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Dyadic risk mechanisms–a nomenclature for 36 proto-cascading effects determining humanity's future

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Abstract

Re-reading the risk literature, I sketch a novel nomenclature for 36 dyadic risk interactions that constitute the prototypes of what eventually become cascading effects. This analysis demonstrates where cascading risk effects originate and also hints at how they get their enormous power. Risk dyads derive from basic first-order interactions across six disruptive forces: sci-tech, governance, economics, social dynamics, ecological impact, and health adversity. I give brief examples of each and provide a short case description of six of the most prominent dyads. Very few of these dyads have an existing shorthand. The exception is NaTech, which denotes natural disasters being amplified by, or amplifying industrial risk, or now more broadly, sci-tech-derived risk. By generalizing the NaTech-style nomenclature across domains, I aim to provide the basic building blocks for a precise understanding of contemporary risk mechanics. This step is often skipped by avid complexity scholars intent on first describing system-wide features. Yet, dyadic analysis is an important prerequisite for systemic understanding of complex cascading effects that depend on triadic or tetradic risk relationships. In reality, even if systemic, and existential risks, as they emerge in the twenty-first century, depend on a myriad of cascading effects, they cannot be fully understood simply by looking at the whole system and attempting to analytically ignore its constituent parts claiming to gain a better overview.

Keywords Risk analysis, Futures research, Governance, Foresight, Technology assessment, Systemic risk, Cascading risks, Existential risks, Disruption, Complexity

Introduction

Cascading risks is a well-known perspective in disaster research [3, 80, 95]. The cascades refer to interacting risk factors that amplify the effect of each individual factor if a hazard occurs. Cascades is also a widely used metaphor in ecology [112]. The cascading lens has already been applied to a wider set of risk phenomena, including risks derived from natural disasters being amplified by or amplifying technology risk [49] and even to geopolitical norms [42]. However, that's only scratching the surface of the cascading risks perceptive.

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The cascading effects lens is currently dominated by scholars with a systems theory inclination [3, 20, 36, 53, 75, 101, 106, 113, 134], who explicitly want to deploy a wide systems lens *instead of* a traditional domain-specific lens. Whilst indeed useful, uniquely using the widest possible systems lens risks missing something essentially important: the core ingredients that go into cascading effects.

In sociology, a dyad denotes a group of two people, the smallest possible social group, who have sustained intimate face-to-face relations over a sufficient amount of time to establish a discernible interacting pattern [13]. In psychology a dyad is used to describe network relationships between significant others or colleagues to understand coping behavior [41, 73]. In epidemiology, a dyad is used to understand risk behaviors affecting community transmission of disease. However, it is also used in political science when analyzing country data [9, 79]. In social network theory, a dyad can also be used to understand the similarity between actors who have not directly interacted [108]. This article extends the dyadic term to look at causal interactions between disruptive forces that indirectly involve humans and which impact humanity's overall risk level.

As a starting point, the relevance of a set of six conceptually distinct, yet related, disruptive forces, namely science and technology ('sci-tech'), governance, economics, social dynamics, and health adversity is assumed [123, 124]. In the management literature, this is known as PEST analysis [28]. There is ample scientific support for the interaction between these forces from fields as diverse as the economics of risk [2], disruptive innovation within management studies [24, 114] via multidisciplinary science and technology studies [25, 56, 65, 60], ethics [76], scenario methods in futures research [27, 87, 91, 126], sociology of risk [14, 38, 45] and risk governance in political science [84], to the social determinants of health approach in public health [16, 47], climate change and sustainability studies [35, 64], or existential risk studies [8, 12, 69, 82, 83, 90, 109, 119, 121, 122, 133] which at times attempt to study incredibly complex sets of risks divorced from evolving findings in adjacent scholarly fields–as if existential risks (x-risks) were qualitatively different.

Not all of these forces are included in all types of analysis. In fact, typically a comparative or correlational study will consider only two or three of these forces, although factorial designs permit looking at multiple independent and dependent variables within those domains. The policy impact and risk analysis might be separate pieces ('deliverables') of such studies, such as in EU-financed R&D, although impact assessments are used as compulsory policy deliberation instruments during the development of new regulations [37, 99].

Assuming a simple dyadic relationship between each playing out at some point in history would result in 36 combinations. Few studies have described all of these combinations and how they might inform a more structured analysis and mitigation of risk. In this article, research objectives include considering the effects of dyadic hazards but will neither consider more complex triadic or tetradic relationships often called 'polycrises' [59], nor will mitigation paths be studied in any detail.

For the record, an example of a four-factor, tetradic risk cascade (a 'polycrisis') would be how an economic crisis could lead to the demise of a technology platform which, in a tense geopolitical environment might lead to single- or multi-government collapse which would have significant adverse health effects. The idea behind the present article is that before such complex analyses can be properly conducted, it is necessary to gain a more comprehensive understanding of dyadic risk relationships. The hypothesis is that dyadic risk is more than sufficiently complex to gain an overall understanding of the constituent factors of potential cascades currently at play, that is, to begin cascading effects analysis.

Looking at Fig. 1, the first aspect is naturally that each factor's interaction with another factor with the same feature represents six of the dyads. A key research question becomes whether each of those is equally relevant or prevalent. Governance is a crucial element affecting risk in society [111]. Additionally, there is the question of whether separate examples for causal relationships are needed or if GovTech should be viewed as 1–1 with TechGov. Such matters are discussed in the methods section. Lastly, note that even though the broader dyadic feature is named Ecological impact, which is more inclusive and representative of broader phenomena including risks to biodiversity, the natural hazards ('na-' or 'nat') nomenclature from the NaTech tradition is kept to ensure it is distinguishable from economic effects ('econ').

