<td>1</td>
<td>Peereman et al., 2020</td>
</tr>
<tr>
<td>4</td>
<td>FEF, Taiwan</td>
<td>Annual peak LAI</td>
<td>10</td>
<td>K. C. Lin et al., 2017</td>
</tr>
<tr>
<td>1-2</td>
<td>FEF, Taiwan</td>
<td>Leaf Area Index (LAI)</td>
<td>13.5</td>
<td>K. C. Lin et al., 2017</td>
</tr>
<tr>
<td>3</td>
<td>FEF, Taiwan</td>
<td>Streamwater nitrate concentration</td>
<td>0.06 (= 3 weeks)</td>
<td>K. C. Lin et al., 2017</td>
</tr>
<tr>
<td>1-5</td>
<td>FEF, Taiwan</td>
<td>Streamwater chemistry</td>
<td>0.06 (= 3 weeks)</td>
<td>C. T. Chang et al., 2013</td>
</tr>
<tr>
<td>3</td>
<td>LEF, Puerto Rico</td>
<td>Canopy Light</td>
<td>4.5</td>
<td>Beusekom et al., 2020</td>
</tr>
<tr>
<td>3</td>
<td>LEF, Puerto Rico</td>
<td>Throughfall Recovery</td>
<td>6.5</td>
<td>Beusekom et al., 2020</td>
</tr>
<tr>
<td>3</td>
<td>LEF, Puerto Rico</td>
<td>N2O fluxes</td>
<td>0.58</td>
<td>Erickson &amp; Ayala, 2004</td>
</tr>
<tr>
<td>3</td>
<td>LEF, Puerto Rico</td>
<td>Streamwater nitrate concentration</td>
<td>1.37 (=500 days)</td>
<td>K. C. Lin et al., 2017</td>
</tr>
<tr>
<td>4</td>
<td>LEF, Puerto Rico</td>
<td>Streamwater nitrate concentration</td>
<td>1.5</td>
<td>McDowell &amp; Liptzin, 2014</td>
</tr>
<tr>
<td>3</td>
<td>LEF, Puerto Rico</td>
<td>Streamwater chemistry</td>
<td>2</td>
<td>Schaefer et al., 2000</td>
</tr>
<tr>
<td>3</td>
<td>LEF, Puerto Rico</td>
<td>Streamwater chemistry (nitrate, potassium, ammonium)</td>
<td>2</td>
<td>Schaefer et al., 2000</td>
</tr>
<tr>
<td>3</td>
<td>LEF, Puerto Rico</td>
<td>Light, Forest mass, Stream Nitrate, Soil Nutirents</td>
<td>1</td>
<td>Zimmerman et al., 2021</td>
</tr>
<tr>
<td>3</td>
<td>LEF, Puerto Rico</td>
<td>Tree Biomass, Litterfall</td>
<td>5</td>
<td>Zimmerman et al., 2021</td>
</tr>
</tbody>
</table>
Studies have compared the number of uprooted trees after major (\(>=\) Saffir-Simpson category 3) hazard events between these two sites and found significant differences. The stronger affected forest in Taiwan had lower tree mortality indicating a higher resistance (T. C. Lin et al., 2011). Ibanez and Keppel (2019) looked at the canopy height between sites and validated it as a globally consistent indicator for tropical cyclone impact. However, no study so far linked interregional hazard occurrence with the prevailing recovery times to quantify ecological resilience. In this thesis, the differences of the return periods with experimentally measured indices of ecological studies were compared. The measure indices considered in this analysis are summarized in Table 8. In the two experimental sites, a variety of indices was measured in pre- and post-hurricane times for mainly category 3 hazards. In the FEF in Taiwan, stream water chemistry recovered mostly within a couple of weeks, LAI within 10-13.5 years, and the Normalized Difference Vegetation Index (NDVI) after 1 year. Depending on the hazard intensity, leaf litter took 1 year to recover after a category 3 hazard or 2-5 years after a category 4 hazard. In comparison, stream water chemistry in the LEF, Puerto Rico, needed 1-2 years to fully recover, leaf litter 5 years, and the available light on the ground 1-6.5 years after a category 3 hazard. Hence, there are some indices measured in both sites with large differences, namely stream water chemistry and leaf litter. Both indices needed longer to recover in Puerto Rico.

