Challenged by Vulnerabilities

A Focus on Climate Change and Disaster Risk Conceptualisations, Semantics, and Debates

Greta Adamo[1,*], Max Willis[2,*], Alessandro Mosca[3] and Anna Sperotto[4,5]

[1]*Free University of Bozen-Bolzano, Italy*
[2]*University Polytechnic of Valencia, Spain*
[3]*Laboratory for Applied Ontology (LOA), CNR-ISTC, Italy*
[4]*Ca' Foscari University of Venice, Italy*
[5]*Basque Center for Climate Change, Spain*

Abstract

Communities worldwide are experiencing increasingly severe impacts of flood, drought, rising atmospheric temperature and sea levels, compounded by threats of war, food scarcity, epidemics, and political upheaval, to name but a few. Vulnerability is a core notion in research and discourses of natural hazards, disaster risk, climate change adaptation, sustainability and environmental justice. Its understanding is pivotal to assess, reduce, anticipate, and adapt to adverse consequences of risks to socio-political, socio-economic and social-ecological systems. However vulnerability, both in its definition, semantics and experience, remains a blurred, often contested concept, and its discontinuous application across a multitude of fields has resulted in information silos and a prevailing lack of ontological clarity, which hinders the inter- and transdisciplinary research into risk communication and reduction. This paper contributes to the discussions on vulnerability by exposing, through an ontological and critical lens, a series of challenges focussing specifically on application to climate change, disaster risk and, more broadly, social-ecological systems research. These challenges encompass foundational, "wicked," and delicate topics, more specifically: (i) intrinsic and extrinsic vulnerabilities, (ii) multi-dimensional manifestations of vulnerability and its complex and dynamic, spatio-temporal aspects, and (iii) the relationship between vulnerability and resilience. In the concluding remarks, we summarise the most salient issues in the form of preliminary suggestions organised in a checklist to assist the tasks of defining, representing, and evaluating climate change and disaster risk vulnerability concept.

Keywords

Vulnerability, Dispositions, Ontology, Climate change, Disaster risk

Proceedings of the Joint Ontology Workshops (JOWO) - Episode XI: The Sicilian Summer under the Etna, co-located with the 15th International Conference on Formal Ontology in Information Systems (FOIS 2025), September 8–9, 2025, Catania, Italy

*Corresponding author.
GretaAdamo@unibz.it (G. Adamo); max@maxwillis.net (M. Willis); Alessandro.mosca@cnr.it (A. Mosca); anna.sperotto@bc3research.org (A. Sperotto)
https://gretaadamo.net/ (G. Adamo); https://maxwillis.net/ (M. Willis)
0000-0001-7116-9338 (G. Adamo); 0000-0002-0877-7063 (M. Willis); 0000-0003-2323-3344 (A. Mosca); 0000-0002-7443-646X (A. Sperotto)

CEUR Workshop Proceedings ceur-ws.org ISSN 1613-0073
published 2026-03-02

1. Introduction

The theoretical and practical relevance of the notion of *vulnerability* [1] is at the heart of research concerned with risk. Its study emerged from the fields of geography and natural hazards, and extended to disaster risk reduction and management, climate change, public health, and sustainable development, among others [2]. Due to this broad scope and application, there is significant confusion regarding the definition, analysis, and observation of vulnerability, yet researchers, policy-makers and practitioners from across these fields share the primary goals of: identifying systems at risk from harmful events [3], understanding how vulnerabilities can lead to negative impacts, and defining workable solutions to overcome them [4].