DYADIC FEATURES	Sci-tech	Economic	Governance	Social Dynamics	Ecological impact	Health adversity
Sci-tech	T^2	TechEcon	TechGov	TechSoc	TechNat	TechHealth
Economic	EconTech	E^2	EconGov	EconSoc	EconNat	NaHealth
Governance	GovTech	GovCollapse	G^2	GovSoc	GovNat	GovHealth
Social dynamics	SocTech	SocEcon	SocGov	S^2	SocNat	SocHealth
Ecological impact	NaTech	NaEcon	NaGov	NaSoc	N^2	NaHealth
Health adversity	HealthTech	HealthEcon	HealthGov	HealthSoc	HealthNat	H^2

Fig. 1 The 36 basic dyadic risk mechanisms

Methods

The 36 dyadic effect combinations that were selected already at the research design stage were subsequently investigated through a systematic review of the risk literature across a myriad of scholarly fields (notably disaster research, innovation studies, public health, risk science, sociology, and sustainability), using search terms such as cascades, existential risk, risk, impact, interaction effects, natural hazards, and systems, as well as using each of the disruptive factors we use for the six dyadic features under investigation. Literature review is a complex research methodology to execute and the key is to be transparent and follow conscious steps that are motivated by gaps in the field, well explained so as to be reproducible, and which lead to novel findings [77, 96, 115]. I conducted the literature search mainly via online databases, prioritizing Google Scholar and Web of Science, and mostly for journal articles because this search strategy helps to create a more transparent process that can be applied globally [66].

Searches, which took place in December 2023 and January 2024, were first conducted in Google Scholar and Web of Science (WoS) using three search strings: "existential risk", "systemic risk", and "cascading risk", with spot checks using other databases (e.g., ABI Inform/ProQuest, EBSCO/Business Source Premier, JSTOR, MENDELEY, PubMed, ScienceDirect, Scopus, and SpringerLink), but given that the two initial databases had the large majority of relevant content, detailed searches in the latter were abandoned. Given the more limited set of hits, all WoS search results were examined, but results from Google Scholar were further narrowed down by period of publication (2008–2024), language (English), and prioritizing peer-reviewed papers. I made exceptions for a few older references [5, 45] that were found to be great or unique examples of dyads. The first usage of "risk cascade" outside biology and on systemic risk outside finance was found in the work of German scholar Dirk Helbing in 2012–2013 [54, 55].

Turning to dyads, two specific searches were conducted: (1) "Risk" AND "topical field" (and so on for all 6 framework terms, e.g., sci-tech, economics, governance, social dynamics, ecological impact, health adversity), including variations of spelling and adjacent terms, and (2) "Risk" AND "[scholarly field]" (and so on for all 6 fields under scrutiny (e.g., disaster research, innovation studies, public health, risk science, sociology, and sustainability). Obviously, a larger set of topical or scholarly fields would have yielded additional results, but a cutoff decision was made based on the 80/20 rule considering my initial literature review of the overall risk field. Given the challenging multi-pronged searches needed, I searched using 'Only in Title', 'in Title and abstract' and only when in doubt or on a hunch, 'in the text'. An abbreviated list of specific search terms from these searches, including various related terms (5–10 for each category) and search results ('hits') is available for interested scholars (see the Supplementary material 1).

For these more extended searches, total Google Scholar hits across these searches were in the millions ($n = 8{,}122{,}670$), so each was rapidly winded down using exclusion criteria such as publication period (2020–2024), and review articles only, which was followed by forward and backward citation searches to identify relevant case studies. From this large set of hits, a matching effort, mapping results to 36 identified dyads (see Fig. 1), resulted in 90 potential abstracts that were reviewed, 30 of which were discarded when looking a bit closer. The 70 remaining papers were subject to full-text eligibility review, and only 10 were discarded. From the 60 remaining papers (including gray literature), a qualitative synthesis of categorized results was created. The peer-reviewed subset of those was 45 articles, in which 205 keywords, 14 keyword clusters, and 4 journal categories were identified (See the flowchart, Fig. 2 and Supplementary material). A total of 12 papers were from Science, Engineering & Technology (SET) journals, 13 from Social Science and Humanities (SOH) journals, 1 from Management journals, and 14 from Interdisciplinary (INT) journals. The average (self-reported or from JCR Clarivate) impact factor across journals was 9.1, with the highest being 64.8 (Nature) and the lowest being 0.58 (Review of Economics De Gruyter).

The goal of the literature review was not an exhaustive list of all examples of such occurrences (which is why a reference list of all initial search hits was not produced). Rather the emphasis was on meta-analysis as evidence of the effect of these dyads on the larger phenomena of cascading risks. The analysis proceeded to search for a few good examples of each to form a basic understanding of how useful the joined-up dyadic lens is likely to be in advancing the field going forward. Future research might discover many more occurrences, possibly also further types of findings within each dyad, and at that level of analysis, each could be separate papers.

Even though causal effects were sought, co-causal relationships (such as between TechGov and GovTech) were handled as if they were one and the same as long as the example we found in the literature allowed us to do so. As can be seen, this did not work in all cases. However, if we do treat them that way, we would be left with only 22 dyads (see Fig. 3). The description of dyadic effects could perhaps be subsumed in the same section, but a remaining challenge would be to select the remaining shorthand; do we use TechGov or GovTech? However, the article scopes out all relevant 36 dyadic relationships.

