Ambio 2023, 52:683–701
https://doi.org/10.1007/s13280-022-01800-5

Sustainable Development Goals and risks: The Yin and the Yang of the paths towards sustainability

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Received: 10 April 2022 / Revised: 30 September 2022 / Accepted: 3 October 2022 / Published online: 11 November 2022

Abstract The United Nations 2030 Agenda and Sustainable Development Goals (SDGs) define a path towards a sustainable future, but given that uncertainty characterises the outcomes of any SDG-related actions, risks in the implementation of the Agenda need to be addressed. At the same time, most risk assessments are narrowed to sectoral approaches and do not refer to SDGs. Here, on the basis of a literature review and workshops, it is analysed how SDGs and risks relate to each other's in different communities. Then, it is formally demonstrated that, as soon as the mathematical definition of risks is broadened to embrace a more systemic perspective, acting to maintain socio-environmental systems within their sustainability domain can be done by risk minimisation. This makes Sustainable Development Goals and risks "the Yin and the Yang of the paths towards sustainability". Eventually, the usefulness of the SDG-risk nexus for both sustainability and risk management is emphasized.

Keywords 2030 Agenda · Environmental risks · Planet boundaries · Risk quantification · Sustainability science · Systemic approach

INTRODUCTION

The anthropization dynamics that affect the Earth generates challenges of unprecedented difficulty for humanity. In particular, the "great acceleration" since the middle of the twentieth century (Steffen et al. 2015) leads to a rapid depletion of resources and biodiversity (Ceballos et al. 2017) and questions the habitability of our planet in the short term (Steffen et al. 2018). These trends were pointed out already by the report for the Club of Rome (Meadows et al. 1972) but for a long time remained overlooked. Now, several planetary boundaries are exceeded (Rockström et al. 2009a, b; Persson 2022), and the need for immediate actions is largely accepted. This has led to the adoption of multiple international action frameworks including the United Nations Paris Agreement on Climate (United Nations 2015), the New Urban Agenda of the European Union (European Union Council 2017), the European Green Deal (European Commission 2019), and the United Nations' action for Disaster Risk Reduction, known as "Sendai framework" (United Nations Office for Disaster Risk Reduction 2015). Whereas the different initiatives were initially more or less disjoined, it has been progressively acknowledged that the interconnected nature of environmental and societal issues makes a broader perspective mandatory (Rusch et al. 2022). This need for systemic, inter-sectorial and interdisciplinary approaches (UNDRR 2019a; IPBES 2019) led to the adoption in 2015 by all 193 member states of the UN of the 2030 Agenda for Sustainable Development (United Nations General Assembly 2015). It consists of 17 Sustainable Development Goals (SDGs), specified by 169 individual targets designed as a global, comprehensive framework potentially capable of guiding the world through complexity on a virtuous path. The underlying assumption is that the fulfilment of all the SDGs will maintain the earth within 'planetary boundaries' (Rockström et al. 2009a) or, in other words, result in a Safe Operating State (SOS), for the Earth System, so that the path towards the SDGs opened by 2030 Agenda should delimit a set of sustainable trajectories. However, the earth system is currently very far to follow this track, with, e.g., goals on natural resources very far

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13280-022-01800-5.

from being met according to the last progress report (Sustainable Development Solutions Network and Institute for European Environmental Policy 2021). Hence, the 2030 Agenda faces double dilemma of risks (United Nations 2021): (i) within the Agenda, risks are "everywhere and nowhere", masked by the positive discourses about solutions, resilience, and prospects related to attainment of SDG goals, and (ii) at the same time, a proper risk assessment and management strategy is lacking, which may preclude attaining some of the targets and, hence, the overall sustainability objective (Section "Background"). This lack of risk awareness and management in SDG definition and implementation is all the more surprising that (i) the risk concept is now at the core of most current environmental impact assessment and policies at the international level (e.g. IPCC 2014; UNDRR 2019a), and (ii) various inquiries support the rising importance of environmental risks in the perception of different actors (Future Earth 2020; World Economic Forum 2020).

Risk is a central concept used for long by many research and expert communities when it is necessary to anticipate, evaluate and mitigate potential damages and, more widely, to act under uncertainty (Renn et al. 2008a, b). Risk science has developed for a long time in economy and social science so as to understand how risks are perceived, understood or even built by actors, and how this affects exposure to risk and risk management (e.g. Gilbert 2003; Beck et al. 2012). Crucial developments notably include relations between the risk and uncertainty concepts, and how decision-making is affected (LeRoy and Singell 1987; O'Donnell 2021). In parallel, mathematics has proposed a formal conceptualisation of risk using the framework and tools of probabilities and statistics to quantify variability and uncertainty sources and build decision theory (Von Neumann and Morgenstern 1953), where optimization is defined with paradigms such as maximisation of expected utility (e.g. Berger 1985). Eventually, risk science has experienced important developments over the last years to describe and assess risks in complex systems, with definition of more or less specific and/or new concepts such as cascading events (Zuccaro et al. 2018), domino effects (Cozzani et al. 2005), multi-risks (Curt 2020), compound effects (Zscheischler et al. 2018) or systemic risks (Renn et al. 2020). These different approaches, with various levels of mathematical formalizations, have in common their focus on dependencies resulting from complex chains of causalities (Pescaroli and Alexander 2018).