Semantic resources, such as ontologies, that include the notion of vulnerability can be found in cybersecurity and security engineering research (e.g. [5]), yet there is an overall lack of formalisation of the concept, in particular when situated within socio-ecological complexity of Climate Change Adaptation (CCA) and Disaster Risk Reduction (DRR) fields. This semantic and ontological deficit results in blurred and approximate conceptualisations of vulnerability, and incomplete and imprecise understandings. This paper advances a discussion on several prominent challenges to the ontological formalisation and representation of climate change and disaster risk vulnerability, drawn from an interdisciplinary literature that encompasses ontological, observational, and critical dimensions, which include (i) the application of dispositional pluralism to vulnerability, (ii) its multi-dimensionality and dynamic complexities, and (iii) the contested relationships between vulnerability and another semantically fuzzy concept, *resilience*. Our analysis extends beyond highlighting ontological and modelling problems of vulnerability to provide possible fixes and initial suggestions for researchers and professionals working with knowledge engineering, ontologies, and conceptual models to (a) develop conceptualisations of climate change and disaster risk vulnerability and (b) evaluate extant artifacts.

The paper is organised as follows: Section 2 outlines relevant background on vulnerability, including a review of semantic and ontological resources; Section 3 elaborates the identified challenges around the notion of vulnerability; and Section 4 concludes the paper, including a recommendation checklist that summarises the points discussed in Section 3.

2. Background knowledge

2.1. Context and definitions

The multidisciplinary grounds from which the notion of vulnerability emerged has led to different terminologies, definitions, approaches, and perspectives in practice. It can potentially be advantageous to have such a wide variety of interpretations and assessments, as well as disadvantageous due to the disciplinary compartmentalization and fuzzy meaning(s) [2, 6]. Historically, vulnerability was considered as the capacity to respond to past and present impacts, without focussing on future stresses [1]. Over time this notion became associated with disasters, conceptualised as a condition arising after a shocking event [1]. Hufschmidt [6] describes two main schools of thought concerning vulnerability, (i) the *human ecologist school* and (ii) the

structural paradigm.[1] The former, once dominant perspective, centred attention on human capabilities to adapt to adverse impacts, either as short- or long-term processes, and considered vulnerability to be simply the "capacity to be wounded" (extracted from [6], citing the original source in [7], p. 17). The latter, structural paradigm, emerged in the 1970's, with a divergent and critical perspective that socio-economic and contextual aspects cannot be overlooked in the comprehension and analysis of vulnerability. Although adaptation to hazards is mandatory to prevent and mitigate future negative impacts, this paradigm elaborates that it cannot be achieved without adequate and accessible resources and knowledge [6]. In this sense vulnerability is driven by socio-economic and political factors, such as power imbalances and inequalities based on gender, age, ethnicity and disability, often connected to marginalisation, (dis)empowerment and control [1]. Sen's *entitlement theory* [8] specifically elaborates these aspects of vulnerability, using the example of famine. While extreme food insecurity events can be brought on by disasters such as drought, flood or pestilence, they are more likely to be driven by war and social inequality, and famine presents less as an issue with the availability of food, and more as one of social and cultural barriers to accessing available food. This example demonstrates how the root causes of uneven experience of risk, and associated vulnerabilities, are socially situated, and regard access to resources, governance, the role of culture in shaping perceptions and responses to impacts, and uneven spread of knowledge and information among affected individuals and communities [9].

Joakim et al. identify four different interpretations of vulnerability [10]: (i) as a *threshold*, a probability that a person, community and system will incur harm if the impact exceeds a certain level, as (ii) the *exposure* to harmful events, wherein physical hazards or disasters impact passive people and systems, as (iii) a *pre-existing condition* which is expressed during impactful events, or over the longer course of unfolding processes, wherein inherent capacities to resist and/or recover are hindered, and (iv) as an *outcome*, the result of impacts that remain after an adaptation. While definition (iii) may seem more broadly interdisciplinary and useful for disaster and climate change research, Eakin and Luers [4] stress that the different conceptualisations of vulnerability are complementary, each important to building a more complete understanding of the concept's complexity.

The CCA and DRR research communities are concerned with the same risk-related notions of vulnerability, impacts, and uncertainty, among others [11], and have similar goals, i.e. to reduce vulnerability and adverse impacts [12], despite each having more specific disciplinary directions. CCA focuses on adjusting systems and practices to long-term climate change impacts, while DRR aims to minimize damage from short- to medium-term natural hazards and disasters.[2] Those communities - linked to large institutional bodies, such as the *Intergovernmental Panel on Climate Change* (IPCC) and the *United Nations Office for Disaster Risk Reduction* (UNDRR) - propose agreements, frameworks, reports, and field-related vocabularies in support of the syntheses, actualisation, operationalisation, and shared understanding of risk and hazards concepts. As mentioned in Cian et al. [13], the IPCC with its *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) [14] began a process of harmonisation of definitions and conceptualisation among communities, an effort

[1] Note that other labels have been assigned to those "schools," as reported in [6].