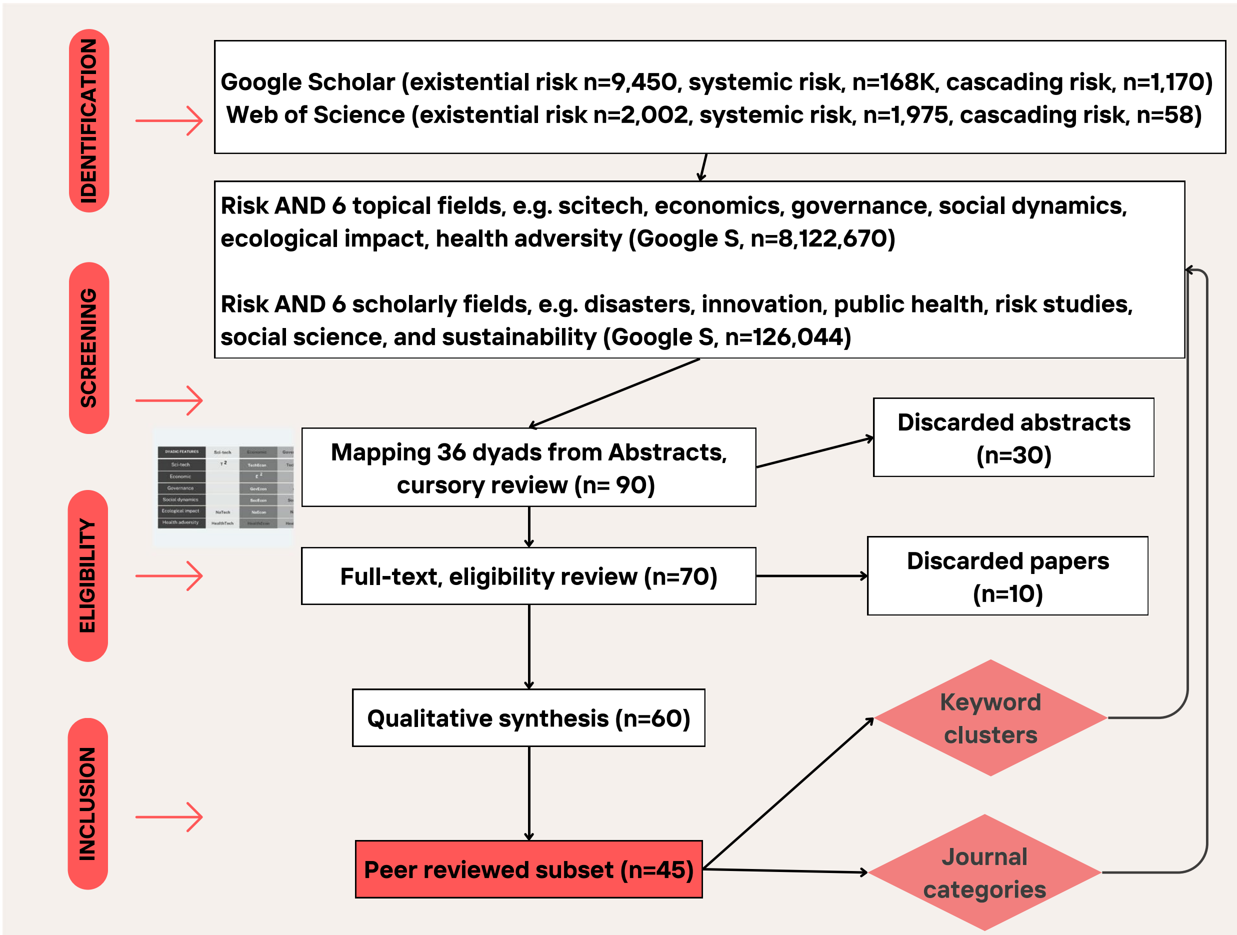

Fig. 2 Dyadic risk—PRISMA review

DYADIC FEATURES	Sci-tech	Economic	Governance	Social Dynamics	Ecological impact	Health adversity
Sci-tech	T^2	TechEcon	TechGov	TechSoc		
Economic		E^2				
Governance		GovEcon	G^2			
Social dynamics		SocEcon	SocGov	S^2		
Ecological impact	NaTech	NaEcon	NaGov	NaSoc	N^2	NaHealth
Health adversity	HealthTech	HealthEcon	HealthGov	HealthSoc	HealthNat	H^2

Fig. 3 The 22 co-causal dyads

Whichever way you handle it, dyadic data analysis presents a number of methodological challenges [86]. Most importantly, dyadic data often violates the assumption of non-independence of variables. In international relations, one study demonstrates how this can lead to overconfidence in the statistical validity of discovered relationships in data on country pairs [39]. Moreover, there may not be enough dyads for sufficient statistical power to create valid data categories. Another challenge might be that each factor or dataset in the dyad may not be on the same analytical level, and as a result, necessitates multilevel analysis.

Additionally, one needs to demonstrate that each of the members of the dyad is distinguishable as separate entities for the purposes of analysis. For that, one needs to show empirically meaningful differences between dyadic factors. One also must show (or assume) that there are no relevant and missed hyperdyadic dependencies, meaning that dyads do not depend upon each other or that there are no systemic effects overriding the dyadic mechanics in importance [29]. Some of these problems can be solved by specific types of regression analysis [79]. Longitudinal data also potentially addresses multilevel or other dyadic challenges.

For the purposes of this article, and because of the large amounts of dyads (36), this paper does not delve further into the methodological challenges of working with dyads as a level of analysis.

Results

I will now present the results of some initial examples of each dyad as found in the literature, with a brief explanation, and as a single data point on the historical trajectory of dyadic risks, denoting the year it was reported. My definitions of each dyad appear in the results section as opposed to in the introduction, because as the empirical work confirmed what each dyadic term would need to include there was considerable refinement needed.

By design, not all examples of risk dyads rise to the level of existential risks which initially were my chief concern. This is appropriate because even midrange risks could become constituent factors of existential risks when occurring as part of a dyadic (triadic or tetradic) cascade of hazards proximate in time and place [125]. Finally, there were literally thousands of articles and examples that could have been used and other scholars will complement this initial selection.