To sum up, there is a difference in modelled hazard return periods between Taiwan and Puerto Rico (Figure 20) and studies indicate resulting effects in site characteristics (canopy height) (Ibanez et al., 2019). Further, experimental field studies indicate longer recovery times in Puerto Rico for some indices compared to Taiwan. However, these values greatly vary with the location and the method of the measurement. Recovery times of leaf area indices in the FEF took 1 year after a category 3 hazard and 10 years after a low-intensity hazard of category 1 (Table 8). This difference shows the consequences of different definitions and measurement techniques (Chung Te Chang et al., 2020; K. C. Lin et al., 2017). Consequently, the variety of measured indices and the different techniques make a comparison of the recovery times difficult. Additionally, measurements after a single or even a couple of events do not represent ecosystem responses for the entire region. Site specific (such as topography, soil, species composition and their characteristics) and cyclone characteristics, which determine a hazards impact, vary greatly already on small scales (Xi, 2015). In the scope of this analysis, local differences in cyclone occurrence can be seen in the wide distribution of return periods in Taiwan where some exposure points experience much more hazards compared to the others within the same region (Figure 20). An example illustrating the differences within sites is shown in the studies of Hogan et al. and Ibanez et al. (2018; 2019): canopy height in Taiwan is 5-10 meters on ridges and 15-20 m in the lowland. These differences in site and cyclone characteristics are even bigger among different sites around the world which further affects comparability of ecosystem response. In order to account for these differences a large enough dataset is needed or the exact same experimental setup in ecologically similar regions (Chung Te Chang et al., 2020; K. C. Lin et al., 2017).
3.4 Areas of interest

The knowledge of the statistical relation between ecosystems and hazards combined with the implications for recovery times yields great potential to investigate upcoming changes through climate change for specific regions. In this section, current and future pattern of natural hazards will be analysed on a set of different areas representing different aspects of ecological importance. A hazards pattern is assessed through the number of affected exposure points within an area. An exposure point is considered as affected when it experiences hazard events of any category. Based on these values, the ratio of affected vs. unaffected points per area of interest was calculated and results are listed as percentage values in Table 9. The analysed datasets cover a variety of ecological aspects (see section 2.1.3). Biodiversity hotspots are the top 10% of exposure points with the highest numbers of species. Coral reefs and mangroves are both heavily threatened habitats with an important role in coastal protection (Spalding et al., 2014). The RAMSAR dataset includes all wetlands of international importance and all regions with a status as protected site are included in the protected areas dataset. The dataset ‘Last of the Wild’ covers all regions without any anthropogenic influence. Overall, some datasets focus on the actual number of species, some on the habitat type and others on the status of a region. In this section the focus is not set on the spatial distribution of a special area or its number of events but rather on the absolute and relative change per group on a global scale.

Current patterns of the four natural hazards (tropical cyclones, river floods, wildfires, European winter storms) are listed in Table 9. Tropical cyclones affect large areas of coastal regions, namely coral reefs and mangroves. Since the river floods and winter storms dataset is only available for terrestrial habitats and wildfires do not occur in marine habitats, coral reefs are not further affected. On the contrary, 24% of Mangrove habitats are additionally affected by river floods and 35% by wildfires. Areas considered as animal or plant biodiversity hotspots are similarly affected by river floods (~32%) and wildfires (~45%). One third of all RAMSAR wetlands experience flooding events, and one third is also affected by wildfires. Out of the protected areas only a few points experience tropical cyclones (~5%) or river floods (~7.6%). Wildfires affect only one tenth of the protected area. Lastly, the wilderness areas experience flooding events and wildfires in 10-15% of their area. Since European winter storms affect 92% of all geometry points within Europe, the percentage of affected area is high for every group.

Table 9 Proportion of the total size of each area of interest that experiences at least one hazard event (of any category).

<table>
<thead>
<tr>
<th>Area of Interest</th>
<th>Natural Hazard</th>
<th>World</th>
<th>Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Tropical Cyclones [%]</td>
<td>River Floods [%]</td>
</tr>
<tr>
<td>Plant Biodiversity Hotspots</td>
<td>5.78</td>
<td>31.84</td>
<td>42.54</td>
</tr>
<tr>
<td>Animal Biodiversity Hotspots</td>
<td>5.01</td>
<td>35.99</td>
<td>47.93</td>
</tr>
<tr>
<td>Coral Reefs</td>
<td>73.43</td>
<td>-</td>
<td>1.17</td>
</tr>
<tr>
<td>Mangroves</td>
<td>11.78</td>
<td>24.03</td>
<td>35.36</td>
</tr>
<tr>
<td>RAMSAR Wetlands</td>
<td>5.86</td>
<td>28.45</td>
<td>30.29</td>
</tr>
<tr>
<td>Protected Areas</td>
<td>4.89</td>
<td>7.62</td>
<td>12.03</td>
</tr>
<tr>
<td>Last of Wild</td>
<td>4.37</td>
<td>11.32</td>
<td>14.45</td>
</tr>
</tbody>
</table>