[2] For discussion of similarities, differences and historical development of CCA and DRR approaches see [11, 12].

Table 1
Climate change and disaster risk definitions.

Concept	IPCC Glossary	UNDRR Glossary & Sendai [16]
Vulnerability	*The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.*	*The 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* [16]. *Vulnerability is the human dimension of disasters and is the result of the range of economic, social, cultural, institutional, political and psychological factors that shape people's lives and the environment that they live in.*
Hazard	*The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.*	*A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation* [16].
Exposure	*The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected.*	*The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas* [16].
[Adaptive]capacity	[**Adaptive capacity**] *The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities or to respond to consequences* [20].	[**Capacity**] *The combination of all the strengths, attributes and resources available within an organization, community or society to manage and reduce disaster risks and strengthen resilience.*
[Coping]capacity	[**Coping capacity**] *The ability of people, institutions, organisations and systems, using available skills, values, beliefs, resources, and opportunities, to address, manage and overcome adverse conditions in the short to medium term* [21, 14].	[**Capacity**] *The combination of all the strengths, attributes and resources available within an organization, community or society to manage and reduce disaster risks and strengthen resilience.*

that continues with the *Sixth Assessment Report* (AR6) [15]. In this setting vulnerability is defined as "The propensity or predisposition to be adversely affected, [...]" (see IPCC Glossary) which corresponds to similar definitions proposed in the disaster risk literature, such as the *Sendai Framework for Disaster Risk Reduction* [16]. Note that identifying the "vulnerability of whom" and "the vulnerability to what hazard" are pivotal in these frameworks.

Table 1 reports the main definitions proposed by the IPCC and UNDRR, wherein vulnerability is conceived as a *propensity*, *predisposition*, *condition* (without being too specific on what those entities are), linked to multi-dimensional factors [17], e.g. physical and social, that might lead to negative impacts. Vulnerability has since been further specified to include internal/physical and external/contextual dimensions [2, 17], the latter presenting challenges concerning direct observability and measurement, which often requires the use of (proxy-) indicators for assessments [17]. For example, the number of hospital beds per 10,000 is used as an indicator to assess social/health dimension of vulnerability [18]. Other elements associated to vulnerability are often instrumental in its assessment [13], particularly in climate change research, which depicts vulnerability as one of the three components of risk, together with *exposure* and *hazard* [15]. In addition, the physical dimension of vulnerability often includes

the notion of susceptibility, while the social dimension encompasses *adaptive capacity* [19] and *coping capacity*, respectively "ex-ante" and "ex-post" hazard responses [13].

2.2. Vulnerability in computational ontologies and semantic resources

Several existing ontologies developed for (cyber)security and information systems (e.g. [5, 22]) aim to capture and formalise vulnerability, however in this article we review only those ontologies and semantic resources that are findable, which directly relate to CCA, DDR, and cognate fields and/or that exemplify applications to those domains. We also examine more general core and mid-layer ontologies that aim to capture cross-disciplinary representations. Note that an in-depth systematic review of ontology for the disaster domain under the lens of the FAIR principles can be found in [23]. Table 2 summarises the most salient resources that include the concept of vulnerability specifying: the name of the ontology, the source, the ontological classification of vulnerability (**VClassification**), its definition (**VDefinition**), the presence of a top-level alignment, and reuse (**R**).

Table 2
Vulnerability in formal ontologies.