Hence, risk is an excessively broad, ambiguous or even polysemous concept (Aven 2016), and therefore not identically understood among disciplines and fields (e.g. Renn et al. 2008a, b), which is reflected by a diversity of research conducted in many fields and disciplines, from basic developments to various applications. However, a common point between the existing corpuses is that the relationship to SDGs—if any—is generally limited to the context description that "sets the scene". This reflects a focus on disciplinary risk research and the lack of a holistic perspective on sustainable development. Besides, even in fields used to work for long with risks related to the environment, there exist important differences among knowledge systems between scientific and technical communities as well as between nations and regions. They relate to different levels of risk acceptance and/or individual or collective behaviour towards different risks (for instance, with the kind of system, damage source, spatio-temporal scale, and socio-economic context) and different positions within the cycle of risk management (e.g. assessment and anticipation, crisis, and recovery). Eventually, within the specific context of the SDGs, an ambiguity exists between risks related to damageable processes and their impacts such as natural disasters or chemical pollutants, and broader risks directly related to the implementation of the 2030 Agenda, such as that of poorly formulated SDG targets and success indicators.

On this basis, there is a lack of a system-wide/holistic approach to (i) account for risks as part of the implementation of the SDGs, and (ii) reinforce conceptual and formal bridges between the communities interested in risk theory/management and sustainability issues. Notably, an explicit link between sustainability expressed in a systemic framework and risk assessment/mitigation is currently lacking. As an answer, in what follows, we first analyse from a large review[1] of scientific and institutional literature and inputs from workshops how SDGs and risks relate to each other's in the work carried out by different communities working on different sustainability issues and different types of environmental risks, from their assessment to their policy implications. We then clarify and formalise how SDGs and risks relate to each other using a formal framework that links system dynamics and risks related to SDGs within planet boundaries. Specifically, we formally demonstrate that acting to maintain a system within its sustainability domain can be done by risk minimisation, which make Sustainable Development Goals and risks "the Yin and the Yang of the paths towards sustainability". Yet, we further show that this is true only if (mathematical) risk definitions wider than those generally used by the risk community are retained. We eventually discuss that acknowledging this duality is extremely useful as (i) it allows, using the whole toolbox of risk assessment and mitigation for sustainability issues, and (ii) the SDG perspective may help this risk community to switch from analyses often too specific to more holistic approaches

[1] Due to the extremely wide scope of environmental risks and SDGs, this review is by essence non-exhaustive.

acknowledging the complexity of current environmental challenges.

METHODS

Background

2030 Agenda and the SDGs

The 17 SDGs and their targets capture many different dimensions of human wellbeing, and recognize the dependence of social and economic development on the sustainable management of our planet's natural systems. Their ambition is to be a universal framework applicable whatever the considered system and scale. It has the holistic perspective to account for potential linkages and trade-offs between, e.g., development, resources and conservation issues. Also, the 2030 Agenda includes indicators to evaluate progress towards SDGs and targets which feed annual progress reports (e.g. United Nations 2020) at different governance levels and motivate further development of data collection and processing. The 2030 Agenda is expected to be implemented in every country and at a global scale with transnational commitments, as a new framework to overcome national disparities around sustainable development. The SDGs are therefore the international standard towards which all environmental policies are invited to be articulated. It is for instance at the heart of European policies, because of the recognition of its mandatory nature for collective survival, and of its potential as a source of development and innovation.

Risk assessment and management in the SDGs

Most of the SDGs and targets are about reducing or controlling risks caused by unsustainable development and overexploitation of resources. Also, implementation of the SDGs involves all key areas of risk governance including risk prevention, risk–benefit balancing, risk communication, uncertainty management and compensation for risks. The 2030 Agenda aims therefore at overcoming risks due to natural hazards, health, and social, technological and financial risks.[2] However, the mention of "risk" per se stays very limited in the SDGs and their targets. Indeed, although these recognize ecological risks and resilience, and include notions of sudden risks and accidents, e.g. with reference to disasters or to gradually accumulating persistent risks (Fig. 1), there is no specific SDG addressing risk assessment. Besides, when risk appears explicitly, as in SDG 13 (climate action), it does not refer to a coherent concept of risk provided by the corresponding field of knowledge (IPCC 2014).

From a different perspective, it is a paradox that the SDGs—as the outcome of political negotiations—rest on an assumption that all the goals can be reached, even though biophysical, economic and social trade-offs and side effects in implementing the goals may hamper their overall achievement. For example, (i) an uncareful expansion of the renewable energy production systems risks to counter the goal to protect and restore ecosystems, (ii) increased food production to fulfil the zero hunger SDG may lead to biodiversity loss, water shortages and potential chemical risks with the use of pesticides in agriculture if the zero hunger goal is understood in isolation. Hence, just maximizing individual goals will likely preclude reaching other goals. Similarly, assuming linear future trajectories without considering cascade effects, and thresholds with tipping points further puts the 2030 Agenda at risk. Eventually, indicators to monitor progress towards SDGs may be biassed towards what is easier to measure/monitor. All in all, a comprehensive framework to assess and mitigate the risk of failure to achieve the goals, including those caused by neglecting the interlinkages among goals and other adverse effects such as political rebalancing (e.g. full priority on economic recovery after the Covid crisis at the 2021 High Level Political Forum) is critically lacking within the 2030 Agenda. Notably, even if more or less sector-specific typologies, atlases and glossaries of risks exist (e.g. Aven et al. 2018; UNDRR, 2020), none of them was so far designed to encompass all the risks relevant for the SDG context. To fill this gap and support our analysis, Appendix S1 provides a categorization of these risks that includes both risks which are formulated in the SDGs (Fig. 1), and risks which are hidden within the formulation and implementation of the 2030 Agenda.