In a next step, these current patterns are compared with future scenarios (Table 10). This analysis of relative changes of the affected proportion per site reveals significant changes for some areas of interest. According to Knutson’s estimates, the affected area will not change more than 1.5% for all areas. This is not surprising since Knutson’s scenarios consider changing hazard intensities and frequencies of a fixed set of tracks and do not consider changes in hazard locations. On the contrary, Kerry’s tracks lead to large increases in some (coral reefs, protected areas, last of wild) and decreasing values in other regions (plant biodiversity hotspots, mangroves). The area affected by river floods remains constant for most datasets except the last of the wild with an increase of +10%.
All the studied areas have experienced natural hazards to some extent so far. Especially wildfires and river floods affect large parts of biodiversity hotspots, mangroves and RAMSAR wetlands. Also, almost the entire area of coral reefs experiences tropical cyclones. Now, future scenarios for 2080 indicate major changes from -77% up to +43% in the affected area of some groups. These changes might require new adaptation strategies which, in turn, might alter the structure of an ecosystem (T. C. Lin et al., 2020). Note however that the analysis presented in this study does not differentiate between different hazard categories. The low relative changes of river floods indicate that no additional points are affected, but potential changes in the hazard category are not included. As has been shown in section 3.2.2, expected average annual numbers of flooding events are increasing almost everywhere around the globe for all categories. Now it is of importance to investigate the actual change of intensity and frequency for each centroid. Depending on the adaptation necessary, the diversity or the status of a region might change. The question that is raised now is if species diversity is positively or negatively connected to hazard occurrence and how it will change with altered hazard patterns.

### 3.4.1 Relation between natural hazards & biodiversity

Ecological resilience is often linked to ecosystem complexity which is correlated to habitat diversity. In theory, heterogeneous habitats provide functional and structural redundancy which increases the complexity and results in higher robustness and tolerance to disturbance (Parrott, 2010). Here, we assume that the complexity of an ecosystem is equivalent to its number of species and the resilience is derived from the number of hazards occurring in the same area. The used dataset to represent the number of species is the plant species richness dataset by Ellis et al. (2012) because of two reasons: Firstly, it covers more species than the IUCN animal species richness dataset. Secondly, it is corrected by the model of Kretz & Jetz (2007) (see section 2.1.3). Based on the continuous data of expected average annual number of events per exposure point and hazard summed over all categories and the number of species per point, the Pearson’s correlation coefficient was calculated to get a first estimation of the potential connection. In addition, a second analysis with a categorical approach was done to analyse the influence of multi-hazards on diversity. To do so, the species richness per exposure point was categorized into three levels according to the occurring number of species. Points with 0 to 1000 species were considered as low, 1000-2230 species as middle, and everything above 2230 was considered as high species richness. With this categorization, 60% of all exposure points