Name	Source	VClassification	VDefinition	Top-level	R
beAWARE	Link,[24]	SuperC:Thing, SubC:Asset,LivingBeing	*Any living being or object that needs to be protected from hazards.*	-	+
Ontology Design Pattern for Referential Qualities	Link,[25]	Relational quality	[...] *the extent to which a natural or social system is susceptible to sustaining damage.*	DOLCE	+
Disaster Risk Properties Ontology	Link,[26]	SuperC:Observable property	UNDRR definition	±	+
EAonto	Link,[27]	SuperC:Thing	*The condition of being susceptible to harm or injury.*	-	±
COVER	Link,[28]	SuperC:Disposition	[...] *enable happenings that hurt one's goals.*	UFO	+
ResiliOnt	Link,[29]	SuperC:Disposition	[...] *are Dispositions that predispose an object to potential detrimental events.*	UFO	+
ShowVoc	Link	SubC:Vulnerable group Socio-economic vulnerability	UNDRR definition	-	+

Those findable and accessible ontologies that include vulnerability as a class do not constitute an extensive list, indeed many of those resources are lacking precision in terms of ontological grounding of vulnerability. Only (4) ontologies were found that specify its superclass beyond the generic "Thing;" these categorise vulnerability as a "Relational quality," "Observable property," or "Disposition," i.e. "Mode." Note that two semantic sources in the list, COVER (*Common Ontology of Value and Risk*) and ResiliOnt (*Resilience Core Ontology*), are both based on the same top-level ontology, the *Unified Foundational Ontology* (UFO) [30]. The latter specialises the former, with many elements in common, providing an ascribed, goal- and context-based formalisation of vulnerability (and risk). Aside from the Table 2's list, the definition of vulnerability as a *disposition* is a common ontological characterisation, both in UFO and the *Basic Formal Ontology* (BFO) [31] literature, and more broadly in applied ontology and philosophy (see e.g.

the *Informed Consent Ontology*, [32, 33, 34, 35, 36]). In terms of alignment and reuse, most of the ontologies adopt and extend existent vocabularies, semantic web standards, and ontologies. Several ontologies directly employ top-level ontologies, such as the *Descriptive Ontology for Linguistic and Cognitive Engineering* (DOLCE) [37] and UFO. While the *Disaster Risk Property Ontology* does not align with a foundational resource, it is situated in a broader Knowledge-Graph ecosystem called *KnowWhereGraph* (knowwheregraph.org/) that includes the *Disaster Management Domain Ontology* which, for some of its modules, reuses the *Sensor, Observation, Sample, and Actuator* (SOSA) Ontology (www.w3.org/2015/spatial/wiki/SOSA_Ontology), part of which involves a preliminary top-level alignment.

3. On the challenges of modelling vulnerability

3.1. Intrinsic and extrinsic vulnerability

The climate change and disaster risk literatures, and those of ontology and philosophy agree to large extent on the (pre)dispositional, qualitative, nature of vulnerability. From a philosophical point of view, vulnerability has often been conceived as a *disposition* (see Section 2.2), a widely discussed notion (see the *Stanford Encyclopedia of Philosophy* [38]). Dispositions, which can also be referred to as "powers," "capabilities," "potencies," and many others, are the manifestation of properties under certain conditions. Common examples of dispositions are physical properties, such as the flammability of wood and fragility of glass, that are triggered in specific situations and events, such as presence of flame, and falling from a hight [38, 39]. This implies that dispositions can exist in potentiality yet may not always be manifested in actuality.

The scope of this work is not to elucidate on dispositions, as has previously been accomplished in-depth, for example in BFO as *realisable entities* [31] and in UFO as *modes* [30], rather to frame vulnerability within the dispositional debate, contextualised within the CCA and DRR discourses. One of those regards the "causes" and/or explanations of dispositional vulnerabilities. As mentioned by Füssel [2], in the climate change literature, many authors separate "internal" and "external" vulnerabilities to hazards, as well as "physical-environmental" vs. "socio-economical." These distinctions capture important aspects of vulnerability, and their influencing and enabling conditions, however they also create terminological confusions and discrepancies. Hence Füssel proposes [2] a more comprehensive framework that includes four independent elements of vulnerability: *internal* and *external scales*, i.e. perspective, as well as *socioeconomic* and *biophysical domains* (similar to the distinction discussed in Gibb [1]). The internal-external distinction proposed in [2] is pertinent, yet mismatched with classic metaphysical arguments about intrinsic and extrinsic properties, and Füssel's internal and external vulnerabilities seem grounded more on common sense understandings. For example, income is considered an internal structural vulnerability, while the absence of public healthcare and education are external structural vulnerabilities. However both vulnerabilities could be considered ontologically extrinsic or relational, w.r.t. the granularity of the observation.