Literature review and inputs from workshops

Grounding on the expertise of the PEER[3] network, we conducted a review of scientific, technical and institutional literature related to risk and sustainability issues. It was supplemented by inputs obtained from two workshops (Lyytimäki et al. 2022) that had participants from the policymaking sector, as well as from the finance, insurance and natural resource management sectors. We focussed on the conceptualisation, acceptance and operationalisation of

[2] Especially Global Catastrophic Risks (GCRs), i.e. high impact/low probability events that can trigger the collapse of humanity. GCRs are often defined by a loss of $>10\%$ of the population (Avin et al. 2018).

[3] PEER is a network of European environmental research institutes. Research particularly addresses interactions between man and nature with a cross-sectorial and cross-disciplinary perspective, with strong interactions with stakeholders.

Target 1.5: "By 2030, build the **resilience** of the poor and those in **vulnerable** situations and reduce their **exposure** and **vulnerability** to **climate-related extreme events** and other **economic**, **social** and **environmental** shocks and **disasters**".

Target 2.4: "By 2030, ensure sustainable food production systems and implement **resilient** agricultural practices that increase productivity and production, that help **maintain ecosystems**, that strengthen capacity for a**daptation to climate change**, **extreme weather**, drought, **flooding** and other **disasters** and that progressively improve land and soil quality".

Target 3.9: "By 2030, substantially reduce the number of deaths and illnesses from **hazardous chemicals** and **air**, **water** and **soil pollution** and **contamination**".

Target 3.d: "Strengthen the capacity of all countries, in particular developing countries, for **early warning**, **risk reduction** and **management of** national and global **health risks**".

Target 6.3 : "By 2030, improve water quality by **reducing pollution**, **eliminating dumping** and **minimizing release of hazardous chemicals and materials**".

Target 6.6 : "By 2020, **protect** and **restore water-related ecosystems**, including mountains, forests, wetlands, rivers, aquifers and lakes".

Target 8.8: "Protect labour rights and promote **safe** and **secure** environment for all workers, including migrant workers, in particular women migrants, and those in precarious employment".

Target 9.1: "Develop quality, reliable, sustainable and **resilient** infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all".

Target 11.5 : "By 2030, significantly **reduce** the **number of deaths** and the number of people **affected** and substantially **decrease** the direct **economic losses** relative to global gross domestic product **caused by disasters**, including **water-related disasters**, with a focus on protecting the poor and people in vulnerable situations".

Target 11.b : "By 2020, substantially increase the number of cities and human settlements adopting and implementing **integrated policies and plans** towards inclusion, resource efficiency, mitigation and **adaptation to climate change**, **resilience to disasters**, and develop and implement, in line with the **Sendai Framework** for Disaster Risk Reduction 2015–2030, **holistic disaster risk management** at all levels".

Target 12.4: "By 2020, achieve the environmentally sound management of **chemicals** and all **wastes** throughout their life cycle, in accordance with agreed international frameworks, and significantly **reduce their release to air**, **water** and **soil** in order to minimize their **adverse impacts** on **human health** and the **environment**".

Target 12.6: "Encourage companies, especially large and transnational companies, to adopt **sustainable practices** and to integrate sustainability information into their reporting cycle".

Target 12.c: "Rationalize inefficient fossil-fuel subsidies that encourage wasteful consumption by removing market distortions, in accordance with national circumstances, including by restructuring taxation and phasing out those harmful subsidies, where they exist, to reflect their **environmental impacts**, taking fully into account the specific needs and conditions of developing countries and **minimizing the possible adverse impacts** on their development in a manner that protects the poor and the affected communities".

Target 13.1: "Strengthen **resilience** and **adaptive capacity** to climate-related **hazards** and **natural disasters** in all countries".

Target 13.3: "Improve education, awareness-raising and human and institutional capacity on climate change **mitigation**, **adaptation**, **impact reduction** and **early warning**".

Target 14.1: "By 2025, **prevent** and significantly **reduce** marine **pollution** of all kinds, in particular from land-based activities, including marine debris and nutrient pollution".

Target 14.7: "By 2020, sustainably **manage** and **protect** marine and coastal **ecosystems** to avoid significant **adverse impacts**, including by strengthening their **resilience**, and take action for their **restoration** in order to achieve healthy and productive oceans".

Fig. 1 References to risks in SDGs and their targets risks currently existing in research and international guidelines and on their uses in practice for environmental risk mitigation and governance. We also identified how these conceptualisations and methods account for (i) the different SDGs, and (ii) the different risks associated with SDGs (Appendix S1). The resulting material was analysed to sum-up and connect the different existing conceptualizations of risk and sustainability paths (section "Environmental risks and their relations to SDGs"). We then used these inputs to develop and feed our systemic framework that explicitly links risks and system dynamics (Sections "Systemic representation of risks and sustainability paths" and "Formal connexion between risks and sustainability paths"). From this analysis, we inferred how the SDGs can contribute to enforce systemic risk management and how, in reverse, risk management can contribute to enforce a systemic approach that fosters the implementation of the SDGs (sections "Usefulness of a risk perspective for sustainability and the 2030 Agenda" and "Usefulness of SDGs and sustainability for environmental risks assessment and mitigation").