<table>
<thead>
<tr>
<th>Area of Interest</th>
<th>Natural Hazard</th>
<th>Tropical Cyclones 2020 by Knutson [%]</th>
<th>Tropical Cyclones 2080 RCP 4.5 by Knutson [%]</th>
<th>Delta Klima [%]</th>
<th>Tropical Cyclones 2020 by Kerry [%]</th>
<th>Tropical Cyclones 2080 RCP 4.5 by Kerry [%]</th>
<th>Delta Klima [%]</th>
<th>River Floods 2020 [%]</th>
<th>River Floods 2080 RCP 8.5 [%]</th>
<th>Delta Klima [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Biodiversity Hotspots</td>
<td>11.84</td>
<td>12.81</td>
<td>+0.97</td>
<td>38.66</td>
<td>8.11</td>
<td>-30.55</td>
<td>31.84</td>
<td>32.32</td>
<td>+0.48</td>
<td></td>
</tr>
<tr>
<td>Animal Biodiversity Hotspots</td>
<td>1.55</td>
<td>1.86</td>
<td>+0.31</td>
<td>15.95</td>
<td>8.39</td>
<td>-7.56</td>
<td>35.99</td>
<td>36.48</td>
<td>+0.48</td>
<td></td>
</tr>
<tr>
<td>Last of Wild</td>
<td>2.27</td>
<td>2.51</td>
<td>+0.25</td>
<td>9.85</td>
<td>20.56</td>
<td>+10.71</td>
<td>11.32</td>
<td>11.51</td>
<td>+10.19</td>
<td></td>
</tr>
<tr>
<td>RAMSAR Wetlands</td>
<td>5.66</td>
<td>5.80</td>
<td>+0.13</td>
<td>12.52</td>
<td>13.15</td>
<td>+0.63</td>
<td>28.45</td>
<td>28.95</td>
<td>+0.50</td>
<td></td>
</tr>
<tr>
<td>Coral Reefs</td>
<td>37.17</td>
<td>38.14</td>
<td>+0.97</td>
<td>40.22</td>
<td>83.24</td>
<td>+43.02</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Protected Areas</td>
<td>3.56</td>
<td>3.89</td>
<td>+0.33</td>
<td>9.31</td>
<td>22.69</td>
<td>+13.38</td>
<td>7.62</td>
<td>7.74</td>
<td>+0.12</td>
<td></td>
</tr>
<tr>
<td>Mangroves</td>
<td>36.21</td>
<td>37.61</td>
<td>+1.40</td>
<td>84.53</td>
<td>7.35</td>
<td>-77.18</td>
<td>24.03</td>
<td>24.95</td>
<td>+0.92</td>
<td></td>
</tr>
</tbody>
</table>
are in the low-, 30% in the middle-, and 10% in the high-richness category. Every geometry point experiencing hazard events of any category is considered as affected and the final number of hazards is the sum of the different hazard types (wildfires, river floods, tropical cyclones for the world and additional winter storms for Europe) occurring per point represents the second categorical variable. Based on this data, a Chi-Square test was performed to analyse the correlation between two categorical variables: the final number of hazards per point and the species richness category.

The Pearson correlation analysis revealed significant positive values between all hazards and species richness values. Tropical cyclones and river floods both have a correlation coefficient of $r_{pb} = 0.15$ with a p-value of 0.0 and wildfires have a stronger connection with $r_{pb} = 0.24$ and a p-value of 0.0. Individually, the hazards are positively connected with species richness. In a next step, the multi-hazard analysis follows. As illustrated in the crosstabulation output (Figure 21), most exposure points (67%) experience low- or middle-levels of species richness and 1 or 2 natural hazards. The low p-value resulting of the Chi-Square analysis indicates a statistical difference between number of hazards and richness category ($p = 0.0$). To determine the strength and direction of the link, the Spearman’s correlation coefficient was calculated which resulted in a statistically significant positive correlation between diversity of hazards and richness category ($r_{sp} = 0.39, p = 0.0$)

![Figure 21: Crosstabulation analysis between the number of hazards (0-3) per exposure site and its species richness category (low, middle, high). The colour indicates the percentage of exposure points within these categories.](image)

The Pearson correlation analysis between individual hazards and plant species richness on the European scale resulted in no significant outcome. The multi-hazard analysis indicates a similar pattern as the global data: most exposure points experience low- or middle- species richness levels and 2 or 3 different hazards (Figure 22). Further, the Chi-Square test indicates a significant difference between the two variables. Again, the Spearman’s analysis is necessary to determine the dimension of the connection which resulted in a statistically significant positive correlation between diversity of hazards and richness category in Europe ($r_{sp} = 0.31, p = 2.93 \times 10^{-26}$).
The results of the Pearson correlation, Chi-Square analyses, and Spearman’s correlation indicate a statistical connection between ecological diversity and hazard occurrence. On a global scale, the occurrence of single hazard types seems to be positively correlated with species richness. Increasing expected average annual number of events lead to higher diversity of plant species. The multi-hazard analysis further indicated a statistically significant difference between number of hazard types affecting a region and the number of species on a global and local level: higher diversity of hazards implies higher species diversity. However, these results must be interpreted carefully because of multiple reasons. Firstly, the multi-hazard approach is based on several assumptions and simplifications which deform the original dataset. Secondly, species richness depends on a variety of aspects (site, location, connectivity, climate, topography). Europe for example has generally low diversity levels because of high rates of artificial pressure. In addition, the constant burning of the tropics is not necessarily connected to its high species richness levels.