The analytical philosophy literature often describes and formalises dispositions as *intrinsic* properties, the so-called *Intrinsic Dispositions Thesis* [39, 40, 41]. Yet many types of dispositions, when subjected to scrutiny, can be considered *extrinsic*, such as recognisability, vulnerability, and even weight [38, 40]. This position is supported by the argument that two entities of the

same type may, or may not, manifest a certain disposition under the same exact conditions. Consider a classic intrinsic dispositional example: water, H2O, has the disposition of boiling, and that disposition manifests when the water temperature reaches 100° (under atmospheric pressure). If a colorless and odorless liquid boils at 100° under atmospheric pressure, it must be water, as that is an intrinsic physical property of that entity. However, if we consider a social vulnerability and its potential trigger, suppose the lack of access to rescue facilities and the occurrence of a hurricane, that vulnerability (i) does not intrinsically define an individual that manifests it,[3] thus (ii) if an entity bears that disposition, or not, it does not affect the intrinsic properties (which sometimes can be considered *essential* properties [39]) of that entity [41]. Additionally, (iii) two individuals sharing similar properties, e.g. elderly people, might manifest that vulnerability, or not, under the same circumstances depending on additional factors, such as their level of social capital. Note that this extrinsic account of vulnerability does not assume that there are no intrinsic vulnerabilities, therefore embracing a *pluralistic view*. A supporter of intrinsic vulnerability might argue that, as also stressed by McKitrick [40], extrinsic dispositions could be reduced to intrinsic ones; however, from a scientific and explanatory point of view, the practical utility of such reductionist perspective is questionable, as understanding the plurality of factors that enable vulnerability facilitates the actions that might save life and prevent harm.

Ontological proposals on pluralistic, causal, and extrinsic accounts of dispositions already exist [35]. Particularly, Toyoshima et al. [35] leverages on McKitrick's dispositional pluralism proposing an extension of BFO's *realisable entity*, e.g. dispositions and roles, as a "lens" through which dispositions can be more precisely analysed. Those extrinsic dispositions depend ontologically upon the existence of other entities, also in potentiality, which opens debate on the causal elements of dispositions, and on past representation of dispositions in foundational ontologies. The proposal of Toyoshima et al., which is situated within the applied ontology community, could be integrated into current interpretations of CCA and DRR vulnerability by complementing in an elegant way external/relational/situational definitions of vulnerability.

3.2. Multi-dimensional, dynamic, and complex vulnerability

The discussion on intrinsic and extrinsic vulnerability overlaps with the challenge of its multi-dimensionality, also mentioned in Füssel [2]. The UNDRR PreventionWeb provides a list of vulnerability classes: (1) (bio)*Physical*, e.g. coastal mangroves and poorly built infrastructure can be harmed by storm surge; (2) *Social*, e.g. marginalisation and discrimination because of gender, age, and educational status can impede access to hurricane shelters; (3) *Economic*, e.g. corruption and political instability can result in unequal distribution of recovery funds; (4) *Environmental*, e.g. loss of biodiversity affecting ecosystem services.

Similarly to analyses of multiple hazards, aggregate and compound risks [17], each of the aforementioned classes must be considered to provide a more holistic and interconnected understanding of vulnerability as one hazard might invoke vulnerabilities within several of those dimensions. For example, the impacts of a heatwave on a community can be assessed based on physical aspects of vulnerability, such as the frailty of aged individuals having greater susceptibility to heatstroke, and environmental aspects, such as with the presence/absence

[3] Consider that the notion of manifestation under certain circumstances is orthogonal to the intrinsic and extrinsic distinction as both types of dispositions/vulnerabilities can be manifested or not.