SciTech risk dyads

Sci-tech risks typically impact risks arising from other disruptive factors such as governance, economics, social dynamics, ecological impact, and health adversity, are in turn also impacted by each, and may also interact with them in various ways (Tables 1 and 2).

Note that even though the year reported might show up as relatively recent, no systematic effort was made to find the first time such a dyad was reported and it could have been several decades earlier. Even though most tech-related dyads have been known for a while, the sheer number of articles describing serious concerns about risks stems from the last thirty years or so [6].

Table 1 SciTech risk dyads: core concepts

Dyad	Definition
T^2	Risks associated with the combined effects of two science and technology-related factors, phenomena, or platforms
TechEcon	Risks associated with the combined effects of science and technology-related factors, phenomena, or platforms and economic phenomena
TechGov	Risks associated with the combined effects of science and technology-related factors, phenomena, or platforms and factors related to governance, including both state-level and non-state governance processes
TechSoc	Risks associated with the combined effects of science and technology-related factors, phenomena, or platforms and social dynamics
TechNat	Risks associated with the combined effects of science and technology-related factors, phenomena, or platforms and ecological factors ('nature')
TechHealth	Risks associated with the combined effects of science and technology-related factors, phenomena, or platforms and health adversity

Economic risk dyads

Economic risks impact risks arising from other disruptive factors such as sci-tech, governance, social dynamics, ecological impact, and health dynamics, are impacted by each, and may also interact with them in various ways (Tables 3 and 4).

I note that the impact of dyads is often multifaceted and can initially be negative and then turn to a positive, both as regards risk and innovation. This relates to the complexity of analyzing dyadic relationships, as hinted at before.

Governance risk dyads

Risks derived from governance impact risks arising from other disruptive factors such as sci-tech, economics, social dynamics, ecological impact, and health dynamics, are impacted by each, and may also interact with them in various ways. Governance is here widely understood as attempts to control, influence, or structure rules, norms, and actions through policy measures, regulatory efforts, and rule-making behavior across public, private, and non-governmental institutions–involving both centralized, decentralized, and mixed approaches (Tables 5 and 6).

Table 2 SciTech risk dyads-examples

Dyad	Example	Year reported
T^2	Experts both applaud and fear the consequences of AI in interaction with synthetic biology as they converge [88]	2020
TechEcon	The technological risks of the digital economy [23], including technology-driven systemic risks affecting the financial sector [46], such as cybersecurity threats	2018
TechGov	Technological risk and policy preferences lead some workers to prefer slowing down technological change to avoid or defer automation risk [48]	2022
TechSoc	(a) Problematic risk-taking behaviors involving emerging technologies (e.g., online gambling and gaming, online sexual behaviors, and oversharing of personal information via social networking sites), [117]. (b) AI letter of 2023 noting severe risks to society from AI and calling for a pause [78]	2020
TechNat	Energy technology's emission challenges began with the Industrial Revolution [5]	2001
TechHealth	(a) Concerns that AI could spark the next pandemic [98]. (b) Medical technologies (imaging, blood tests) shape the experience of illness, reveal risk factors for developing diseases, and alter social norms for vulnerability, change perceived symptoms, or what counts as being healthy or ill [57]	2018

Table 3 Economic risk dyads–core concepts

Dyad	Definition
EconTech	Risks associated with the combined effects of the economy and science and technology-related factors, phenomena, or platforms
E^2	Risks associated with the combined effects of two or more actors or factors within the financial system or affecting the economy
EconGov	Risks associated with the combined effects of the economy and governance, notably how the economy impacts governance
EconSoc	Risks associated with the combined effects of the economy and social dynamics, notably how the economy impacts social dynamics
EconNat	Risks associated with the combined effects of the economy and ecological impact, notably how the economy impacts ecology
EconHealth	Risks associated with the combined effects of the economy and health adversity, notably how the economy impacts health adversity

Table 4 Economic risk dyads-examples

Dyad	Example	Year reported
EconTech	(a) Economic recessions/depressions can impact big tech or tech startups negatively (in the short term) but spur innovation in the medium term for resilient companies [116]. (b) Compare with TechEcon (see Table 1)	2018
E^2	Systemic risks from financial system linkages lead to the co-occurrence of two negative economic phenomena (such as recessions, inflation, undercapitalization, exchange rate fluctuations, and collapse of too-big-to-fail institutions), leading to cascading failure of the financial sector [4, 81]	2018
EconGov	Economic risks lead to government collapse or worse, failed states [103, 128]	2003
EconSoc	The Great Depression led to mass unemployment [50]	2009
EconNat	Economic growth from industrialization has led to climate change [89]	2012
EconHealth	The Great Depression led to increased mortality and lower life spans [50], as well as cognitive disparities [52]	2009

Broadly, the governmental dyadic risk effects were reported earlier than other areas, perhaps because risk is a relatively obvious concern when it comes to the government's core responsibilities.

Social dynamics risk dyads

Risks derived from social dynamics, broadly understood as group behavior, relationships, and interactions, impact risks arising from other disruptive factors such as sci-tech, governance, economics, ecological impact, and health adversity, are impacted by each, and may also interact with them in various ways (Tables 7 and 8).

