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Disaster-related losses of ecosystems and their services. Why and how do losses matter for disaster risk reduction?

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ABSTRACT

Climate-related hazards, more specifically droughts, floods and storms, cause the largest share of people affected by disasters and major economic losses. While social and economic disaster-related losses are monitored and documented, this is not well established for the environmental losses. It is well known that environmental degradation is a key driver of disaster risk. As such, healthy ecosystems are acknowledged to contribute to disaster risk reduction (DRR) through their ecosystem services (ES). Yet they are at the same time heavily affected by disasters. Disaster-related losses of ecosystems and their services as well as the implication on overall DRR are not well understood. To address this knowledge gap, this research builds on a structured review of peer-reviewed literature and Post-Disaster Needs Assessments (PDNAs) to generate scientific evidence of disaster-related losses of ecosystems and ES to the climate-related hazards droughts, floods and storms. The established database of disaster-related losses of ecosystems provided the basis to further explore the link between disaster-related losses of ecosystems and related losses of ES. An additional review of scientific literature delivered evidence that losses of ES are many times higher than documented so far. In order to better understand, how disaster-related losses of ecosystems and ES ultimately alter disaster risk, we showcase the link between disaster-related losses of ecosystems and their services against the three dimensions of disaster risk. Regulating ES reduce disaster risk through mitigating hazard and exposure. Provisioning, regulating, habitat and cultural ES help to reduce vulnerability. Disasters diminish the capacity of ecosystems to provide ES, which leads to increasing disaster risk. We conclude this research with three constructive recommendations for integrating disaster-related losses of ecosystems and ES in a more comprehensive manner into disaster risk monitoring – notably the monitoring structure of the Sendai Framework for Disaster Risk Reduction. The aim of these recommendations is to support a more comprehensive monitoring of disaster-related losses including the environmental dimension and better acknowledge the role and contribution of ecosystems for advancing DRR.

1. Introduction

Climate-related disasters have accounted for 91% of the recorded disaster events over the past 20 years [1]. Thereof, droughts, floods and storms alone have affected 3.8 billion people, or 94% of all people affected by disasters [2]. According to the latest Global Assessment Report [3], climate change is considered to be a major driver of disaster-related losses, since it amplifies disaster risk and hampers development. A non-linear change in hazard intensity and frequency has already become a reality, for example through more powerful storms, exacerbated coastal flooding, higher temperatures and longer droughts (*ibid*).

Disasters affect all three dimensions of sustainable development, namely society, economy and the environment. Since the recording of disaster-related losses, impacts of disasters on society and economy have been captured and monitored by leading global disaster loss databases, like DesInventar [4], the Sendai Monitor [5], the international disaster database EM-DAT [6], or reinsurance databases like Sigma of the SwissRe [7] or NatCatService of MunichRe [8]. With regard to the environmental dimension, only the loss of provisioning ecosystems services, such as loss of crops or livestock, has been reported on despite the fact that ecosystems have been well recognized by researchers and

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policy makers globally for their contribution to development, disaster risk reduction (DRR) and climate change adaptation (CCA) [9–11].

Ecosystems provide provisioning, regulating, supporting and cultural services for human wellbeing [12,13]. Ecosystem services (ES), particularly regulating and supporting services, are relevant to help people adapt to the adverse effects of climate change and reduce disaster risk. For example, coral reefs can dissipate wave energy [14], mangroves can protect shorelines [15], wetlands can regulate flood events [16], and forested slopes can protect from avalanches [17]. Recent review papers provide comprehensive scientific evidence on the potential of ecosystems and their services to attenuate hazards, reduce exposure and vulnerability, and with this reduce the overall disaster risk (e.g. Refs. [18,19]).

However, ecosystems themselves are also impacted by natural hazards leading to losses of ecosystems and their services. Hauser et al. [20] showed in their analyses that Hurricane Sandy caused major losses to a large area of a coastal wetland in New Jersey, USA. A comparison of ecosystem assessments before and after the disaster event has revealed that erosion, deposition of sediments and marsh salinization has caused severe degradation of 40% of the wetland area and long-term degradation of 50% of the area. This event caused major losses of flood regulating services, water filtration and water supply (*ibid*) amounting to ES losses up to $4.4 billion of the total $9.4 billion provided by this wetland area (*ibid*).

The Sendai Framework for Disaster Risk Reduction (SFDRR) was adopted in 2015 by 187 countries with the aim to foster DRR efforts globally, by substantially reducing "losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries" [21, p.12]. In this paper, disaster-related losses of ecosystems and ES are viewed as actual losses covering the entire spectrum of adverse effects of extreme events (unlike the UNFCCC definition of loss and damage [22]) including everything from disturbance or damage to destruction or loss [23]. Thus, disaster-related losses of ecosystems and their services may entail "degradation" (i.e. the condition or process of wearing down), "decrease" (i.e. a reduction of some kind), "damage" (i.e. a physical harm), "disruption" (i.e. a disturbance), "impacts" (i.e. effects), "costs" (i.e. amount to be covered or paid), or "destruction" (i.e. an action or process causing damage or disruption to a degree that it no longer serves) as losses.

The Sendai Framework Monitor (SFM) facilitates the monitoring of disaster-related losses in order to measure progress on global targets for DRR. However, the SFM has very limited options to capture disaster-related losses of ecosystems and their services. One entry point for the consideration of ecosystem losses are the indicators for infrastructure damage and loss, where "green infrastructure should be included where relevant" ([24], p. 39). Green infrastructure can be understood as natural or semi-natural areas that deliver ES. Still, this opportunity is not straightforward considering that the terminology, conceptualization, and valuation of green infrastructure, ecosystems and their services are not widely shared among academia and practitioners [25].

Against this background, we argue that there is a lack of understanding and consideration of ecosystems and their services in the context of disaster-related impacts and what this means in terms of advancing DRR efforts. To address this knowledge gap, this review paper aims to assess the scientific evidence on losses of ecosystems and their services due to climate-related disasters and how these losses alter ES in the first place and ultimately disaster risk in all its three dimensions of hazard, exposure and vulnerability. The specific objectives of this paper are to: (i) document and synthesize losses of ecosystems and their services due to droughts, floods and storms from the scientific literature and Post-Disaster Needs Assessments (PDNAs); (ii) evaluate the link between disaster-related losses of ecosystems and related losses of ES; (iii) interpret the role of disaster-related losses of ES in the context of disaster risk; and (iv) discuss how disaster-related losses of ecosystems and their services could be monitored based on the established set of Sendai indicators.

2. Material and methods

This review uses a semi-systematic approach to analyze scientific and non-scientific literature to document disaster-related losses to ecosystems and their services. The analysis of the scientific literature aims to provide facts about disaster-related losses to ecosystems and their services in the academic field, and the analysis of grey literature aims at complementing this with disaster-related losses of ecosystems and their services that have been reported in PDNAs.