Systemic representation of risks and sustainability paths

System theory is a standard framework to study the behaviour of complex socio-environmental (or socio-ecological) systems (Ostrom 2009), whose sustainability can be conceptualised as staying within desired range conditions or states (Mäler 2008; Walker et al. 2010). Hence, the resilience concept easily connects with system dynamics (Martin 2004), and many applications to natural resources management have used viability theory and optimal control tools extensively (Rougé et al. 2015; Oubraham and Zaccour 2018). However, such approaches remain to be generalised at the scale of the entire earth system with SDGs as desired range conditions, and very few attempts have been made so far to link them with the extensive literature and developments on risk measures, risk assessment and risk mitigation. Here, we provide a synthetic formal framework that allows linking risks and paths towards sustainability in the context of SDGs and planet boundaries. We consider any socio-environmental system S_t taking the form of different 'states' with time t, following the consequences of its natural evolution and various decisions/actions a, and note $p(S_t|a)$ the distribution of the states of the system at time t conditional to actions a, where $p(.|.)$ denotes conditional probability (Figs. 2, 3). Following risk theory, risks for the system can be expressed in a very generic way as statistics—punctual or defined over trajectories—of the distribution $p(f(S_t))$, where $f(.)$ is a function to be chosen depending on the considered problem. We set the system's sustainability boundaries as its safe operating space SOS_t, which can be understood as corresponding to planet boundaries as defined by Rockström et al. (2009b) as soon as the whole earth system including societies and ecosystem is considered. Within the context of 2030 Agenda, these boundaries are assumed to be defined by the 17 SDGs and their 169 targets, and maintaining the sustainability of socio-environmental systems resumes as acting to stay within these boundaries on the basis of surveyed indicators. Hence, the overall ambition of SDGs can be reformulated as granting that $S_t \in SOS_t \, \forall \, t \in [t_o, t_h], S$, namely that all socio-environmental systems including the full earth system stay within their safe operating space all over the journey from an initial time t_o to an horizon t_h, and potentially beyond. Section "Formal connexion between risks and sustainability paths" uses this framework to demonstrate that (i) acting to fulfil SDGs and mitigating risks for socio-environmental systems is formally equivalent, (ii) yet, a mathematical definition of risks broader that the one generally retained is required to account for all risks related to the SDG context. Appendix S2 further details our modelling framework, notations and provides explicit examples of risk measures.

ENVIRONMENTAL RISKS AND THEIR RELATIONS TO SDGS

Within international assessments and guidelines

IPCC and climate action

IPCC assessments (e.g. IPCC 2021) include an explicit formalisation of risks and uncertainty in the form of a degree of confidence regarding changes and/or their attribution to anthropogenic activities. Communication regarding this uncertainty is included in policy recommendations. Over the years, the IPCC has given increasing importance to the risk concept, promoting now an almost universal trefoil figure, where risks result from the intersection of three components: hazard, exposure and vulnerability (Fig. 4A). With regard to the formal framework introduced in section "Systemic representation of risks and sustainability paths", this involves isolating within the system at risk (i) the potential source of losses (most often a meteorological variable or a direct consequence such as a river runoff), (ii) the elements at risk (e.g. people, infrastructures, ecosystems) and, (iii) for each of them, their vulnerability, namely the relation between the hazard magnitude and the damage level. Hence, climate change

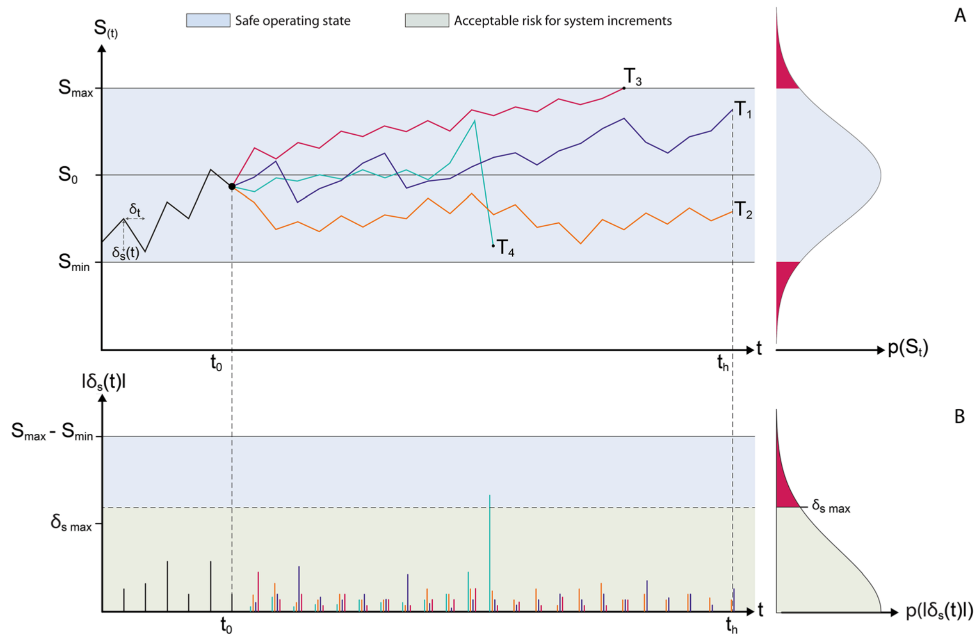

Fig. 2 Duality between risks and sustainability paths for a synthetic socio-environmental system. **A** Four possible trajectories beyond initial time t_o highlighting different possible behaviours: sustainable trajectories more (trajectory T1) or less (trajectory T2) variable with time, and non-sustainable trajectories (T3 and T4) for which the system fails before t = t_h; **B** Corresponding system absolute increments (Appendix S2). A hard definition of the SOS is chosen, meaning that the system fails as soon as its trajectory leaves the SOS (trajectory T3) or as soon as a maximal admissible loss δ_s max defined on the absolute increments is exceeded (trajectory T4). Risk measures (Appendix S2) are defined with $f(.) = I_d(.)$ as percentiles from the distribution of the states of the system (**A**) or of its absolute increments (**B**). Specifically, values at risk are the boundaries of the SOS of the system, $(S_{\min}, S_{\max})$, and the maximal admissible loss δ_s max corresponding to the probabilities $p_{dt} = P(S_t \notin SOS) = P(S_t \notin [S_{\min}, S_{\max}])$ and $P(|\delta_s(t)| > \delta_s \text{ max})$, respectively. SOS, distribution of states and risk measures are constant over time

assessment and climate action may be seen as a model in terms of the articulation between science and policy, and the global scale and ambition of the approach. By contrast, its concrete results in terms of climate change attenuation remain insufficient so far. One possible explanation is the historically too sectoral nature of climate change attenuation approaches which neglected connections and trade-offs with, e.g. development issues.