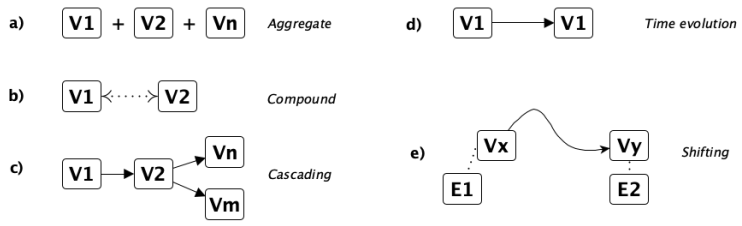

Figure 1: Complex vulnerability (*a simplified sample*) [43, 44].

of green spaces in their communities, on economic aspects, regarding the affordability and availability of air conditioning, and social aspects, for example the presence of family members to attend to elderly populations. Schneiderbauer et al. [17] and Thomas et al. [9] add further specialisations of vulnerability, such as: (5) *Institutional/governance* and (6) *Cultural* vulnerabilities. Institutional/governance vulnerability manifests for instance in the lack of appropriate action before, during and after a disaster. Cultural *foci* of vulnerability, can include the loss of cultural heritage, e.g. the destruction of historical sites due to armed conflict. These additional classes enrich the taxonomic structure of vulnerability as a system of categories, and provide further explanations and grounding, yet remain fraught with ontological challenges. Several of these classes (economic, social, institutional/governance and cultural) overlap without further specification. Therefore the incorporation of a vulnerability classification requires more sophisticated distinctions capturing fine-grained properties of social ontology [42], e.g. *agency*, *intentionality*, *organisations*, *gender*, *money*, *norms*, and so on. Another challenge regards source-target labelling of classes: while some are named after the affected sector (e.g. cultural), others are named after the affecting sector, i.e. the origin of the harm (e.g. institutional).

In addition to multi-dimensionality, vulnerabilities present complex spatio-temporal dynamics. Inspired by the framing in [43], we outline complex vulnerabilities interacting (see Figure 1) as **(a) Aggregate:** multiple independent vulnerabilities to a single or multiple hazards can manifest simultaneously, e.g. a coastal island community's concurrent vulnerabilities to inundation from storm surge and flooding due to heavy precipitation during a hurricane; **(b) Compound vulnerability:** multiple interacting (not necessarily causal-like) vulnerabilities are exacerbated by a single, or multiple hazards, to increase negative impacts, e.g. environmental degradation compounded by social inequalities, economic instability as well as institutional weaknesses. **(c) Cascading:** a larger chain of interrelated, interacting vulnerabilities propagating disruption across interconnected systems, e.g. vulnerability to inundation from storm surge, resulting overflow of sewage treatment plants, leads to e. coli contamination of drinking- and coastal zone water with consequent public health crisis. Additionally vulnerabilities are subject to **(d) Time evolution:** change over time and can **(e) Shift:** passing between one entity and another due to maladaptation [44], e.g. installation of coastal protection at a harbour shifts vulnerability of coastal erosion to local beaches. The situation becomes more complicated when focussed on multi-risk, i.e. multiple hazards, exposures, and vulnerabilities, wherein vulnerabilities could

increase over time and affect different entities, e.g. people, ecosystems, infrastructures [45, 43].

Representing these complex dynamics of vulnerability with ontologies requires a theory of dispositional vulnerability, both intrinsically and extrinsically grounded and explicitly aware of the type/token distinction, that in the very least (a) formalises its relations with hazards, considered as perdurants/occurrents [46], e.g. processes and events, also in complex forms such as one to many and many to many, (b) captures changes in objects manifesting vulnerabilities while offering explanations[4] for those changes, also considering how complex vulnerabilities influence each other, and categorical properties that influence vulnerabilities; and (c) provides a dedicated account for the aggregation and composition of vulnerabilities (i.e. mereology). Additionally, important aspects such a theory must encapsulate concern (d) the modelling of future perdurants/occurrents and vulnerabilities to capture evolutions over time and (e) uncertainty associated with complex vulnerability.