First a systematic review of scientific literature was performed using the databases "Web of Science" and "Scopus". A set of search terms was used in two different combinations to identify relevant scientific literature and gain information about disaster-related losses of ecosystems and their services: 1) TITLE-ABS-KEY (flood* OR drought* OR storm* OR hurricane* OR typhoon* OR cyclone* AND loss* OR damage* AND "ecosystem service*" OR "green infrastructure") AND DOCTYPE (ar OR re), and 2) TITLE-ABS-KEY (flood* OR drought* OR storm* OR hurricane* OR typhoon* OR cyclone* AND "impact on ecosystem*") AND DOCTYPE (ar OR re) (see also Tables S–1 in the supplementary material). The review focused on specific climate-related hazards: droughts, floods and storms, because they affected the majority of people (94%) in the last 20 years [2]. The search covered the time span until December 2019 and was limited to original research articles and review papers; however, only original research papers were used for compiling the database for further analyses. This systematic search was complemented by the review of further scientific literature using the snowball principle, mainly based on highly relevant references provided by articles from the systematic review. In addition, a review of PDNAs covering any of the three above-mentioned climate-related hazards was undertaken. PDNAs were retrieved from the Global Facility for Disaster Reduction and Recovery [25] and are performed to assess the extent of a disaster's impact directly after an event and serve as the basis for designing a recovery strategy. As such, they provide information on losses, and include consideration on reducing future disaster risks. Against this background, we decided to combine scientific literature and PDNAs in order to retrieve the most pertinent sources of information from which we can learn about disaster-related losses of ecosystems and ES.

The main inclusion criteria for this review was that it documents losses of ecosystem or ES due to floods, droughts or storms. The selected documents were coded applying a methodology based on descriptive codes and analytical codes. For the descriptive codes, MaxQDA12 software [26] was used to identify general aspects (e.g. type of hazard, type of research, geographical) and to generate a list of negative impacts on the ecosystem and their services reported in the literature.

In a second step this list of impacts was grouped through an analytical coding, creating general categories of disaster-related losses using MS Excel [27]. Table 1 illustrates the process from raw data (i.e. the entire length of each document) to analytical coding and Tables S–2 provides a list of key words identified in this process.

One hypothesis of this paper is that losses of ecosystems are resulting in losses of ES which in turn increases disaster risk. To establish the link between ecosystem losses and ES losses, the scientific literature was further reviewed. This literature search focused on all combinations between a specific ecosystem loss, as identified in the first review, and any ES following the classification scheme of The Economics of Ecosystems and Biodiversity (TEEB) [13]. The most recent paper that documented the link between a specific ecosystem loss and an ES was referenced to provide evidence for the respective relation.

Finally, disaster-related losses of ecosystems and their services derived from this review were linked with measuring progress in DRR, particularly for the SFM. For this, the disaster-related losses of ecosystems and their services were first analyzed and interpreted in the context of their potential impact on all three dimensions of disaster risk, namely hazard, exposure and vulnerability [26,27]. And second, all existing

Table 1
Example coding process. The coding scheme for descriptive and analytical codes is provided in Tables S–2.

Raw data	Descriptive codes	Analytical codes
Due to the drought, increased livestock and wildlife mortality rates. Death of fishes (…) Direct drought impact includes damage to plant and animal species (…) Lack of food normally results in reduced reproduction by adult animals, such as the production of milk by lactating animals. Consequently, this leads to food deficiency for the young wildlife. With reduced production of milk, young animals are likely to starve or succumb to diseases, parasites, and predation. With the shrinking growth of vegetation which provides cover for wildlife, animal species such as antelopes will be more vulnerable to predators. Lack of water will provide fewer habitats for waterfowl, and other species which may crowd them into smaller areas and make them more vulnerable to diseases, predators as well as competition with members of the same species (…) Due to drought, the number of flamingos in Lake Nakuru is diminishing as a result of diminishing water levels of the lake. The great migration of the wildebeest across the Mara River is under threat as the river's flow is reduced (…)	Increased livestock mortality; Increased wildlife mortality; Death of fishes; Damage to plant; Damage to animal species Food deficiency affecting young wildlife Shrinking growth of vegetation Cover for wildlife Lack of water Number of flamingos diminishing River flow reduced	Livestock; Biodiversity; Fisheries Vegetation; Biodiversity Biodiversity Vegetation Biodiversity, Habitat services Water Biodiversity Water

Table 2
Distribution of the 51 retrieved scientific papers, 50 retrieved PDNAs and the combined set of retrieved publications by hazard type, spatial scale, continental distribution, biomes, and assessment methods. Numbers relate to the amount of documents that represent the respective characteristics.

		Scientific papers	PDNA	Sum of publications
Hazard type	Drought	25	5	30[a]
	Flood	3	27	30[a]
	Storm	23	18	41[a]
Spatial scale of assessment	Global	2	0	2
	National	2	13	15
	Sub-national	0	0	0
	Regional	29	30	59
	Local	22	7	29
	Combined	2	0	2
	Continental	1	0	1
Continental distribution of assessments	Africa	1	17	18
	Asia	4	18	22
	Europe	10	2	12
	North America	29	0	29
	South America	7	1	8
	Central America	2	5	7
	Oceania	1	7	8
Biomes	Polar	1	0	1[b]
	Urban	2	0	2[b]
	Coastal	13	20	33[b]
	Inland water	8	19	27[b]
	Forest and Woodland	32	22	54[b]
	Drylands/ Grasslands	4	0	4[b]
	Mountains	1	1	2[b]
	Cultivated	7	51	58[b]
Assessment methods	Qualitative	49	46	95[b]
	Quantitative	41	50	91[b]

[a] Several publications document multi-hazard events.
[b] Publications fall under more than 1 category and the sum may thus exceed the total number of papers/PDNAs.

indicators of the Sendai targets as well as custom indicators that are embedded in the SFM were reviewed with the aim to understand to which degree these could be used to report on disaster-related losses of ecosystems and their services.

3. Results

The systematic literature review resulted in 24 original research papers. The snowball sampling resulted in 27 additional relevant original research papers, which provided a set of 51 scientific papers in total for the analysis. In addition, 50 PDNAs were considered as relevant based on the inclusion criteria (see Tables S–1 in the supplementary material). Thus a total of 101 publications were analyzed (see Tables S–3 in the supplementary material).

Table 2 provides a summary of the distribution of the 101 publications across hazard type, spatial scale, region and biome covered. Among the three reviewed climate-related hazards, storms were considered most often (41 publications), followed by droughts and floods (with 30 publications each). The majority of the publications focused on regional assessments (59 publications). Furthermore, most retrieved publications originate from North America (29 publications) and Asia (22 publications). The majority of papers reported disaster-related losses both in a quantitative and qualitative manner, with 95 papers reporting losses qualitatively and 91 publications reporting losses quantitatively. Most of the retrieved publications assessed the biome of cultivated ecosystems (58 publications) and of forest and woodland (54 publications), and by far neglected mountainous biomes (2 publications) and polar (1 publication).

3.1. Disaster-related losses of ecosystems and ES

This review provides scientific evidence for disaster-related losses of ecosystems and ES. The descriptive coding of disaster-related losses resulted in more than 500 individual losses of ecosystems or ES, with 60% of them being reported as quantitative data and 40% of them being reported as qualitative data (see Tables S–4). The analytical coding of all disaster-related losses of ecosystems and ES linked to drought, flood and/or storm events result a total of 25 losses, which are summarized in Table 3. The analysis of disaster-related losses of ecosystems and ES has been stratified by the following categories of biomes as provided by the Millennium Ecosystem Assessment MEA [28]: marine, coastal, inland water, forest and woodland, drylands/grasslands, mountains, cultivated, polar, urban.