IPBES and the protection of nature and of the benefits it generates to society

The global IPBES assessment report (IPBES 2019) gives a large place to risk expressed in terms of biodiversity loss (Fig. 4B). This exactly corresponds to our definition of leaving a SOS, either at the global or local scales. IPBES also considers "downstream" risks such as those associated with the loss of ecosystem services, a point that has been further developed by other assessments (Dasgupta 2021). In addition, IPBES strongly advises on the interdependency of all environmental issues, as (i) land-use is the major driver for habitat loss and fragmentation, causing anthropogenically driven biodiversity loss globally (Dirzo et al. 2014), (ii) the piecemeal development of infrastructure severes ecological networks and causes an unprecedented nature decline worldwide, and (iii) climate change acts on top of these land-based dynamics, often exacerbating these downwards trend, and accelerating the path leading to tipping points. The report also highlights the cumulative effects of changes in land-use and infrastructure development, often exacerbated by climatic changes. Eventually, IPBES (2019) states that the SDGs will not be achieved based on current declining trajectories of biodiversity and ecosystem functions.

UNDRR, Sendai framework and disaster risk reduction

The 2015–2030 Framework for Disaster Risk Reduction (DRR), known as "Sendai framework", renewed the United Nations' action in the field of disaster risk management (United Nations Office for Disaster Risk Reduction 2015), with a main focus on risks due to natural hazards and Natech[4] risks. The four main objectives of this framework are the reduction of impacts, the establishment of effective governance and strategies for prevention, mitigation and adaptation, the strengthening of international cooperation and the development of alert systems. Also, the new urban

[4] Risks from Natural Hazards at Hazardous Installations. An example is the 2011 Tohoku earthquake and the resulting tsunami and Fukushima nuclear accident (Krausmann et al. 2019).

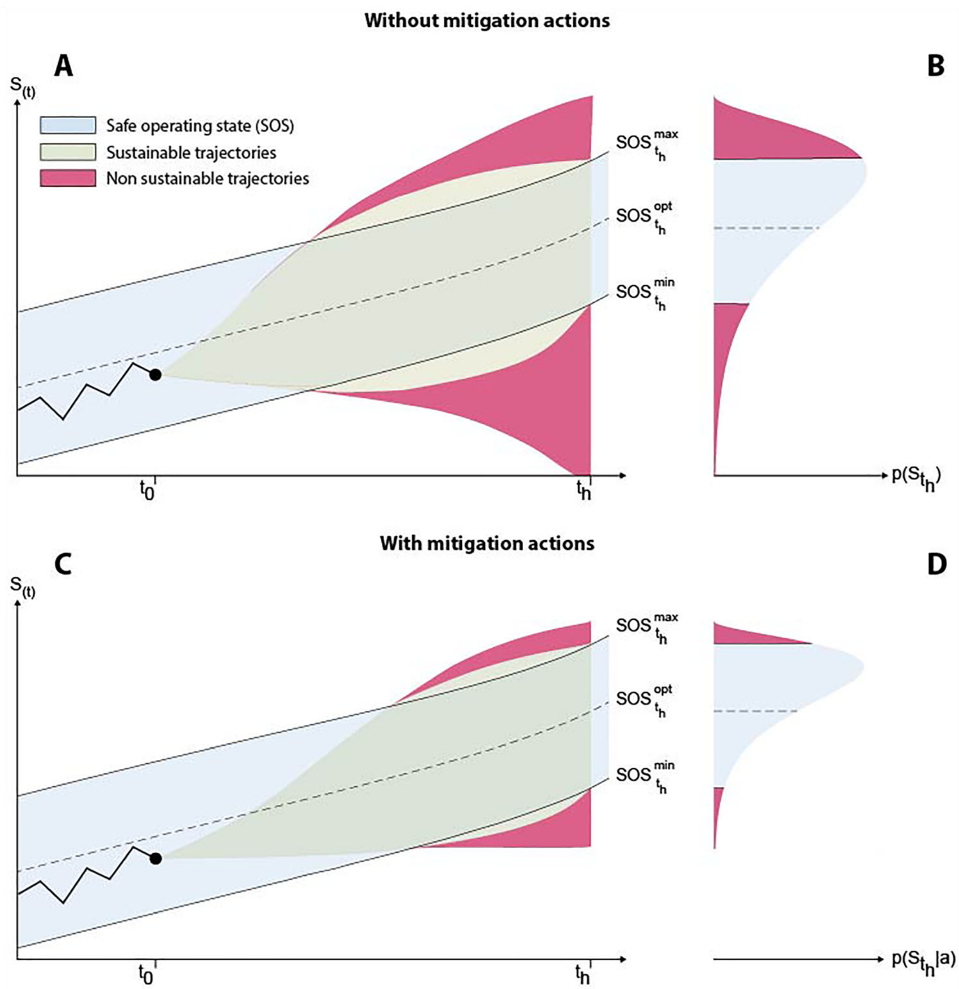

Fig. 3 Ensemble of sustainable trajectories beyond initial time t_o (**A–C**) and corresponding distribution of states at t=t_h (**B–D**) for a synthetic socio-environmental system without (**A**, **B**) and with (**C**, **D**) risk mitigation actions. The SOS evolves with time, making the distribution of states within the SOS changing with time. A soft definition of the SOS is chosen, meaning that sustainable trajectories can temporarily leave the SOS as soon as they are within it at t = t_h. In both cases, the risk measure is the percentile of the state distribution (Appendix S2) and the values at risk are the system states corresponding to the probability $p_{dt_h}|a = P(S_{t_h}|a \notin SOS_{t_h})$ of being outside the SOS at t = t_h. The latter is lower with mitigation actions, highlighting their efficiency for increasing sustainability chances. Same conclusion holds if risk measures defined over the system states trajectories (e.g. ratios between green and red areas within the considered temporal boundaries) are considered