In applied ontology there are efforts in these directions, yet often not all at once and not all specific for dispositions. E.g. Toyoshima and Barton [47] explore the identity of processes and outline types of changes under the BFO perspective, i.e. changes as processes, also following a dispositional account. Another proposal advanced in Guarino et al. [48], while not including dispositions, presents an extensive ontological and semantic theory of qualitative changes in relation to events. Several articles of Galton and co-authors contribute to the understanding of temporal entities, e.g. [49] elucidates the causal relations among processes, states and events, and [49] examines the ontological dependence between objects and processes, also investigating the notion of change. Barton et al. [50] instead present a taxonomy of mereological relations for dispositions, including chain triggers. Specifically relevant to the ontological vulnerability discourse is the work of Lombard [51] that delves into the distinction between non-relational and relational changes, the latter sometimes called Cambridge changes, as it extends the reflections on intrinsic and extrinsic vulnerability and its multi-dimensionality by explaining how an entity x can change because being in relation with another entity y.[5] Using the example of Lombard, Xantippe became a widow due to the death of Socrates, and considering a more domain appropriate example, an household become food insecure due to a change in family composition. Concerning future and ongoing perdurants/occurrents, while an ontological analysis and formalisation of future events and processes is recognised as complicated, Guarino [52] provides a tensed characterisation of future events as variable embodiments. Finally, a first attempt to provide a COVER-based ontological unpacking of uncertainty in the climate change risk context is offered in [46], in which uncertainty can be interpreted as (i) a meta-belief, (ii) an an emergent quality, and/or (iii) an external aspect of a situation.

3.3. Vulnerability and resilience

Another recurrent theme in vulnerability literature is its description as an *antonym* of resilience [53]. This reflects initial *engineering perspectives*, which proposed that every system has an optimal balance of functioning, an *equilibrium*, and resilience is a property of the system to "bounce back" after an impactful event. Vulnerabilities are seen as flaws in a system which

[4]Here we refer to *explanation* as a complementary concept to the heavy debated notion of causation.

[5]Note that relational changes need not be associated only to extrinsic vulnerabilities and that changes for Lombard are events, a commitment that we report for completeness.

allow hazards to make a negative impact and reduce its resilience. That an object may be either resilient or vulnerable may hold true for intentionally-designed entities (i.e. artefacts, both material and conceptual) for which redesign can potentially control or mitigate vulnerabilities. Fortifying dykes, for example, can reduce vulnerability to rising floodwaters, as redirecting a river can potentially render an urban area more resilient. However the engineering perspective can be insufficient to describe ecological and social systems [54], as the relationships between resilience and vulnerability are more nuanced [55, 10]. Additionally an entity can exhibit resilience while remaining vulnerable, as research on the livelihoods and well-being of people living in extreme poverty elaborates [54]. Sustainability and climate change sciences further differentiate an *ecological resilience* [56] pertaining to complex adaptive systems, which diverges from the dichotomous vulnerability/resilience viewpoint. In this case "bouncing back" from an impact is not always possible (or desirable) and an ecological system may transform as a result of impacts beyond a certain threshold, and enter a new configuration with an altered state of equilibrium [56]. The drying of coastal wetland ecosystem manifests the vulnerability of mangrove plants, for example, to hydro-geologic or human impacts, yet its evolution into a coastal forest ecosystem supersedes the initial system's vulnerabilities.

From a social-ecological systems perspective, Gallopín [57] advances that resilience could be interpreted as a *capacity of response*, i.e. a disposition, which is a component of vulnerability. This reflects on Wisner's extensive analysis of vulnerability [58] that includes in the concept a dependence on capacities to anticipate, cope, resist and recover from impacts. While the latter three are capacities inherent in ecological systems, anticipation, and learning are aspects of *social- or community resilience* [59], which also diverge from the engineering concept of equilibrium. From an adaptation perspective, for a coastal population impacted by storm surges, responses to a hurricane typically aim to build resilience, not to return to an initial state of vulnerability. Wisner, following Nussbaum [60], distinguishes between *capacities* as intentional dispositions of agents to respond to hazards, and *capabilities*, the interaction between those dispositions and political, social and economic environments, reminiscent of the aforementioned intrinsic and extrinsic vulnerabilities. Thus capacities are influenced by factors beyond a single agent's control, and it is relevant to distinguish between these aspects for vulnerability assessment.