Figure 22 CROSSTABULATION analysis on the European level between the number of hazards (0-4) per exposure site and its species richness category (low, middle, high). The colour indicates the percentage of exposure points within these categories in Europe.
4 Conclusion

The findings presented in this thesis show that CLIMADA is a useful tool to determine the impact of natural hazards i.e. tropical cyclones, wildfires, winter storms and river floods on ecosystems. With the categorical approach, the impact per ecoregion was calculated in a globally consistent way and allowed a comparison between locations and vegetation types. As a result, patterns of natural hazard distribution can be assessed on different ecological levels (realm – biome – ecoregion vs. habitat classes) as described in Section 3.1. On the on hand, the ecoregion analysis reveals specific hazard patterns for geographically distinct ecological communities (see Section 2.1.1). On the other hand, globally linked habitat types as presented with the terrestrial habitats (see Section 2.1.2) allowed an analysis of potential linkages between hazard and habitat distribution. Both approaches together allow a detailed description of the hazard pattern affecting an ecosystem.

The comparison of the current equilibrium between the ecoregions and hazard activity with future scenarios revealed global changes in hazard activity within the next 60 years (see Section 3.2). Many ecoregions will experience increasing or decreasing intensities and frequencies and, thus, must adapt to new hazard regimes. The implications of these changes are uncertain. As described in Section 3.2, changing hazard patterns can increase biodiversity but also result in severe ecological damage of specific species. However, resilience is the key to investigate future implications. The attempt of connecting hazard return periods with recovery times to quantify ecological resilience revealed differences in the reaction of an ecosystem in response to a hazard event. Sites experiencing tropical cyclones less frequently, require more time to recover to pre-disturbance levels. However, modelled return periods and measured recovery times greatly vary within a region depending on site and hazard characteristics. These differences within and among sites complicate a global comparison of ecosystem response.

Despite the remaining uncertainties, there is a relation between ecosystems and hazards with implications for recovery times. This knowledge yields great potential to investigate the impact on specific regions of interest. The analysis of current hazard activity within areas of ecological importance revealed that these areas have experienced natural hazards to some extent so far. Especially wildfires and river floods affect large parts of multiple areas of interest. Therefore, the question whether there is a connection between ecological status and the occurrence of natural hazards arises. Particularly given that future hazard activity within these areas of ecological importance will experience major changes. A first analysis with species richness patterns revealed a significant positive relation, but these results need careful interpretation.

All in all, CLIMADA has a great potential to investigate the impact of natural hazards on ecosystems and a variety of aspects can be investigated depending on the focus and scope of the analysis. However, such global analyses always require many assumptions and simplification which limit the accuracy and reliability of the model output.
4.1 Limitations

Sources of uncertainties are located in each component of the impact modelling platform (hazard, exposure, vulnerability). The description of the hazard patterns depends crucially on the performance and reliability of the hazard datasets which are limited by the data availability of the past. Wildfire measurements cover only the last 20 years; a period characterised by major anthropogenic influence. It is questionable whether this represents the disturbance regime of the past. Considerable differences in the modelled output depending on the used data were shown in Section 3.2. Depending on the climate model, future scenarios of hazard patterns vary greatly.

As illustrated in Section 3.1, the selection of the ecological dataset determines the modelled hazard impact and needs careful interpretation. It is also important to mention the resolution of ecological and hazard data. Depending on the focus of the analysis, the resolution of the natural hazards with 4 km on land and 100 km in marine areas might result in distorted pictures. Since the focus of the analysis presented in this thesis was terrestrial, most exposure points where within the 4 km resolution. However, the coral reefs verge on the lower resolution zones.

The categorial approach used for the work underlying this thesis allows a global comparison among ecological sites but does not represent the effective impact of a natural hazard. As described in Section 3.3, the impact of a natural hazard depends on hazard and site characteristics (topography, soil, species composition and their characteristics). Furthermore, the statistical analysis of hazard-habitat interactions is useful to look at spatial connections but is biased towards larger areas. On the contrary, the proportion of affected area per habitat is biased towards smaller areas. The comparison of both approaches compensates their distortion but is still not optimal.

4.2 Outlook

This Master Thesis serves as a first explorative work investigating the potential of CLIMADA to analyse the impact of natural hazards on ecosystems. Further research could focus on every aspect presented in this study (specific regions, more natural hazards, multi-hazards or coupled events, different RCP trajectories). From my point of view, particularly interesting would be the further investigation of the hazard-diversity-resilience relation. By looking at one particular area of interest and the prevailing regime of one or multiple natural hazards, one could analyse the regions way of dealing with disturbances and the local level of adaptation. Since these areas of interest are globally distributed, the local levels of adaptation could be compared to the ecosystem diversity and the hazard regime as it was done in Section 3.3. A scientifically proven link yields great potential to understand current diversity and resilience patterns and to analyse implications of future changes in hazard regimes.