Agenda from the EU "smart cities" encourages the adoption and implementation of DRR (European Union Council 2017). DRR was historically envisaged as a "top-down" approach with main focus on the technical evaluation of potential hazards. It now insists on the crucial role of science–society interaction to design efficient strategies (Albris et al. 2020), and promotes an approach of risks which jointly addresses hazards, vulnerability and exposure (Fig. 4C), in total agreement with the one of IPCC (2014). Even more innovatively, DRR now strongly grounds on a systemic risk conceptualization (UNDRR 2019a; Renn et al. 2020). The latter favours deciphering of the causal mechanisms leading to disasters, which allows, when properly carried out, their anticipation and a better prioritisation of remediation actions (Fig. 4D).

Cross-sectorial assessments and guidelines.

International initiatives addressing risks and sustainability issues are gradually joining each other's on what is referred as the "disaster risk reduction—global change—sustainable development nexus" (Mysiak et al. 2018; Peduzzi 2019) or the "disaster risk reduction—Paris agreement—SDGs nexus" (Handmer 2019). This has recently led to deepened reflections conducted jointly by the IPCC and IPBES regarding interactions between climate change and biodiversity losses (Pörtner et al. 2021), as a step towards the level of generality required for the implementation of the SDGs. Also, within the 2019–2030 IPBES program, a new thematic nexus assessment of the relations between biodiversity, water, food and health is underway. Within

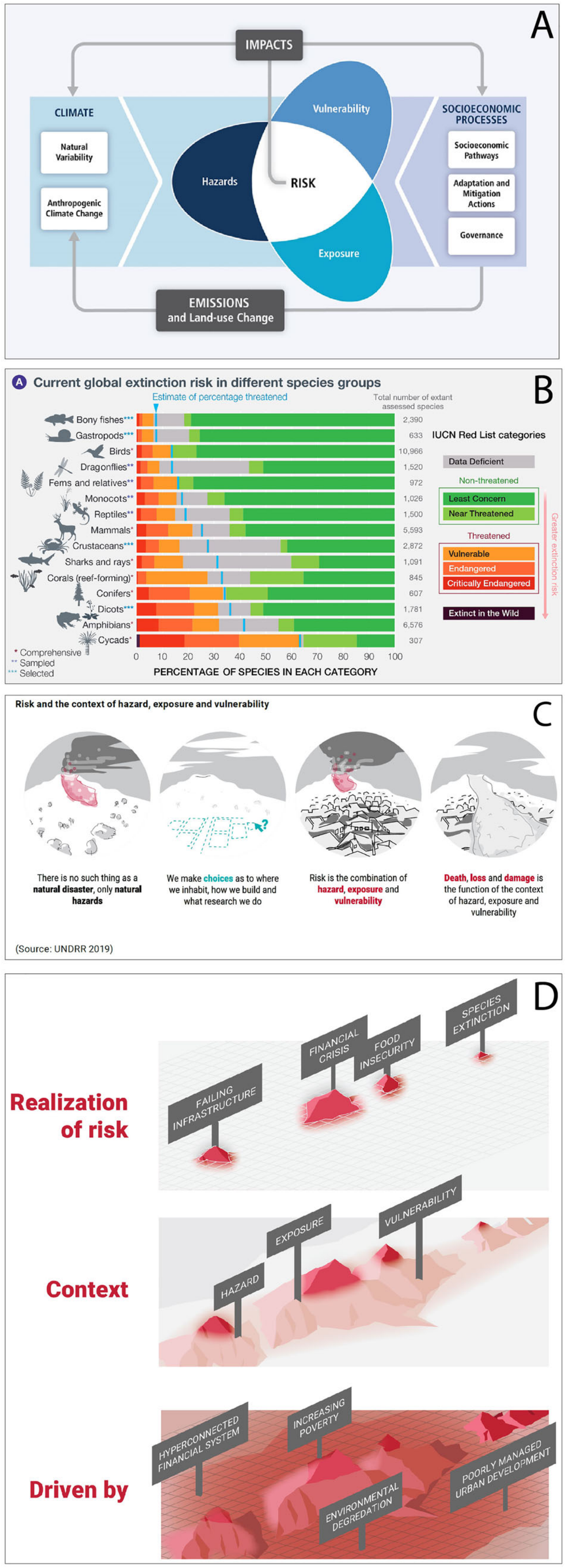

Fig. 4 Reference to risks in international environmental assessments and guidelines. **A** Risk conceptualisation from IPCC (2014), **B** risk for IPBES (2019), **C** risk definition for UNDRR (2019a) and **D** systemic risk according to UNDRR (2019a)