Among the 25 disaster-related losses of ecosystems and ES (see Table 3 - rows), 20 referred to physical losses of ecosystems or elements of ecosystems at different scales and 5 specifically addressed losses of ES. The top three most recurring disaster-related losses that have been represented by the publication database were crops, forests and livestock. The loss of crops was reported in 6 scientific papers and in all of the analyzed PDNAs, representing 55.4% of the reviewed publications. This loss can to some degree be merged with the disaster-related losses of arable land. The loss of forest was reported in 31 scientific papers and 17 PDNAs covering 47.5% of all reviewed publications. In addition to forests in general, there were several additional losses of specific forests mentioned, such as mangrove forests, coastal forests, riverine forests or urban forests. Finally, loss of livestock was reported in 43 documents,

Table 3
Summary of the analytical coding of documented disaster-related losses of ecosystems and ES resulting from the review of scientific literature (Lit) and Post Disaster Needs Assessments (PDNAs) (see source data in Tables S–3 in the supplementary materials and coding scheme in Tables S–2). 1 to 20 lists the physical losses and 21 to 25 shows losses of ES. The [numbers] in squared brackets refer to the documents as indicated in the list of references. The column "Total" refers to the final amount of reviewed documents (Lit and/or PDNA) per each reported disaster-related loss (e.g. among the reviewed documents, the total amount of reported disaster-related losses regarding coral reefs is 10).

Reported disaster-related loss		Marine		Coastal		Inland Water		Forest and woodland		Drylands/ Grasslands		Mountains		Cultivated		Polar		Urban		Total
		Lit	PDNA	Lit	PDNA	Lit	PDNA	Lit	PDNA	Lit	PDNA	Lit	PDNA	Lit	PDNA	Lit	PDNA	Lit	PDNA	
#1	**Coral reefs**	[29–31]	[32–38]																	**10**
#2	**Dunes**			[39,40]	[36]															**3**
#3	**Mangrove forests**			[29–31, 41–44]	[32–38, 45–50]															**20**
#4	**Coastal forests**			[29,39, 51]	[32–36, 45]															**9**
#5	**Riverine forests**					[52, 53]	[48, 54–58]													**7**
#6	**Forests**							[31,40, 59–82]	[33,37, 46,47, 49, 55–58, 83–90]	[91–93]		[94]	[33]							**48**
#7	**Urban forests**																	[72]		**1**
#8	**Vegetation**	[30]	[33]	[51,95]	[34,36, 38,47, 96–98]	[53, 99]	[58]	[61,63, 74,100]		[101]				[102]		[103]				**21**
#9	**Wetlands**			[20,31, 39,73]	[34,38, 49,89]													[20]		**8**
#10	**Protected areas**			[29,39]	[35,38, 47,96, 104]	[52, 99]	[56,58]		[84,85, 87,89]											**15**
#11	**Biodiversity**			[29,31]	[33,34, 36,38, 45,47, 48,50, 96–98, 104]	[53, 99, 105]	[55,57, 58,106]	[79]	[86–89]						[107]					**28**
#12	**Soils**			[29,30, 39–42, 51]	[32, 34–36, 45–49, 97,98, 107]		[55–58]	[62,65, 66,75, 76,79, 81,108]	[83,86, 88,89, 109]			[94]				[103]				**38**
#14	**Crops**													[39, 63,70, 74,95, 100]	[32–38, 45–50, 54–58, 83–90, 96–98,104, 106,107, 109–126]					**56**
#15	**Livestock**														[32,33,35, 37,38,45–50, 54–58, 85–90, 96–98,104, 106,107, 109–113, 115,					**43**

(*continued on next page*)

Table 3 (*continued*)

Reported disaster-related loss		Marine		Coastal		Inland Water		Forest and woodland		Drylands/ Grasslands		Mountains		Cultivated		Polar		Urban		Total
		Lit	PDNA	Lit	PDNA	Lit	PDNA	Lit	PDNA	Lit	PDNA	Lit	PDNA	Lit	PDNA	Lit	PDNA	Lit	PDNA	
															117–119, 121–126]					
#16	**Fisheries**														[32,35–38, 45,47,48,50, 54,55,57,58, 84–88,96,97, 104,110, 112,116, 118–120, 122]					**28**
#17	**Aquaculture**														[35,46,47, 58,87,96, 104,106, 112]					**9**
#18	**Forestry**														[32,37,45, 49,54–56,83, 88,90,96, 106,111, 112,118, 122]					**16**
#19	**Water**	[29,31]		[39,40]	[34,35, 38,45, 47–50]	[99, 102, 105, 108, 127]	[54–58, 83,85,86, 88–90, 96–98, 106,107, 113,125]													**35**
#20	Carbon processes			[42,51]	[47]			[61,63, 65,67, 68, 75–77, 79–81, 91,108, 128]	[55,84, 86]							[103]				21
#21	**Provisioning services**			[42]		[127]	[85,88]													**4**
#22	**Regulating services**			[42]	[35,37, 47]			[105, 127]	[55,56, 58,85, 86,88]											**12**
#23	**Habitat services**	[29]		[31,39, 42]	[33,34, 36,37, 47,48]	[53]			[88,89, 96,97]											**15**
#24	**Cultural services**				[34,36, 47,50]		[56]	[127]	[87,88, 90,96, 118]											**11**
#25	**Ecosystem services**			[39]	[32,33, 35–37]			[105]	[86,88, 104]									[20]		**11**

Table 4
Linkage between ecosystems identified as having experienced disaster-related losses in Table 3 and ES, following the TEEB classification. References were inserted whenever literature was providing evidence to link these ecosystems from Table 3 to a specific ecosystem service; "NA" represents a "non-applicable" combination between the ecosystem and the ecosystem service; and "X" indicates that no literature could be found to demonstrate the link between the ecosystem and the ecosystem service. The [numbers] in squared brackets refer to the documents as indicated in the list of references.