Table 5 Governance risk dyads-core concepts

Dyad	Definition and example
GovTech	Risks associated with the combined effects of governance and science and technology-related factors, phenomena, or platforms
GovEcon	Risks associated with the combined effects of governance and the economy
G^2	Risks associated with the combined effects of two governance factors within or across governance entities
GovSoc	Risks associated with the combined effects of governance and social dynamics
GovNat	Risks associated with the combined effects of governance and the natural environment
GovHealth	Risks associated with the combined effects of governance and health adversity

Table 6 Governance risk dyads-examples

Dyad	Example	Year reported
GovTech	Government R&D [34] or regulation impacts tech innovation, sector development, could harm national security [72], poor, little, or too much regulation in the wrong places could increase risks from emerging tech [127]	2023
GovEcon	Government shapes the economy by creating, maintaining, and regulating markets [44] but politics, laws, tariffs, debs, or policies, bailouts/firm rescues (or absence thereof) can also create dangerous unintended consequences, such as moral hazard, overheating the economy and inflation, firm collapse, too-big-to-fail institutions, and more [118]	2002
G^2	Dyadic intra- or inter-government relationships, either rivalries, or partnerships can create excessive risk-taking, competition, and eventual resource collapse and failed states [103]	
GovSoc	a) Government crisis or lack of foresight spills over into society, yet long-term risk governance is rare [111] even though existential risk is a whole-of-society challenge [8]	2019
GovNat	Government's impact on the natural environment is enormous, yet/and so two-thirds of Americans think the government should do more on climate [120]	2020
GovHealth	The increase in government efficiency can significantly improve health outcomes [33]. In the US, the government has a relatively small role in the direct delivery or financing of health insurance and health services. Global health risks are significant, including biorisk, and can be affected by regulation [10, 18, 105]	2014

Table 7 Social dynamics risk dyads-core concepts

Dyad	Example
SocTech	Risks associated with the combined effects of social dynamics and science and technology-related factors, phenomena, or platforms
SocEcon	Risks associated with the combined effects of social dynamics and the economy
SocGov	Risks associated with the combined effects of social dynamics and governance
S^2	Risks associated with the combined effects of two social dynamics factors
SocNat	Risks associated with the combined effects of social dynamics and the natural environment
SocHealth	Risks associated with the combined effects of social dynamics and health adversity

Social dynamics surrounding technology have been analyzed almost since the beginning of industrialization, beginning with the founding fathers of the discipline of sociology. More recently, the field of science and technology studies (STS) has taken up the challenge [107], and in the last decade, a growing body of findings from complex science and systems perspectives has started to shape the field [75].

Ecological risk dyads

Natural hazards impact risks arising from other disruptive factors such as sci-tech, governance, economics, social dynamics, and health adversity, are impacted by each, and may also interact with them in various ways. Natural hazards are events (geological hazards, hydrological meteorological hazards, or biological), such as avalanches, blizzards, cold waves, droughts, earthquakes, fires, floods, heat waves, hurricanes, landslides, storms, tornadoes, tsunamis, volcanoes, or wildfires, with a likely negative impact, potentially killing thousands of people and destroying billions of dollars of habitat each year.

Ecological risks are wider than natural hazard risks because they include risks potentially with no immediate event associated with it (air contaminants, biodiversity collapse, harmful chemicals, infectious diseases, pandemics, pesticides, plant and animal invasions, toxic waste, water-borne diseases) but rather may stretch out in time with a more insidious impact (Tables 9 and 10).

It took a significant amount of time for NaTech risks, risks associated with the combined effects of natural hazards and releases from industrial facilities, to be identified and properly discussed [106]. It is now important to broaden the scope of analysis to wider science and technology-related factors, phenomena, or platforms, whilst keeping a focus on the negative impact of industrialization and industrial infrastructure on nature.

Health adversity risk dyads

Health adversity risks impact risks arising from other disruptive factors such as sci-tech, governance, economics, social dynamics, and ecological impact, are impacted by each, and may also interact with them in various ways (Tables 11 and 12).

The risks of health adversity have long been a subject of study in the field of public health. With the increased potential for innovation using emerging technology also comes greater risks, which have so far received far less attention. This is strange, given that health consequences are the ultimate impact that matters most to humanity. It also matters a

Table 8 Social dynamics risk dyads-examples

Dyad	Example	Year reported
SocTech	(a) To critically examine how its current configuration is developed, negotiated, or sustained, public responses to technological risks, including by emerging social movements, and also how risk is framed by institutional actors, need to be systematically studied by sociology, and not just studied as a policy concern [45]. Example: nuclear power. (b) Social dynamics around AI include a multitude of factors such as ethics, psychological effects, work and employment, human intelligence, transparency, and bias, for example, ChatGPT [100]. (c) Science and technology studies (STS) wider concerns. Example: energy field [56]	1992
SocEcon	Large-scale societal dynamics (such as the flow of the stock market) are reflected in human mood and brain, with some sub-populations particularly vulnerable to economic turbulence, such as individuals with low and very high income [67]**,** supporting the socioeconomic hypothesis of "social mood" as a driving factor in global societal processes, with economic indicators affecting population well being. (a) social influence (by neighbors upon investors) on asset prices [61], shows market dynamics are more nuanced and cannot be assumed to be simply "efficient". (b) the instability of financial markets may be attributed to insufficient social control mechanisms including social order based on shared social norms (Helbing 2012) [54]	2012
SocGov	Social impact bonds have emerged as a way to structure social programs as investment vehicles and (at times) better control their risk, with risk being at the core of contemporary forms of (networked) governance [51], (b) human behavior is driven by risk perception, not facts or what is understood as facts by risk analysts and experts [101]	2021
S^2	(a) The consequences of risk events (for example: seismic risk-earthquakes) ripple across jurisdictions, communities, and organizations in complex societies, triggering unexpected alliances but also exposing social, economic, and legal gaps [26]. (b) 'rebound dynamics' between social risk (risk to people) and business risk (risk to business), if not emphasizing directionality [63]. Example: mining industry. (c) Public trust is a significant factor for effective risk governance and public perception can amplify or attenuate risk and change organizational behavior [106]	2016
SocNat	Social risks to biodiversity arose from human intervention and incursion into animal and plant habitats in the Anthropocene era and such vulnerability not only be analyzed top-down (impact) but also bottom-up, to capture the entire risk chain, including possible adaptations and mitigation [97]	2021
SocHealth	Social determinants of health [17]	2014

Table 9 Ecological risk dyads-core concepts

Dyad	Definitions
NaTech	Risks associated with the combined effects of natural hazards and science and technology-related factors, phenomena, or platforms, initially focused on releases from industrial facilities [30, 106], a phenomenon perhaps better named NaIndustry
NaEcon	Risks associated with the combined effects of natural hazards and the economy
NaGov	Risks associated with the combined effects of natural hazards and governance
NaSoc	Risks associated with the combined effects of natural hazards and social dynamics
E^2	Risks associated with the combined effects of two natural hazards
NaHealth	Risks associated with the combined effects of natural hazards and health

lot to distinct and often disadvantaged social groups. Lastly, health adversity, as well as its corollary, perceived wellness, is a powerful individual concern and a motivating force.