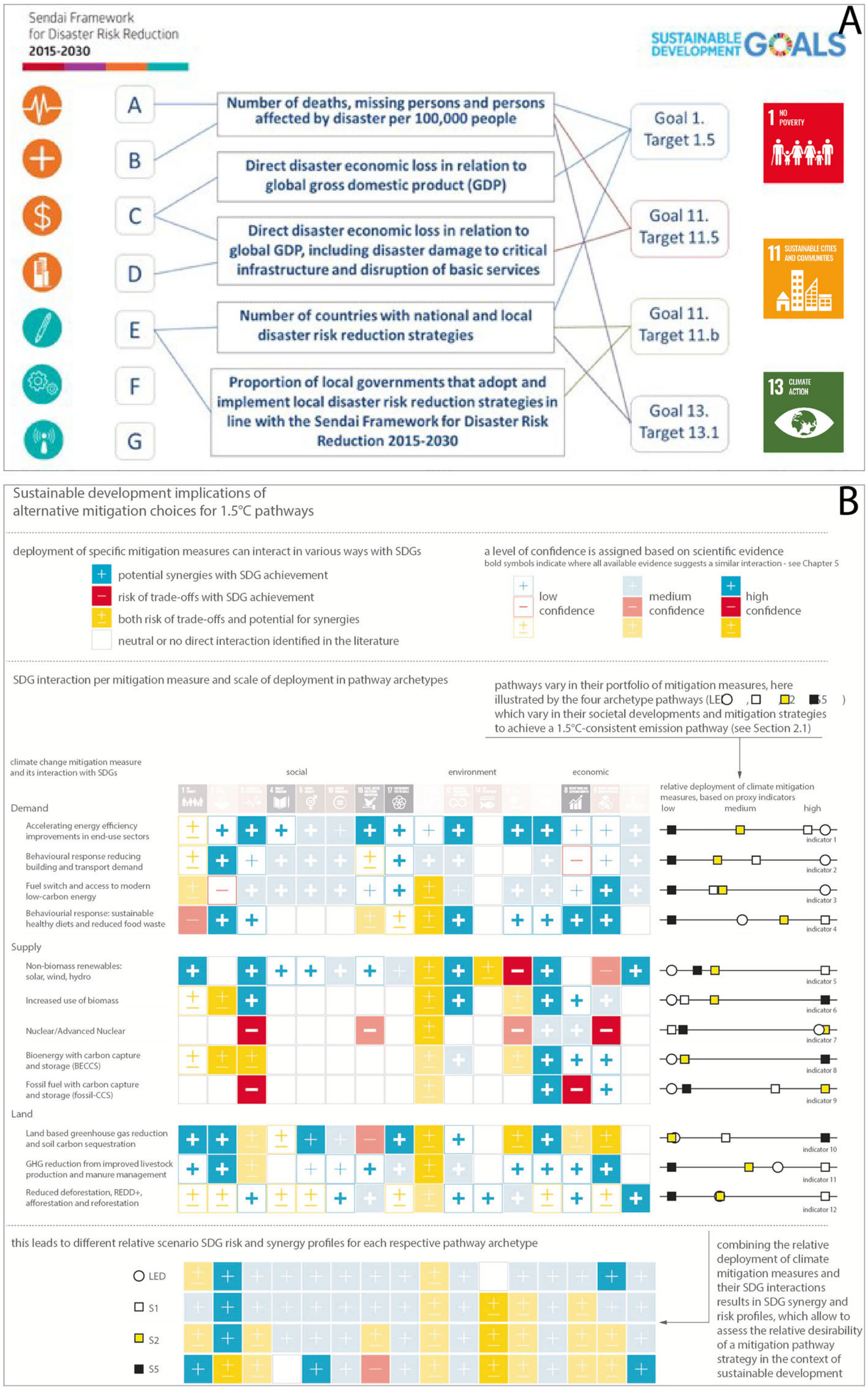

Fig. 5 Emerging convergence between SDGs and risks. **A** Mapping between the targets of the Sendai Protocol and Horizon 2030 (UNDRR 2019b), **B** risks and sustainable development implications related to the impacts of global warming of 1.5 °C above pre-industrial levels and related greenhouse gas emission pathways (IPCC 2018)

the same line, a recent report of the United Nations points to the crucial role of complex cascade of causality chains in the occurrence of disasters, and to the necessary consideration of trade-offs to avoid them (UNU and ESH 2021) in full agreement with the systemic approach provided by UNDRR (2019a). As an explicit support, the United Nations propose a correspondence between the targets of the SDGs and those of the Sendai Framework (Fig. 5A). Eventually, within its special report on global warming of 1.5 °C above pre-industrial levels, IPCC (2018) explicitly analyses risks, trade-offs and synergies within a framework based on SDGs (Fig. 5B).

Within specific research fields

Environmental risk is a broad domain, and each field of research has more or less its own approach (Caquet et al. 2020). This has led to silos, which remain hard to break, and to very different levels of conceptualizations and level of complexity from one field to another. For instance, whereas widespread risks such as those related to climate warming and earthquakes benefit from the latest developments in risk research (e.g. Le Roux et al. 2020), "smaller" risks still stick to simpler methods. Moreover, the causal link between different types of risks, such as the risk of habitat loss caused by ongoing infrastructure development and land-use changes, and the consequent risk of biodiversity loss and tipping points affecting entire ecological networks are rarely adequately conceptualised and quantified.