List of physical losses identified in Table 3 (see Table 3)	Provisioning services				Regulating services							Habitat or supporting services		Cultural services				
	Food	Raw materials	Fresh water	Medicinal resources	Local climate and air quality	Carbon sequestration and storage	Moderation of extreme events	Waste-water treatment	Erosion prevention and maintenance of soil fertility	Pollination	Biological control	Habitats for species	Maintenance of genetic diversity	Recreation and mental and physical health	Tourism	Aesthetic appreciation and inspiration for culture, art and design	Spiritual experience and sense of place	# ES provided (total)
#1 **Coral reefs**	[32,36–38]	[129]	NA	[130]	X	X	[34,37]	X	[29]	NA	X	[29,34,37]	X	[131]	[36]	X	[132]	9
#2 **Dunes**	[133]	X	[134]	[135]	NA	NA	[39]	[136]	[39]	NA	NA	[137]	X	[39]	[138]	[39]	[39]	11
#3 **Mangrove forests**	[35,42,44,49,50]	[35,42,44,49]	[42]	[139]	[42]	[33,37,42]	[34,35,37,43,44,47,104]	[140]	[30,104]	NA	[41]	[33–35,37,41,42]	[33]	[42,50]	[34,37,42,50]	[33,34]	[141]	16
#4 **Coastal forests**	[142]	[33]	[143]	[144]	[39]	[33]	[145]	[39]	[39]	NA	[146,147]	[33,39]	X	[39]	X	[39]	[39]	14
#5 **Riverine/riparian forest**	[52,148]	[55]	[52,149]	[85]	[52,58]	[55]	[35,55,56,85]	[150]	[35,58,85]	NA	[151]	[52,58]	[55]	[55]	X	X	X	13
#6 **Forest**	[37,47,88,89,122,152]	[37,65,82,89,96,125,152]	[47,65,72,88,96,152]	[153]	[51,65,72,76,93,152]	[33,37,47,51,62,63,65,70,71,76,77,80–82,84,91,152,154,155]	[37,72,89,104]	[47]	[69,88,94,96,124,152]	NA	[69,92]	[37,69,71,88,152]	[37,53,59–61,65,76,78,93,96,152]	[47,72]	[37,88,152]	[152]	[118]	16
#7 **Urban Forest/GI**[a]	[156,157]	[157]	[72]	[156,157]	[72]	[158]	[72]	[159]	[160]	NA	[161]	[162]	[163]	[72]	[164]	[165]	[166]	16
#8 **Vegetation**	[97]	[167]	[167]	[168]	[167]	[74,101,169]	[170]	[171]	[30]	NA	[95]	[97]	X	[172]	x	[167]	[167]	14
#9 **Wetlands**	[39,58]	NA	[20,39,58]	[173]	[39]	[58]	[20,35,36,39,49,58,104,125]	[39,125]	[20]	NA	[174]	[20,39,49,73]	[49,50,58]	[39,50]	[175]	[39]	[39]	15
#10 **Protected areas**	[176,177]	[177]	[56]	[178]	[179]	[180,181]	[56]	[182]	[56]	NA	[147]	[183]	[84]	[50]	[50,56,114,125]	[152]	[184]	16
#11 **Biodiversity**	[47,50,105]	NA	[105]	[185]	NA	[105]	NA	NA	NA	[186]	[105]	[39,99,105]	[53,99]	[29,50,105]	[36,50,96,105]	[58]	[187]	12
#12 **Soil**	[188]	NA	[48,104]	NA	X	[189]	[48]	NA	[104]	NA	NA	[34]	X	X	[30,34]	[34]	[190]	9
#13 **Arable land**	[191]	[192]	NA	[193]	X	[194]	NA	NA	X	NA	NA	X	NA	X	X	X	X	4
#14 **Crops**	[47,54]	[195]	NA	[196]	X	X	NA	NA	X	[39]	[39]	X	NA	[197]	[198]	X	[199]	8
#15 **Livestock**	[200]	[192]	NA	X	NA	NA	NA	NA	NA	NA	NA	NA	NA	[201]	X	X	X	3
#16 **Fisheries**	[86,97,104,116]	[202]	NA	x	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	[203]	3
#17 **Aquaculture**	[32,47]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	x	NA	NA	NA	NA	NA	1
#18 **Forestry**	[35]	[88,90,111,122]	[90]	[90,204]	[205]	[205]	[35,204]	[205]	[204]	[205]	[205]	[205]	[205]	[204]	[204]	[204]	[205]	17
#19 **Water**	[206]	NA	[31,39,49,102]	NA	[207]	NA	[207]	X	[102]	NA	[49]	[208]	[99]	[39]	[209]	[39]	[210]	12
#20 **Carbon processes**	X	X	X	X	X	X	NA	NA	NA	NA	X	[211]	NA	NA	NA	NA	NA	1

[a] GI: Green infrastructure.

exclusively PDNAs, representing 42.5% of the publication database.

In terms of number of reported cases by biome (see Table 3 - columns), it's important to consider that one single document can report several losses, meaning it can appear several times along the above mentioned 25 disaster-related losses of ecosystems and ES. With this in mind, our analyses show that loss of vegetation (see row #8 in Table 3) is the most widespread loss appearing in seven of the nine biomes. Coastal and forests and woodlands represent the biomes most often addressed across the 25 identified disaster-related losses, with 15 and 10 entries, respectively. The highest concentration of losses in coastal biomes are linked to mangrove forests (see row #3 in Table 3), while the forests and woodlands biome have most losses linked to forests (see row #6 in Table 3). Cultivated ecosystems are also heavily impacted, with reports in 8 of the identified disaster-related losses, mostly linked to arable land, crops, livestock, fisheries, aquaculture and forestry (see rows #13 to #18 in Table 3). Losses in marine areas, inland waters, drylands/grasslands, urban areas, mountain and polar biomes were reported less frequently.

3.2. Implications of disaster-related losses of ecosystems for ES

The literature review documented disaster-related losses of ecosystems and, to a lesser extent, ES. Although loss of provisioning, regulating, habitat and cultural services as well as ES in general have been mentioned in the reviewed publications (see Table 3), reporting is unsystematic and rare. Additionally, the terminology is used inconsistently. For example, some documents refer to "environmental services", which is fuzzy and does not adhere to most frequently accepted ES categories. Documented losses of ES therefore do not sufficiently contribute to fully understanding disaster-related impacts. Consequently, an additional analysis of scientific literature was conducted to provide evidence for the link between physical disaster-related losses identified in the review and ES. This allowed documenting which ES are provided by each ecosystem and thus which ES may be disrupted as a result of the physical disaster-related losses identified in the review.

The 20 physical disaster-related losses of ecosystems identified in Table 3 were assessed against the 17 ES according to the TEEB classification [13]. Of the overall 340 potential relations in this matrix presented in Table 4, 86 were considered not applicable (NA) by the authors, i.e. where the link of the ecosystem and the service is not possible, such as, for instance, coral reefs providing freshwater. For the remaining 265, the search resulted in significant scientific evidence demonstrating the link between ecosystems identified for being affected by disasters and the provision of ES. Literature could not be found for 44 of the 265 possible links with ES, meaning this analysis provides evidence for 83.4% of possible linkages between disaster-related losses of ecosystems and ES in the literature.

As illustrated in Table 4, with the exception of aquaculture and carbon processes, which could only be linked to one ES, the remainder of impacted ecosystems identified in Table 3 could be linked to at least three ES. On average, the literature links disaster-related losses of ecosystems to eleven ES, though the total amount of ES linked to each row ranges from 1 to 17 (see last column on the right in Table 4). For seven ecosystems identified in Table 3 (mangrove forests, forests, urban forests, wetlands, protected areas, biodiversity and forestry), evidence was found for all ES according to the TEEB classification. Evidence was less for linkages between human interfered environments such as arable land, crops and livestock and ES.

3.3. Linking disaster-related losses of ecosystems and their services to DRR

The analysis of scientific literature and PDNAs resulted in evidence for different disaster-related losses of ecosystems and ES (Table 3). Further analyses of scientific literature provided evidence that a broad range of ES can be directly related to the manifested disaster-related losses of ecosystems (Table 4). At the same time, ecosystem-based approaches have been well recognized for DRR [10,11]. This chapter elaborates on the role of ecosystems and their services and the consequences of their disaster-related losses on the different dimensions of disaster risk.