As indicated in the description of the current hazard patterns in Sections 3.1.1-3.1.4, extreme weather and climate events are not the only disturbance regime affecting ecosystems. Anthropogenic pressure influence ecosystems worldwide in the past and present. The question is the dimension of change in both disturbance regimes (natural hazards, human influence) in future and if there are mutual interdependencies intensifying the pressure on ecosystems. A brief outlook about the current anthropogenic pressure is presented in the Appendix A.1.

The approach applied in this study allows a globally consistent analysis of a hazards impact on different ecological scales. As a result, a variety of different aspects can be analysed, whether the focus is a social-ecological (nature-based solutions, ecosystem services), a biogeochemical (nutrient cycles), or an ecological (specific animal of plant species) perspective.
5 Bibliography


UNEP-WCMC. (2021). *Protected Area Profile from the World Database of Protected Areas.* https://www.protectedplanet.net/en


A) Appendix

A.1 Anthropogenic pressure in comparison to hazard patterns ........................................... 52
A.2 Additional hazard patterns .................................................................................................. 53
A.3 Hazard patterns in larger format .......................................................................................... 65
A.4 Visualizations of future scenarios in larger format ............................................................... 77
A.1 Anthropogenic pressure in comparison to hazard patterns

A subject of increasing importance for ecosystem diversity, integrity and resilience is the anthropogenic pressure. Studies have shown that artificially altered ecoregions like plantations or pasturelands are more susceptible and less resilient to wildfires, winter storms and tropical cyclones (Milad et al., 2011; Pausas et al., 2008; Tsai et al., 2009). Lotic ecosystems fragmented by dams have reduced levels of environmental variation and as a result reduced biodiversity in downstream communities. Such artificially altered ecosystems react differently to flooding events, potentially as a result of a reduction in biodiversity that leads to lower resilience (Rader et al., 2008).

According to the artificial land cover data of the terrestrial habitat map (Jung, Dahal, Butchart, Donald, De Lamo, et al, 2020) resampled to 1km by majority, 1’203’593 exposure points were identified as artificial, and 34 ecoregions got completely lost. This is approximately 14.3% of the terrestrial land. Especially threatened regions are Europe, India, eastern and southeast Asia and North America. All of them have multiple ecoregions that lost over 50% of their extent. In addition, the highly threatened European west coast experiences the highest expected average annual numbers of winter storms and has to cope with more river flood events in future. Eastern and southeast Asia experience world’s highest tropical cyclone activity which will increase according to Knutson and Kerry, are frequently affected by high intensity wildfires, and will experience increasing numbers of river floods in future. Hence, those regions are facing multiple hazard events with predicted changes in future intensity and frequency together with strong artificial pressure.

![Fraction of naturalness per ecoregion given in percent. 100% indicates a completely undisturbed ecoregion, whereas 0% indicates urban areas.](image)

To validate the human influence, the same analysis was done with another dataset. With the ESA Climate Change Initiative - Land Cover led by UCLouvain (2017) Data resampled to 1km by majority, 35 ecoregions are completely lost and in total 1’142’581 centroids are artificial. That’s approximately 13.5% of all centroids. In comparison, Jung et al., (2020) identifies 15.52% of the world area as artificial. In the near future, humans will further expand and increase anthropogenic disturbance. Ultimately, this influences ecosystem integrity and resilience. The question now is which disturbance regime change (hazard patterns or anthropogenic pressure) has larger impacts on ecosystems. In the past century, climate change had negligible impacts on forest loss and mammal extinction rate. The main predictor for these two aspects was anthropogenic disturbance and its indirect effects (Andermann et al., 2020; Danneyrolles et al., 2019).
A.2 Additional hazard patterns