Discussion

The alignment of dyads

A basic clustering of the papers used to exemplify dyads reveals 14 clusters with cross-cutting issues such as finance, environment, governance, health, social impact, and technology, closely matching our input framework's six dimensions (see Fig. 4). Whilst not particularly surprising, this also validates the use of that framework. Despite the complexity of dyads, they align along commonly considered dimensions. What's lacking is putting these insights together to understand how they can cause cascading interactions or possibly can be mitigated before they do.

Table 10 Ecological risk dyads-examples

Dyad	Example	Year reported
NaTech	There are a number of risks associated with the combined effects of natural hazards and releases from industrial facilities, especially in densely populated areas [30, 106]. Example: release of hazardous materials after an earthquake	2008
NaEcon	Direct economic risks of nature loss to a company (agricultural companies impacted by decreased pollination services or soil nutrition or pollution), or as a result of inability to source essential raw materials, lack of access to water needed for factory production, business disruption (by floods or stormwater), or indirect effects (the risk to any entity of zoonotic disease emergence driven by land-use change or wildlife trade) [40, 85]. The initial concern of this kind was climate change	2023
NaGov	(a) Exposure to environmental, social, and governance risks (ESG risks) adversely affects firm value but can be mitigated by a governance measure such as a sustainability committee [35]. (b) SDG goals have had limited political impact [15]. (c) The economic consequences of complex climate change risks cannot yet be quantified which impacts the ability of governance intervention [102]	2022
NaSoc	Natural disasters are, at times, followed by social conflicts, and almost always increase social risk, deepen overall social conflict, and destroy local people's lives, with particularly negative effects for children and older people [129] but the negative effect depends on social capital, trust in neighbors and communities in small-scale disaster, and depends on "networks" in the case of large-scale disasters [68]. (b) in special instances, natural disasters reduce social crises by "keeping people together" [31]	1999
E^2	The extent of multi-hazard risk (the risk of a series of hazards occurring in the same region) depends on the degree of overlap in time and space, and may or may not be independent or may be interacting phenomena [32]. Example: Earthquake that weakens a levee system which collapses and leads to a flood	2022
NaHealth	(a) Natural disasters can threaten health and well-being, often leading to losses in resources, such as economic and property loss, injury, and death, yet some people show greater resilience to post-disaster distress and depression than others and healthcare capacity can also mitigate adverse effects [110]. (b) The potential risks of multiple disaster exposure affecting mental health, physical health, and well-being, may exceed those of single disaster exposure [71]. Cumulative environmental health risks from multiple chemical exposures, particularly children's exposure to neurodevelopmental toxicants, mean the analysis cannot be contained in a single risk assessment [93]	2021

Table 11 Health adversity risk dyads: core concepts

Dyad	Definition
HealthTech	Risks associated with the combined effects of health adversity and science and technology-related factors, phenomena, or platforms
HealthEcon	Risks associated with the combined effects of health adversity and the economy
HealthGov	Risks associated with the combined effects of health adversity and governance
HealthSoc	Risks associated with the combined effects of health adversity and social dynamics
HealthNat	Risks associated with the combined effects of health adversity and natural hazards
H^2	Risks associated with the combined effects of two health adversity factors

The complexity of dyads

The paper sought to illustrate how dyadic risk is more than sufficiently complex to gain an overall understanding of the constituent factors of potential cascades. Looking across dyads, the phenomena described are intricate yet addressable within their field of study. To what extent does the analysis of these 36 combinations inform a more structured analysis and mitigation of risk? It turns out that it is difficult in most of these 36 dyads to separate out the causal relationships from the analysis of the dyad. In other

Table 12 Health adversity risk dyads: examples

Dyad	Example	Year reported
HealthTech	Already unhealthy, unskilled, or socio-economically or otherwise disadvantaged groups don't have the same access to technology (a) potentially caused by access to digital health tech or health information mediated by technology in various ways [131]	2022
HealthEcon	Poor health leads to lower socio-economic status if health conditions limit workforce participation which, in turn, results in job loss [70]. (b) Poor health generates costs for employers, and according to the CDC, 90% of the nation's $4.1 trillion annual healthcare costs are for patients with chronic diseases [21]	2017
HealthGov	Poor health contributes to reduced income, creating a negative feedback loop ('the health-poverty trap') which affects voting behavior and turnout, and democratic engagement [19, 130]	2019
HealthSoc	The quality and quantity of individuals' social relationships have been linked not only to mental health but also to both morbidity and mortality comparable in effect to well-established mortality risk factors [58]	2010
HealthNat	Unhealthy human behavior both at the individual level (household pollution, burning fossil fuels, consuming cellulose), organizational (industrial waste, oil, and chemical spills), city (sewage, wastewater treatment plants), and societal level (overpopulation) negatively impacts the natural environment, triggering climate change, soil erosion, poor air quality, undrinkable water, and other negative effects on habitats, plants and wildlife, including disrupting reproduction, immune systems, or causing disease [1]	2009
H^2	Cumulative early exposure to health adversity (for example psychosocial adversity) within the family is a strong risk factor for later childhood health problems that often co-occur, including ADHD and autism, which means family-based or other genetically informative designs may help explain etiology [62]	2023

Fig. 4 Keyword clusters

words, are we looking at one factor's impact on the other or is there a systemic interaction within the dyad that is responsible for the impact? This is relevant for assigning causality (and risk responsibility) but also for understanding the nature of emerging risks.