The three main dimensions of disaster risk are hazard, exposure and vulnerability [212]. Hazard is defined as the process, phenomenon or human activity that may cause disaster-related losses (e.g. drought, flood, storm) [213]. Exposure refers to the situation of people, infrastructure, housing, production capacities and other tangible assets located in hazard-prone areas (*ibid*). Vulnerability describes conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards; however, vulnerability can at the same time be reduced by capacities that increase the ability of people to cope with hazards (*ibid*).

Fig. 1 provides a synthesis of all ES of the TEEB classification, which contribute to reduce risk of climate-related disasters. It can be clearly recognized that there is one set of ES, which mainly contribute to the mitigation of hazards that as such results in the reduction of exposure. On the other hand, there are numerous ES, which contribute to the reduction of vulnerability. Following our interpretation, 16 out of the 17 ES as classified by TEEB actively contribute to DRR in its different dimensions. In the following paragraphs we elaborate on the contribution of ES according to TEEB [13] to reducing risk to droughts, floods and/or storms.

3.3.1. ES for mitigating hazard - exposure

There is a considerable number of ES, which mitigate the severity of droughts, floods and/or storms and with this reduce overall hazard - exposure. The ES *local climate and air quality regulation* is mainly provided by forests, and reduces heat stress [214], which is often linked to droughts. At the same time forests influence rainfall and water availability locally and regionally [215]. Another relevant ES, which is mainly provided by forests and vegetation in general, is *sequestration and storage of carbon* [216]. With this service, ecosystems contribute to mitigating the impacts of climate change by removing carbon dioxide from the atmosphere [217]. The latest assessments of the Intergovernmental Panel on Climate Change [218,219] provide evidence that the reduction of carbon dioxide in the atmosphere is urgently needed to reduce global warming, climate variability and heavy rainfall events, which are directly connected to droughts, floods and storms. *Moderation of extreme events* is a regulating service provided by several ecosystems, which directly indicates the contribution to mitigating hazard severity [10]. Ecosystems such as coral reefs and mangroves protect coastlines from storm surges and flooding [16], wetlands can regulate flood water [16] and forests reduce the wind speed [220]. Especially in the context of flooding and storms, forest and vegetation cover stabilize the ground with their roots, providing the essential ecosystem service *preventing soil erosion* (*ibid*). In the case of flooding, water gets often contaminated with both human and animal waste, which is wide spread. Ecosystems, such as wetlands and soils reduce the water flow velocity, allow infiltration and, with this, act as filter for *treatment of waste-water*, where microorganisms break down the waste, eliminate pathogens and reduce the level of nutrients and pollution through their biological activity [221]. All ES that mitigate hazard exposure belong to the group of regulating services. These regulating functions are hampered if ecosystems are not intact and/or impacted by disastrous events.

3.3.2. ES for reducing vulnerability

ES can reduce the vulnerability of people to climate-related disasters, mainly through increasing the coping and adaptive capacity of the population. People and households who have access to provisioning ES such as *food, fresh water, raw materials and medicinal resources* are in a better position to cope with losses due to hazards than people who have very limited access. Provisioning ES are vital to human survival, providing food and access to safe drinking water, as well as providing medicinal resources [13,28]. Access to a great diversity of raw materials from ecosystems can increase the capacity to cope with impacts from disasters, e.g. access to wood for building shelters after a flood, cooking and heating in the case of disrupted services, etc. [223]. At the same time, access to natural resources also enables people to prepare for disasters or to mitigate their effects (e.g. by building dams for flood protection or storing resources to prepare for drought), thereby additionally reducing vulnerability. In a similar way, cultural ES are considered to support the health and well-being of people having access to them and, with this, reduce their susceptibility to experience harm. Despite being less tangible, it is a scientifically well-established concept that ecosystems, especially green spaces, significantly support the *mental and physical health* of people [224]. Also the *spiritual experience and sense of place service* reduces vulnerability through increasing health and well-being [225], and on the other side leads to protection of (sacred) ecosystems, which can lead to reduced impacts due to climate-related hazards. In the context of vulnerability reduction, the cultural ES on *aesthetic appreciation and inspiration for culture, art and design* can essentially contribute to the generation of new science and knowledge about biodiversity, ecosystems and landscapes [225], which may ultimately lead to the consideration of ecosystems in the context of DRR efforts.