Figure A2 A) Map of the Indomalaya with coloured ecoregions according to their average annual number of low-intensity tropical cyclones in absolute values. B) List of ecoregions with the highest number of low-intensity tropical cyclones on average per year.
Figure A3 A) Map of the Indomalaya with coloured ecoregions according to their average annual number of middle-intensity tropical cyclones in absolute values. B) List of ecoregions with the highest number of middle-intensity tropical cyclones on average per year.
Figure A4 A) Map of the Indomalaya with coloured ecoregions according to their average annual number of high-intensity tropical cyclones in absolute values. B) List of ecoregions with the highest number of high-intensity tropical cyclones on average per year.
Figure A5  A) Map with coloured ecoregions according to their average annual number of low-intensity wildfires in absolute values. B) List of ecoregions with the highest number of low-intensity wildfires on average per year.
Figure A6 A) Map with coloured ecoregions according to their average annual number of middle-intensity wildfires in absolute values. B) List of ecoregions with the highest number of middle-intensity wildfires on average per year.
Figure A7 A) Map with coloured ecoregions according to their average annual number of high-intensity wildfires in absolute values. B) List of ecoregions with the highest number of high-intensity wildfires on average per year.
Figure A8 A) Map of the Europe with coloured ecoregions according to their average annual number of low-intensity winter storms in absolute values. B) List of ecoregions with the highest number of low-intensity winter storms on average per year.
Figure A9 A) Map of the Europe with coloured ecoregions according to their average annual number of middle-intensity winter storms in absolute values. B) List of ecoregions with the middle number of middle-intensity winter storms on average per year.
Figure A10 A) Map of the Europe with coloured ecoregions according to their average annual number of high-intensity winter storms in absolute values. B) List of ecoregions with the highest number of high-intensity winter storms on average per year.
Figure A11 A) Map with coloured ecoregions according to their average annual number of low-intensity river floods in relative values. B) List of ecoregions with the highest number of low-intensity river floods on average per year and km².
Figure A12 A) Map with coloured ecoregions according to their average annual number of middle-intensity river floods in relative values. B) List of ecoregions with the highest number of middle-intensity river floods on average per year and km².
Figure A13 A) Map with coloured ecoregions according to their average annual number of high-intensity river floods in relative values. B) List of ecoregions with the highest number of high-intensity river floods on average per year and km².
A.3 Hazard patterns in larger format

Figure A14 A) Map of the Indomalaya with coloured ecoregions according to their average annual number of low-intensity tropical cyclones in relative values. B) List of ecoregions with the highest number of low-intensity tropical cyclones on average per year and km$^2$. 
Figure A15 A) Map of the Indomalaya with coloured ecoregions according to their average annual number of middle-intensity tropical cyclones in relative values. B) List of ecoregions with the highest number of middle-intensity tropical cyclones on average per year and km$^2$. 

A) 

B) 

Expected Average Annual Number of Events summed over all locations per Region Area [km$^2]$
Figure A16 A) Map of the Indomalaya with coloured ecoregions according to their average annual number of high-intensity tropical cyclones in relative values. B) List of ecoregions with the highest number of high-intensity tropical cyclones on average per year and km².
Figure A17 A) Map with coloured ecoregions according to their average annual number of low-intensity wildfires in relative values. B) List of ecoregions with the highest number of low-intensity wildfires on average per year and km².
Figure A18 A) Map with coloured ecoregions according to their average annual number of middle-intensity wildfires in relative values. B) List of ecoregions with the highest number of middle-intensity wildfires on average per year and km$^2$. 

A) 

B)
Figure A19 A) Map with coloured ecoregions according to their average annual number of high-intensity wildfires in relative values. B) List of ecoregions with the highest number of high-intensity wildfires on average per year and km².
Figure A20 A) Map of the Europe with coloured ecoregions according to their average annual number of low-intensity winter storms in relative values. B) List of ecoregions with the highest number of low-intensity winter storms on average per year and km^2.
Figure A21 A) Map of the Europe with coloured ecoregions according to their average annual number of middle-intensity winter storms in relative values. B) List of ecoregions with the highest number of middle-intensity winter storms on average per year and km$^2$. 

A)

B)
Figure A22 A) Map of the Europe with coloured ecoregions according to their average annual number of high-intensity winter storms in relative values. B) List of ecoregions with the highest number of high-intensity winter storms on average per year and km$^2$. 