Logically, if A and B represent each of the dyadic factors in a pair, the basic causal options are:

A—>B (A directly causes B effects) or B—>A (B directly causes A effects). However, we must also account for co-causality, meaning that A and B—>A (A and B jointly cause A effects) or A and B—>B (A and B jointly cause B effects), or A and B—>Both A effects and B effects. In reality, of course, both A and B are embedded in far more complex causality chains where there are intervening variables (A—>C—>B) or even spurious effects with an unknown factor causing A B or both A and B (C—>A and/or B) or even pure coincidence because so many factors could have caused a change in either A or B, for which there are now formal coincidence analysis methods [11]. Systemic risks in complex coupled systems are not obvious because causality is obfuscated by a multitude of intermediary factors (C, D [...] to Z—>A and/or B) whose relationships (how C relates to D, etc.) may lack predictability [106].

Although we have not assessed the causality implications of all the examples provided in our sample of 36 dyads, it would probably be fair to say that correlation is more prevalent than causality. I should be quick to point out that some of the problems noted with dyadic analysis are not necessarily a problem with the original studies cited because they were discussed and appropriately handled by those researchers. Dyadic causality only becomes a larger issue when we attempt to use those same studies for a multi-dimensional cascading risk analysis.

If we even just consider one of the two factors in a given dyad (A and B), each of the 36 pairs had quite complex relationships even within each factor, with potential relationships between thousands of variables. If we consider EconSoc or TechSoc, the relationships between the economy and society, for example, are manifold and are the main preoccupation of the entire field of economic sociology. Both the economy of risk and social dynamics of risk are complex fields subject to varied scientific analysis (from across the social sciences and beyond), as we saw when looking at E^2 and S^2.

Looking across a few dyads, it is not clear that we can analytically separate economic from governance effects. Indeed, the field of political economy, which involves the study of how economic theories such as capitalism or communism play out in the real world was a reaction to this. Adam Smith, Thomas Malthus, David Ricardo, and later, Keynes and others, criticized mercantilism's limited understanding of economic nationalism, the idea of a zero-sum game of trade where some benefit at the expense of others. To understand the economy, they argued, we need to understand politics and the economy as one system [7].

We should be careful in interpreting surface-level observations about dyadic risk relationships, and making inferences about wider cascades, both for methodological and practical reasons. Each example given above needs to be examined closely to figure out what the timelines were and how each dyad is likely to be affected by the passage of time. However, for historical examples, we can already do so. A recent study of the history of risk-tracking semantic patterns over a period of 150 years found that the risk discourse reflects changes in terms of the type of threats (away from wars and toward chronic disease) as well as changes in the potential to forecast, prevent, or mitigate them [74]. How much of these effects only represent increased confidence within the growing risk literature as opposed to real ability to predict future risk, is another question.

Dyads as building blocks for causal analysis

Broadly, then what have we learned about dyadic relationships of risk? We can certainly now in an easier manner, using the shorthand provided, cursorily describe a huge amount of risk data and some macro effects that govern their relationship. This could be useful for policymakers, in risk assessment, or in communicating broad areas of risk to the wider public. We have also provided a basic building block for more complex factor analysis that might lead to more advanced cascading effects models (of pentads, hexads, heptads, octads, and onwards).

Having said that, the number of factors escalates with each level of interaction (6 to the power of 2 is 36, but 6 to the power of 3 is 216). Thoroughly describing the 216 triadic risk relationships in the manner we have done here for 36 dyads, for example, would likely be out of scope for a scientific paper. Imagine that we had to consider 1000 variables within each factor (A1-A1000) and how they interrelate even before the dyadic and triadic analysis. It is highly possible that the future of cascading risk analysis lies in AI-assisted factor analysis to complement advanced statistical techniques such as multivariable logistic regression. So far, this type of approach has been usefully applied to cybersecurity, where the ability to *quickly* detect, analyze, and respond to threats is paramount [22]. However, we would rapidly reach the limit for human interpretability of the results, a problem all too common with AI-powered analysis. Also, we would likely need quantum computers to analyze the results.

Economists have, of course, with the crude powers of statistically empowered economic analysis, and notions of limitless growth, had the hegemony within most governmental administrations for the latter part of the century [104]. Adding a second factor to the mix, tech, the techno-economic paradigm has dominated the last few decades [94]. Modernists would make a similar argument for focusing on sci-tech innovation and impact [132]. Is that role now challenged as powerful methods and approaches are also increasingly available in other domains? The impact and explanatory powers of other domains of inquiry (across the social sciences) are becoming clearer. Given the broad scope of impacts upon lifestyle, quality of life, longevity, suffering, inequality, life and death, and more, we might make a similar argument for health innovation [43] or health adversity effects [92]. However, the fact that disciplines do already meaningfully engage with risks that, when interacting, constitute cascading risks is comforting. Stepping up that effort might be possible from within scholarly fields and may not require as much of a step change in existential risk studies as that discipline assumes [90]. On the other hand, grasping existential risks requires a deeper engagement with existing scholarly findings in the six fields tracked here than is currently the common practice in the x-risk literature.