Vulnerability to climate-related hazards can also be reduced by

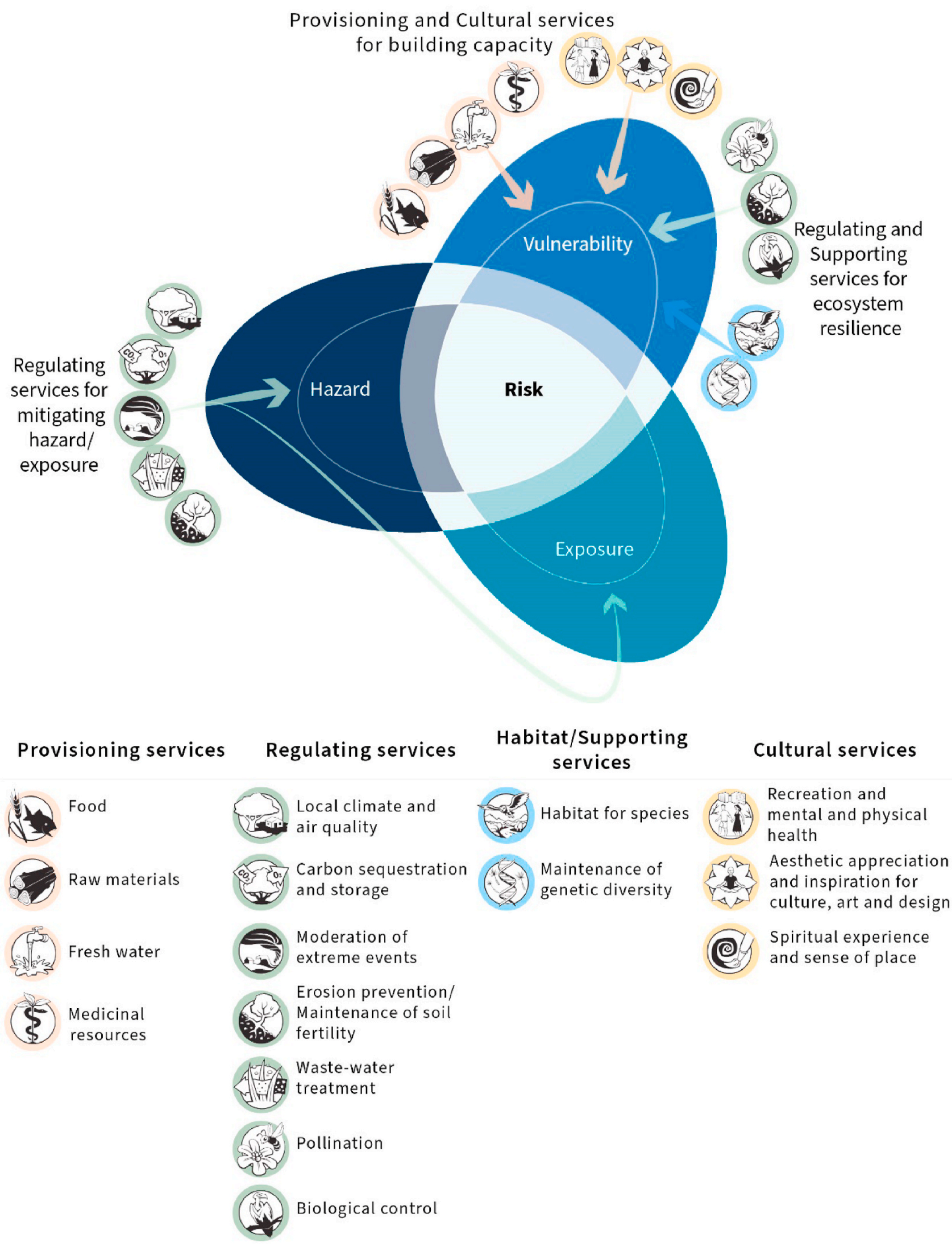

Fig. 1. ES (based on the classification and illustration from TEEB [13]) are linked to the three dimensions of disaster risk (Risk propeller adjusted from Abram et al. [222], Fig. CB2.1). The label of illustrated ES is provided in the legend below the image.

regulating and habitat or supporting ES in a way that these ES contribute to the overall health of the ecosystem itself. An intact and healthy ecosystem is able to maintain its metabolic activity level and its internal structure and organization to resist external stresses [226]. A healthy ecosystem is thus more resistant and considered less vulnerable to disturbances compared to a degraded ecosystem [217,227]. An intact ecosystem is furthermore in a better state to support the provision of ES [228]. The provision of ES very much depends on the health of the ecosystem itself [229]. Degradation of ecosystems is in fact reflected in the reduction of ES provisioning and benefits to people [230]. The *maintenance of soil fertility* is one example, where ecosystems, such as forests and vegetation in general, provide an essential contribution for supplying the soils with new nutrients, which are required to support the growth of plants. *Pollination services* e.g. through insects, birds or bats, are essential for the development of fruits, vegetables and seeds. This regulating service reduces vulnerability not only through providing the basis for a healthy ecosystem, but also for enabling the richness of provisioning services [231,232]. *Biological control* is another regulating ES, where ecosystems play a major role for regulating pests and vector-borne diseases that attack plants, animals and people through predators and parasites [233,234]. This regulating ES plays an important role to buffer the impacts of climate-related hazards, where for example pest infestation is concurrent with droughts [235]. Next to regulating services, ecosystems provide diverse *habitats and* supporting *services* that species need for completing their lifecycles. It has been shown that biodiversity is an essential indicator for ecosystem health [236], which can be again linked to the reduction of ecosystem vulnerability in the context of climate-related hazards. Another ES which is linked to habitats and biodiversity is the *richness in genetic diversity*. Ecosystems which are rich in genetic diversity are considered less susceptible to diseases and other damage such as climate-related hazards [237].

The above analyses show that all categories of ES are relevant for vulnerability. The provisioning and cultural services mainly reduce vulnerability of people through increasing their coping capacities, health and well-being. The regulating and habitat or supporting services mainly reduce vulnerability through maintaining ecosystems intact and healthy and with this enable ecosystems to provide services.

3.4. Monitoring disaster-related losses of ecosystems and their services in the SFM

In the following paragraphs, we evaluate to which degree disaster-related losses of ecosystems and their services are covered by the existing set of indicators in the SFM [238], which provides the most recent and internationally agreed scheme for monitoring loss and damage as basis for advancing progress in DRR. For this, we link disaster-related losses from Table 3 (in reference to their analytical coding in Tables S–2 and the specific documented losses as listed in Tables S–4) with relevant indicators of Targets A to D on loss and damage of the SFM (Table 5).

Within the SFM, only some indicators of Targets B, C and D aim to capture loss and damage in relation to ecosystems and ES. For Target B, ecosystems and ES are linked to indicator B-5, which aims to quantify the number of people whose livelihoods were disrupted or destroyed, attributed to disasters. This indicator covers the loss and damage of agricultural land and assets in relation to the number of people depending on it. In specific, the hectares of crops affected and the number of livestock lost due to disasters are quantified and provide an input for calculating the sub-indicators B5a and B5b (Table 5). Our review resulted quantitative data on hectares of cropland affected (e.g. Refs. [35,38]) and number of livestock lost (e.g. Refs. [38,110]) in the analytical codes #13 - #15 (arable land, crops and livestock), however, these type of losses were also very often reported only as percentage of losses in reference to the given inventory (e.g. Refs. [33,35]).

Target C aims to quantify economic loss due to disasters and has two indicators, which consider ecosystems and ES in the economic quantification of disaster-related losses. Indicator C-2 aims to quantify the direct agricultural loss attributed to disasters in economic terms and integrates the following elements of the agricultural sector: crops, livestock, forestry, aquaculture, and fishery. Our review resulted some quantitative data on economic losses for all these elements in different currencies, which are linked to the analytical codes #14 - #18 (crops, livestock, fisheries, aquaculture, forestry) [e.g. Refs. [32,33,36,37]). Another indicator of Target C, which considers ecosystems and ES in a more indirect way is indicator C-5. This indicator aims to quantify direct economic loss resulting from damaged or destroyed critical infrastructure attributed to disasters, and refers - due to a footnote provided in the technical guidance of the SFM [238] - also to the economic value of green infrastructure elements lost. Within the SFM, the pre-programmed categories related to green infrastructure that can be accounted for are: coastal defenses, mangroves, parks and green space, green infrastructure, urban tree canopy, regional storm water reservoirs, rain gardens, rainwater harvesting, ground reinforcement for landslide prevention, and underground water infiltration trenches and storage systems. Our review resulted some losses, which provided an economic valuation of green infrastructure elements lost. Examples are disaster-related monetary losses due to impacted coral reefs (e.g. Refs. [32,37], linked to analytical code #1 – coral reef); to mangrove forests (e.g. Refs. [32,35], linked to analytical code #3 – mangrove forests), or to native, natural forests in general ([e.g. Refs. [32,37], linked to analytical code #6 – forests). However, as the real value of losses of green infrastructure including the services they provide is hard to quantify in economic terms, the economic valuation refers in most cases to the costs of replanting or measures of ecosystem rehabilitation post-disaster [35,110,121].

The Sendai Target D aims to monitor critical infrastructure and basic services, which are disrupted due to disasters. Although this target addresses predominantly the health and education sector, the SFM refers also here to the option that protective and green infrastructure should be included where relevant for the indicator D-4 when measuring the number of other destroyed or damaged critical infrastructure units and facilities attributed to disasters. Our analyses showed that there are numerous green infrastructures destroyed or damaged due to climate-related hazards, which can be either counted as number of green infrastructures damaged or the affected area is quantified. Examples are coral reefs damaged or destroyed due to storms considered as coastal defenses (e.g. Ref. [35], linked to analytical code #1 – coral reef), mangroves destroyed or damaged due to sedimentation of roots (e.g. Refs. [36,48,49], linked to analytical code #3 – mangrove forests), wetlands affected due to sedimentation or saltwater intrusion considered as regional storm water reservoirs (e.g. Refs. [20,36,49], linked to analytical code #9 – wetlands), or damaged groundwater wells due to salt water intrusion and water pollution (e.g. Refs. [38,49,98], linked to analytical code #10 – water).