Of formal ontologies that address resilience, the literature provides few examples. A UFO-based core ontology of resilience, ResiliOnt, has been proposed [29] (see Section 2.2) in which *vulnerability* is defined as a negative disposition that inheres in a (value) object, which is counteracted by some other *capability*, a positive disposition, of the object, thus rendering it resilient. Its current version, while suitable to express relational properties, posits resilience and vulnerability as counterbalancing dispositions, which cannot account for dynamic or interacting vulnerabilities, or co-occurring *levels* of vulnerability and resilience that may inhere in an object or system. One DOLCE-based ontology design pattern [25] phrases resilience and vulnerability as referential, relational qualities (akin to relational properties in UFO [30]), rather than as dispositions, using the notions of *quale* and *quality space*. Considering the aforementioned BFO account of extrinsic dispositions [35] and the COVER ontology's UFO-based allowance for vulnerability as a subclass of an Intrinsic Mode or Extrinsic Mode (see https://purl.org/krdb-core/cover), each of these three widely applied foundational ontologies can potentially articulate vulnerability and resilience with internal and external determinants, but a unified approach remains elusive.

4. Conclusions and future works

This paper discusses some prominent challenges in the ontological representation and formalisation of climate change- and disaster risk vulnerability, drawn from pertinent literature and linked to possible solutions, existent in the state of the art, yet not fully articulated in a comprehensive theory. Table 3 summarises the paper's major points as an initial guiding checklist for evaluating semantic resources and developing ontologies, models and frameworks that address vulnerability. In demonstration, two resources included in Table 2, selected due to their domain-specificity and scope of application, are assessed. In *(i)* beWARE, only B and C are explicitly formalised, and partially F, which might be explained by that ontology's strong focus on crisis management. In contrast, *(ii)* the Disaster Risk Properties Ontology (in the Table "DRPO"), a broader DRR ontology, captures C and G explicitly, while I, and several others are partially modelled (see ± symbol), e.g. in H, only [adaptive]capacities are considered. Note that G and I are included as data properties.

Table 3
Minimal ontological checklist for CCA and DDR vulnerability.

id	**Suggestion**	beWARE	DRPO
A	☐ consider both intrinsic and extrinsic vulnerabilities	-	-
B	☐ address multi-dimensional vulnerability	✓	-
C	☐ formalise vulnerabilities' relations with hazards (perdurants/occurents)	✓	✓
D	☐ capture changes in objects and manifestations of vulnerabilities	-	±
E	☐ account for the aggregation and composition of vulnerabilities	-	-
F	☐ model future perdurants/occurrents and vulnerabilities	±	±
G	☐ explicitly address uncertainty related to vulnerability	-	✓
H	☐ distinguish between capacities and capabilities	-	±
I	☐ model vulnerability (and resilience) as scalar, not "on/off"	-	✓
J	☐ differentiate between vulnerabilities that can be reduced and not	-	-

Future works will continue evaluating the checklist with domain experts, and its application to assess the vulnerability concept in domain-specific semantic artefacts. Additional research directions can include the investigation of the emergence of vulnerability in relation to its triggering by and manifestation with other dispositions.

Acknowledgments. We gratefully acknowledge the support of EG2401 "Fondo sviluppo e nuovi progetti," the Italian PNRR MUR project PE0000013-FAIR, Future Artificial Intelligence Research, and iNEST funded by the European Union Next-GenerationEU, ECS_00000043 (PNRR).

Declaration on Generative AI. *Grammarly* was used for grammar and spell-check, text was reviewed and the authors take full responsibility for the written content.

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