Dyadic governance

Given the importance of gaining confidence in society's ability to manage risk, getting a better grasp of the six core governance effects (GovTech, GovEcon, G^2, GovSoc, GovNat, and GovHealth) is certainly crucial. GovNat effects, arguably one of the great contradictions of our time, maybe self-inflicted but are hard to counteract given that they are steeped in power structures and long-term cycles. At this point, industrialization's effect on global warming has been analyzed to death, and the effects are well known [64], but the mitigations are ineffective, expensive, and politically difficult to implement given that they would deteriorate industrial conditions affecting the world's largest companies even beyond industrial actors. Moreover, they would reshape the destinies of powerful nation-states and economic actors such as the US, the EU, China, and India. Negotiating solutions will certainly occupy the world's elite for decades, potentially centuries to come. However, would an even more useful path for researchers be to start mapping out more recently emerging GovNat effects so that we could potentially forecast, prevent, or mitigate some of those? Governmental influence upon biodiversity would seem to be the next frontier and the amount of work ongoing is far inferior to the effort currently going into climate change engagement. Mapping these dyads indicates that governance-related dyads are crucial because they have the potential to shape all other dyads. This is not to say the task is easy–there is still complexity inherent in learning the right lessons and establishing and maintaining governance across this wide scope of topics and fields.

Scholarly engagement complementing interdisciplinary outlooks

It is currently common to argue in favor of the urgent need for inter- or transdisciplinarity and systemic perspectives on risk [75]. This paper is not an argument against that but provides a supplementary motivation: disciplinary engagement with risk could also be pivotal. The good thing is that the present study found ample examples of engaging with dyadic risk across disaster research, innovation studies, public health, risk science, social sciences, and sustainability studies. Mapping the impact against the likelihood of individual risks is a true and tested approach in engineering-driven risk management of large-scale industrial endeavors. Establishing true values for these risks is no trivial task. Even delineating which factors need to be included in the matrix is tough to do, even if I have simplified that process by assessing 36 dyadic risk pairs. However, there can be no path to mitigation without having at least a cursory understanding of which factors might matter, which might impact each other, and how large the combined effects might be. Part of this work entails scholarly risk studies within the highlighted disciplines. Part of it consists of existential risk studies engaging more deeply with the findings of those disciplines. Very little cross-referencing between these literatures was found in our sample to indicate that this is the case.

Conclusion

In this paper, through a systematic literature review, I analyzed 36 dyadic risk mechanisms that emerged from a juxtaposition of pairs of two ('dyadic features' of risk) derived from six previously identified disruptive forces: sci-tech, governance, economics, social dynamics, ecological impact, and health adversity [123, 124]. Future research is needed to determine whether additional forces, institutions, sectors, or spheres, such as culture, media, industry, education, the nonprofit sector, religion, space, or others also deserve their own shorthand acronym and inclusion in a comprehensive dyadic risk mechanism review.

Even though there is a large body of research that has touched on the themes covered, no previous studies have covered all of them systematically. Present findings show how complex risk relationships can be, even at their most embryonic stages. In the real world, risk rarely shows up as a phenomenon only impacted by two main factors. As a caveat, most of the dyads illustrated here are so complex that they definitely qualify as systems themselves. Even if a larger systems perspective might be the ideal tool in the risk analysis toolkit it would seem that a lot of the preliminary work of analyzing simpler phenomena and how they interconnect has to be carried out simultaneously, or even before attempting such a feat. Our current understanding of systemic risks is so limited, and the need to go deeper so pressing, that delving into such dyads seems a necessary step towards tackling cascading risks more generally and expansively, and certainly before attempting to thoroughly describe existential risks that would entail a plethora of interacting factors. There can be power in simplicity, too.

Another benefit of the dyadic approach is that it complements the systems theoretical approaches taken by the disaster research community as well as the existential risk community with the notion that existing scientific knowledge and scholarship increasingly need to take on board risk mechanisms instead of attempting to simply separate them into distinct fields of disaster risk and existential risk. If this could happen, the available scientific talent to address concerning risk challenges would multiply. Both the disaster research lens, the futures research lens, and the existential risk lens are missing elements that may be fundamentally important for the scientific validity and political legitimacy of necessary foresight, innovation, resilience, and mitigation efforts surrounding the totality of such risks. However, risk engagement cannot simply be a side deliverable, it has to be embedded from the start.

The research question in this paper was whether each of the 36 dyadic risk mechanisms is equally relevant or prevalent. Naming them and developing a concept sentence for each is the first research contribution made in the present article. I determined that six of the most dire cascading risk mechanisms were T^2, NaEcon, GovNat, G^2, NaHealth, and TechGov effects, and each deserves considerable scrutiny in the time to come.

Moreover, the argument could be made that the six governance-related mechanisms are of primary importance at least from the perspective of risk mitigation. Among those, the GovNat effects such as governmental (non-) regulation of climate change, are the most impactful at present. However, those effects are directly related to the TechGov and GovTech effects because government R&D often finances platform technology [34] and definitely has the potential and responsibility to regulate impactful platforms once formed.

Given the progress and increased interaction of emerging technologies and platforms, there is also the argument that T^2, T^3, and T^4 effects should receive more attention in the years to come. That will require expertise across those technologies and platforms and talent with those skills and also willing to dedicate themselves to assessing risk as opposed to, or in addition to innovation will be in short supply.

Future research should definitely focus on creating a more exhaustive list of research and case studies underpinning each of the 36 dyads sketched in the present paper, including establishing the year when each dyad was first reported. Moreover, future research should also attempt to further simplify this framework, or if found useful, expand the number of core factors, and should aim to discover whether and in what contexts a few of the core mechanisms determine the bulk of the risk. This could be a subject of historical significance. But in a rapidly changing world, we also need to beware of making too many assumptions based on the past. Dyadic risk mechanisms seem to have been important factors in shaping our past. Armed with that insight, we can perhaps soon make a more informed decision about whether they should also determine our future.

Supplementary Information

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Supplementary Material 1.

Author's contributions

Trond Arne Undheim: conceptualization, methodology, data curation, writing—original draft, visualization, investigation, writing—review and editing. The author read and approved the final manuscript.

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