In addition to the official set of indicators, the SFM has a set of custom indicators. We interpret the following two custom indicators, which originate from the Resilient Cities Campaign [239], to support the monitoring of disaster-related losses of ecosystems and ES:

- Ecological health
- Identification of critical environmental assets

These custom indicators follow a self-scoring system from 1 to 5. This review identified several losses, which could be related to ecological health, such as climate-related hazards harming biodiversity due to impact on native and endemic species (e.g. Ref. [33], linked to analytical code #11 – biodiversity) and the damage and destruction of their respective habitats (e.g. Ref. [33], linked to analytical code #23 – habitat services), or the impact on sensitive ecosystems such as mangroves, wetlands or protected areas due to e.g. erosion, sedimentation, or salt water intrusion (e.g. Ref. [38], linked to analytical codes #3 –

Table 5
Synthesis of reported disaster-related losses of ecosystems and ES (Table 3), which are directly covered by indicators of the SFM [238]. The #numbers in the second column of this table refer to the number of reported disaster-related losses in Table 3.

Indicators of the SFM relevant for disaster-related losses of ecosystems and ES	Disaster-related losses of ecosystems and ES (see Table 3) linked to SFM indicators
B-5: Number of people whose livelihoods were disrupted or destroyed, attributed to disasters	
B5a: Hectares of crops affected * average workers per hectare	#13; #14 – Arable land; Crops *(area of cropland/agricultural land)*
B5b: Number of livestock lost * average workers per livestock	#15 – Livestock *(counts)*
C-2: Direct agricultural loss attributed to disasters	
C–2C: Direct Crop loss	#14 – Crops *(economic valuation)*
C-2L: Direct Livestock Loss	#15 – Livestock *(economic valuation)*
C–2FO: Direct Forestry Loss	#18 - Forestry *(economic valuation)*
C-2A: Direct Aquaculture Loss	#17 - Aquaculture *(economic valuation)*
C–2FI: Direct Fisheries Loss	#16 – Fisheries *(economic valuation)*
C-5: Direct economic loss resulting from damaged or destroyed critical infrastructure attributed to disasters - economic value of green infrastructure elements lost	#1, #3, #6 #9, #22 *(economic valuation)*
D-4: Number of destroyed or damaged critical infrastructure units and facilities attributed to disasters - area in square meters of green infrastructure elements	#1, #2, #3, #9, #10 *(counts, area)*

mangroves, #9 – wetlands, #10 – protected area).

4. Discussion and recommendations

This review provides evidence from more than 100 publications that ecosystems and ES have been largely impacted by the climate-related hazards droughts, floods and storms. The descriptive coding of disaster-related losses of ecosystems and ES resulted more than 500 reported losses, with 60% of them being reported as quantitative data and 40% being reported as qualitative data (see Tables S–4). This ratio of more quantitative than qualitative data can provide a good basis for integrating disaster-related losses of ecosystems and ES in the SFM.

The publication database used for this review is composed of peer-reviewed scientific literature and PDNAs. While peer-reviewed publications provide clear scientific evidence for disaster-related losses of ecosystems and ES, PDNAs are mainly field-based assessments of impacts after a disastrous event with the purpose to support the recovery process and provide an evidence base for resource mobilization [240]. Data on disaster-related losses of ecosystems and ES collected in the field using the PDNA methodology provided essential information for this research. One limitation of this global scale review approach is that the publication database is limited to English literature only.

The analyses of disaster-related losses of ecosystems and ES have shown that crops, livestock, and forests have experienced most losses from climate-related hazards. With the analytical coding, we aimed at aggregating reported and described losses into tangible physical losses of ecosystems, which are relevant for ecosystem management, and at the same time consider categories that are relevant for indicators of the SFM, such as crops, livestock, forestry, aquaculture and fisheries. We also identified very few reported losses of ES linked to climate-related hazards, which received their own categories. The derivation of analytical codes followed a deductive approach and represents losses of ecosystems and ES at different scales, which is a well-known phenomenon in ecological research [241] and scale-independence one element of the definition of ecosystems. A key finding of this review is that ES were hardly reported as disaster-related losses (overall 13 publications), and when mentioned, only in a very unsystematic way and at the level of categories of services.

Against this background, our research built on the hypothesis that losses of ecosystems are resulting at the same time in losses of ES, which is based on the well-established concept that healthy ecosystems provide ES [12,13]. Scientific literature has been found for 83.4% of possible linkages between disaster-related losses of ecosystems and ES following the TEEB classification. The disaster-related losses reported in this review linked to agro-ecosystems (e.g. here as crops or livestock), which are managed to maximize the delivery of provisioning services, have only very low diversity of ES. In contrast, disaster-related losses reported for natural ecosystems, such as coral reefs, dunes, mangroves, forests, or wetlands, provide the full spectrum of the 17 ES of the TEEB classification at a time. Unfortunately, all these additional losses of ES as a result of experienced losses due to climate-related hazards are hardly reported on. Our analyses show that these ecosystems provide next to provisioning and cultural services also regulating and supporting ES. This analysis provides scientific evidence that ES can be directly related to manifested disaster-related losses of ecosystems and explains further that the full dimension of disaster-related losses is yet far neglected.

To address the question on why and how losses of ecosystems matter for DRR, we interpreted the role of ES for the three dimensions of risk, namely hazard, exposure and vulnerability, as provided by the framework of the Intergovernmental Panel on Climate Change (IPCC) [212]. The assessment resulted that 94% of the ES provided by the TEEB classification scheme are actively contributing to DRR.

We showed that five regulating ES play a major role in mitigating climate-related hazards (see Fig. 1), mainly through buffering hazards and with this reducing the overall hazard intensity. As exposure is directly linked to the hazard through a spatial explicit overlay, regulating ES by mitigating the hazard also indirectly help to reduce the exposure. It has to be mentioned here, that the latest definition of exposure doesn't refer to ecosystems as relevant exposed elements [213]. However, this review provides clear evidence that ecosystems are exposed to and impacted by droughts, floods and storms and that resulting losses of ecosystems have a strong feedback on overall disaster risk. Thus, we argue that ecosystems should be included in the definition of exposure as essential element and considered as such in any future risk assessments.

In addition, we could show that overall twelve ES from all four categories play a major role to reduce vulnerability. We demonstrated that provisioning and cultural services ensure and enhance human health, well-being and the capacity of the population to cope with and prepare for disasters, while regulating and supporting services provide an essential contribution to maintain ecosystems intact, resilient and healthy. This is at the same time a prerequisite for the provision of ES. The contribution of ES to vulnerability reduction is less hazard-specific and can be linked to a broader context of vulnerability and ecosystem resilience.

This interpretation of the role of ES for DRR demonstrates that disaster-related losses of ecosystems have major implications on overall disaster risk, because they hamper or prevent the ability of ecosystems to provide their services, resulting in overall increasing disaster risk. On the other hand, during a hazard event, ecosystems may be lost while they are effectively mitigating hazard intensity, and thus successfully contributing to reduce overall disaster-related losses in the social and economic dimension. However, these ecosystems might not be able to provide the same level of regulating service in the face of a future event. The losses of ecosystems and their services as well as the perspectives of how they modify disaster risk means that these losses also need to be monitored in order to holistically understand disaster risk and achieve progress in DRR.