A)

B)

Expected Average Annual Number of Events summed over all locations per Region Area [km$^2$]
Figure A23 A) Map with coloured ecoregions according to their average annual number of low-intensity river floods in absolute values. B) List of ecoregions with the highest number of low-intensity river floods on average per year.
Figure A24 A) Map with coloured ecoregions according to their average annual number of middle-intensity river floods in absolute values. B) List of ecoregions with the highest number of middle-intensity river floods on average per year.
Figure A25 A) Map with coloured ecoregions according to their average annual number of high-intensity river floods in absolute values. B) List of ecoregions with the highest number of high-intensity river floods on average per year.
A.4  Visualizations of future scenarios in larger format

Figure A26 Relative change of low-intensity tropical cyclone activity by Knutson between 2020 and 2080 (RCP 6.0) per ecoregion. The scale is logarithmic with blue as negative and red as positive values in percent. Purple areas are newly affected by such hazard intensities. Grey areas are not affected by tropical cyclones.
Figure A27 Relative change of middle-intensity tropical cyclone activity by Knutson between 2020 and 2080 (RCP 6.0) per ecoregion. The scale is logarithmic with blue as negative and red as positive values in percent. Purple areas are newly affected by such hazard intensities. Grey areas are not affected by tropical cyclones.
Figure A28 Relative change of high-intensity tropical cyclone activity by Knutson between 2020 and 2080 (RCP 6.0) per ecoregion. The scale is logarithmic with blue as negative and red as positive values in percent. Purple areas are newly affected by such hazard intensities. Grey areas are not affected by tropical cyclones.
Figure A29 Relative change of low-intensity tropical cyclone activity by Kerry between 2020 and 2080 (RCP 6.0) per ecoregion. The scale is logarithmic with blue as negative and red as positive values in percent. Purple areas are newly affected by such hazard intensities. Grey areas are not affected by tropical cyclones.
Figure A30 Relative change of middle-intensity tropical cyclone activity by Kerry between 2020 and 2080 (RCP 6.0) per ecoregion. The scale is logarithmic with blue as negative and red as positive values in percent. Purple areas are newly affected by such hazard intensities. Grey areas are not affected by tropical cyclones.
Figure A31 Relative change of high-intensity tropical cyclone activity by Kerry between 2020 and 2080 (RCP 6.0) per ecoregion. The scale is logarithmic with blue as negative and red as positive values in percent. Purple areas are newly affected by such hazard intensities. Grey areas are not affected by tropical cyclones.
Figure A32 Relative change of low-intensity river floods between 2020 and 2080 (RCP 8.5) per ecoregion. The scale is logarithmic with blue as negative and red as positive values in percent. Purple areas are newly affected by such hazard intensities. Grey areas are not affected by tropical cyclones.
Figure A33 Relative change of middle-intensity river floods between 2020 and 2080 (RCP 8.5) per ecoregion. The scale is logarithmic with blue as negative and red as positive values in percent. Purple areas are newly affected by such hazard intensities. Grey areas are not affected by tropical cyclones.
Figure A34 Relative change of high-intensity river floods between 2020 and 2080 (RCP 8.5) per ecoregion. The scale is logarithmic with blue as negative and red as positive values in percent. Purple areas are newly affected by such hazard intensities. Grey areas are not affected by tropical cyclones.
Eigenständigkeitserklärung


Die Dozentinnen und Dozenten können auch für andere bei ihnen verfasste schriftliche Arbeiten eine Eigenständigkeitserklärung verlangen.

Ich bestätige, die vorliegende Arbeit selbständig und in eigenen Worten verfasst zu haben. Davon ausgenommen sind sprachliche und inhaltliche Korrekturvorschläge durch die Betreuer und Betreuerinnen der Arbeit.

**Titel der Arbeit** (in Druckschrift):

Impact of natural hazards on global ecosystems

**Verfasst von** (in Druckschrift):

*Bei Gruppenarbeiten sind die Namen aller Verfasserinnen und Verfasser erforderlich.*

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<td>Vaterlaus</td>
<td>Lisa Sue</td>
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Ich bestätige mit meiner Unterschrift:
- Ich habe keine im Merkblatt „Zitier-Knügge“ beschriebene Form des Plagiats begangen.
- Ich habe alle Methoden, Daten und Arbeitsabläufe wahrheitsgetreu dokumentiert.
- Ich habe keine Daten manipuliert.
- Ich habe alle Personen erwähnt, welche die Arbeit wesentlich unterstützt haben.

Ich nehme zur Kenntnis, dass die Arbeit mit elektronischen Hilfsmitteln auf Plagiate überprüft werden kann.

**Ort, Datum**

Zürich, 20.12.21

**Unterschrift(en)**

Beim Unterschriften sind die Namen aller Verfasserinnen und Verfasser erforderlich. Durch die Unterschriften bürgen sie gemeinsam für den gesamten Inhalt dieser schriftlichen Arbeit.