In terms of monitoring disaster-related losses, the SFM has been established as standardized platform to measure progress towards the implementation of the internationally agreed SFDRR in a quantitative manner. In this paper, we analyzed how reported disaster-related losses of ecosystems and ES are covered by the established framework of the SFM. While indicators of Target A on disaster-related mortality provide no entry points for considering ecosystems, there are some indicators of Targets B to D, which however mainly focus on losses in the social and economic dimension, but directly connect to disaster-related losses of ecosystems and ES. Our analyses showed that a number of quantitative losses found from our review, can be directly linked to indicators and sub-indicators of B-5, C-2, C-5 and D-4 of the SFM. In summary, these indicators integrate information on cropland and livestock affected, on economic losses in the agricultural sector and green infrastructure, and account for damaged or destroyed green infrastructure, when considered as critical infrastructure. While numerous publications have reported on the area of cropland affected and the number of livestock lost, which are essential measures of indicator B-5 according to the SFM, we argue that livelihoods in relation to ecosystems should be considered far broader than only limited to cropland and livestock. This is further demonstrated by sub-indicators of C-2, where next to crops and livestock, also forestry, aquaculture and fisheries are accounted for in terms of economic loss, and which all provide a basis for livelihoods.

Our review showed that reported disaster-related losses of ecosystems and ES contained to some extent the economic valuation of agricultural losses attributed to disasters as requested by C-2 of the SFM. However, it has to be mentioned that the economic values of indicator C-2 are only considering provisioning ES, which are according to our analyses only one of several other important services ecosystems provide, mainly with regard to forestry or fishery. While economic loss is clearly a major indicator for countries, and this type of information is important especially in PDNAs to enable reconstruction, it is notoriously difficult to adequately value ecosystems and their services beyond provisioning services [242].

On the other hand, indicators C-5 and D-4 also consider green infrastructure in a broader sense. While the economic valuation of green infrastructure (C-5) is very difficult, the indicator D-4 provides a very valuable entry point to formally account for disaster-related losses of ecosystems through accounting for the number of green infrastructure that is damaged or destroyed. However, according to the indicator design, only the number of destroyed or damaged green infrastructure can be accounted for, which does not reflect at all the degree to which ecosystems have experienced losses and does not account for the ES they provide. In addition, the definition of green infrastructure as provided in the SFM provides some examples, which are not clear exactly as to how they could relate to ecosystems. For example, regional storm water reservoir, could be interpreted as a wetland, but more likely than not it is viewed as a hard infrastructure.

Furthermore, our results also show that not all disaster-related losses of ecosystems can be reported under green infrastructure in the SFM as the SFM provides a rather narrow definition of green infrastructure. Nevertheless, they provide a large number of relevant services and with this have a strong influence on disaster risk, thus can be considered and reported as critical infrastructure in the SFM. Examples are protected areas and soils, or also coral reefs, wetlands, and waterbodies in general. However, no country has currently reported ecosystem losses as critical infrastructure or green infrastructure losses in the SFM. Instead, only losses of provisioning services linked to agricultural land are monitored and considered, which does by no means represent the real disaster-related losses of ecosystems and very much limits the perspective to consider ecosystems for DRR.

Next to the established set of indicators, custom indicators have been derived with some relevance for disaster-related losses of ecosystems and ES. The indicator ecological health is considered as the sole existing indicator, which integrates disaster-related losses reported as qualitative data. At the same time, ecological health is essential for ecosystems so they can provide their services. However, it would not be particularly easy to rate this without other indicators behind them. For example, ecosystem health is often measured through a series of “state” and “pressure” indicators [243]. The custom indicator on the identification of critical environmental assets could be considered as a preparatory step for monitoring disaster-related losses to critical green infrastructure as requested by indicator D-4. Countries could provide their own indicators related to ecosystem loss, if they so choose. But without any established ones, this is likely to make it more difficult.

This review provides scientific evidence that ecosystems and ES are experiencing losses due to climate-related hazards. We further provide evidence that the dimension of disaster-related losses of ecosystems is many times higher when considering also the losses of their ES. At the same time, we showed that ES provide major contributions for DRR, which is, however, limited, when ecosystems experience disaster-related losses. Additionally, we argue that the current design of the SFM does not sufficiently integrate disaster-related losses of ecosystems and ES due to its focus on the economic dimension of their provisioning services. Against this background, we provide the following constructive recommendations for integrating disaster-related losses of ecosystems and ES in a more comprehensive manner into the SFM, and with this acknowledge the role and contribution of ecosystems for advancing DRR:

1.) The reporting of livelihoods lost due to disasters should go beyond crop and livestock and consider other relevant ecosystems and ES which provide a basis for livelihoods. (Target B)
2.) Most ecosystems should be considered as critical infrastructure, which can be well justified by the role ecosystems and their services play for DRR. The reporting of the area of damaged or destroyed green (and blue) infrastructure would be more meaningful than the sole number of items affected. Green infrastructure needs a more clear and applicable definition in the SFM and complemented with blue infrastructure. (Target D)
3.) The majority of ES can be considered as basic services that are needed for society to function, such as fresh water supply, waste water treatment or services that are relevant for human health and well-being. Against this background, ES could be integrated into indicator D-8 (disrupted services) and reported in reference to ecosystem losses under green (and blue) infrastructure (monitored by indicator D-4). (Target D)

5. Conclusion

This review paper shows that ecosystems and ES have been largely impacted by the climate-related hazards droughts, floods and storms. The analysis of ES in relation to manifested disaster-related losses of ecosystems reveals that the full dimension of impacts due to climate-related hazards has been neglected. The analysis and interpretation of disaster-related losses of ecosystems and their services demonstrates on the one hand that ecosystems and their services play a major role for DRR in all its dimensions. This is mainly achieved through regulating services, which mitigate hazard – exposure, and through provisioning, regulating, habitat and cultural services, which reduce vulnerability in the overall disaster risk context. On the other hand ecosystems experience disaster-related losses, which affect their capacity to provide ES, leading to increasing disaster risk. To achieve progress in DRR as envisioned by the SFDRR, we argue that currently neglected ecosystems and their services need the same attention than social and economic disaster-related losses have in terms of monitoring. As a result of this research, we provide specific recommendations on how ecosystems and their services can be integrated in the existing framework of the SFM. Given the direct link between ecosystems and DRR, the comprehensive monitoring of disaster-related losses of ecosystems and their services is essential for planning sustainable DRR strategies and measures.

Author contribution

YW designed the overall structure of the review paper. YW, SJ, LN, AOV and JW identified literature, discussed the coding schemes and were involved in the review of all publications. SJ and LN lead the descriptive and analytical coding of disaster-related losses of ecosystems

and ES. YW lead the chapters on implications for DRR with inputs from ND on the Sendai indicators. YW drafted the full manuscript with inputs from all authors. All authors revised and approved the manuscript. The authors would like to thank two anonymous reviewers for their feedback on the paper.

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Appendix A. Supplementary data

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