Further, some communities still stick to approaches that rely on the hazard component of the risk only. For instance, many engineering applications rely on a return period (generally measured in years), a concept that corresponds to the mean time separating two occurrences of the return level exceedance for a stationary system.[5] Evaluation of such return periods involves very advanced approaches, including explicit consideration of non-stationarity and extreme value tail risk properties (e.g. Nicolet et al. 2018), but the limitation of not considering elements at risk explicitly is drastic (e.g. Eckert et al. 2018). It indeed precludes taking into consideration possible trade-offs between different goals, such as, e.g. climate action (SDG 13) and terrestrial biodiversity protection (SDG 15). Also, the insurance and finance sectors have extensively used fine-tuned risk assessment procedures but do not decompose risks between hazard/vulnerability/exposure components, as they work directly on a system that is simply a monetary amount, e.g. a portfolio of actions. The main issues are often dimension reduction and tail risks to avoid large claims within a multivariate setting (e.g. Embrechts et al. 1997). Recently, the community has become increasingly open to sustainability considerations, with e.g. the development of "Green Bonds" and guidelines for sustainable financing such as the EU taxonomy for sustainable activities.[6] Similarly, the recent launching by major financial institutions, corporates and governments, of a task force on Nature-related financial disclosure (TNFD 2021) aims at "supporting business related to the assessment of "emerging nature-related risks".

However, most of the communities concerned by risks due to natural hazards including biological risks and chemical risks use a decomposition of risks at the intersection between a potentially damaging phenomenon (sometimes called danger rather than hazard) and exposed and vulnerable stakes in agreement with the IPCC (2014)/UNDRR (2019a, b) schemes (Eckert et al. in press). Reference to the framework is not always explicit, and sometimes exposure and susceptibility to loss are not clearly distinguished, as in the seminal framework of disaster risks (e.g. IUGS 1997). Also, some communities readily integrate the adaptive capacities within the risk formulation (Wisner et al. 2012). A critical aspect concerns the variability of the hazard, which is not explicit in IPCC (2014) trefoil. Indeed, in some cases, risk assessment remains limited to the evaluation of losses related to one or a few reference scenarios (e.g. Fuchs et al. 2007). However, more comprehensive approaches considering the full randomness are now common, generally on the basis of the expected damage as risk measure, or even using percentile-based risk measures (Farvacque et al. 2021). Within our formal framework (Appendix S2), the considered risk is either on the system state, or on its negative increments only. It is worth noting that some studies are already conducted within the systemic spirit promoted by UNDRR (2019a), so as to understand and quantify how and why the evolution of the interactions between society and its environment gradually modifies risks and their components (Zgheib et al. 2020). Eventually, some communities conduct analyses related to environmental risks, but without advocating the concept explicitly, addressing similar problems but with different language habits and methods. For instance, the literature on regime shifts, resilience and/or bifurcations is large in ecology (Folke et al. 2002; Scheffer et al. 2003; Lade et al. 2013) and physics (Kuznetsov et al. 1998; Ashwin et al. 2012), to, e.g., investigate how different socio-ecological or physical systems react to perturbations/and or changes in their environment.

In terms of spatial scale, most risk assessment approaches are undertaken at a rather small scale, where the damageable impacts can be more easily measured and mitigated (e.g. Favier et al. 2016). Examples at larger scales are primarily from climate risk. For example, Magnan et al. (2021) estimate an overall one-third increase of risk due to climate change for every additional degree of warming. Yet, global risk models are now being developed in other fields, such as insurance/finance, geosciences or biodiversity, in order to provide diagnoses able to guide policies. However, these models remain arguably insufficiently holistic for this purpose. For example, for glacier

[5] In the framework of Appendix S2, its inverse identifies to the probability of failure for the system restricted to the sole hazard.

[6] Sustainability taxonomy aims at scanning development projects with criteria related to the SDGs. https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance/eu-taxonomy-sustainable-activities_en.

melting, it is currently possible to evaluate the global risks due to of sea level rise (Zemp et al. 2019), but not the brutal risks related to glacier outburst floods, icefalls etc. Besides, an explicit link to SDGs within the formulation and results of these global models remains to be developed. Hence, all in all, even if some approaches now tend to reduce the gap with SDG goals, convergence between risk and sustainability issues is arguably less advanced in risk research than in policy guidelines. Notably, existing risk assessment approaches generally (i) do not refer to the SDGs explicitly, (ii) are not able to cope for several SDGs simultaneously, and (iii) are simply not designed to account for specific risks related to the 2030 Agenda and its implementation (e.g. governance, indicators, etc., see below). To fill these gaps, in what follows, we explicitly connect risk and sustainability paths using our framework based on system dynamics.

THE SDG-RISK NEXUS

Formal connexion between risks and sustainability paths

Minimising the probability of failure as a strategy towards sustainability

According to the 2030 Agenda, for any socio-environmental system, meaningful actions to reach sustainability result in favouring system trajectories that stay within the safe operating space defined by the 17 SDGs. Within our formal framework (Appendix S2), this writes $P((S_{t_1},...,S_{t_2}|a) \in SOS_t) > P((S_{t_1},...,S_{t_2}) \in SOS_t)$ for $[t_1,t_2] \in [t_o,t_h]$, with the ultimate goal to bring $P((S_{t_1},...,S_{t_2}|a) \in SOS_t)$ as close as possible to one. For simplicity, we now focus on a single instant t. Acting towards sustainability to keep a socio-environmental system within the sustainable range defined by the 17 SDGs turns into minimising the failure probability[7] $p_{dt}|a = P(S_t|a \notin SOS_t)$. Formally, $p_{dt}|a$ identifies a percentile-based risk measure on the distribution $p(f(S_t)|a)$ with $f(.) = I_d(.)$, the identity function (Appendix S2). Assessing and mitigating this failure probability is thus the right primary strategy to fulfil SDGs (Fig. 3).[8] Considering instead risk measures that consider the distribution of states along a trajectory towards a time horizon h is formally straightforward, and sustainable trajectories, in turn, correspond to those over which the failure probability until h is controlled. A direct example is the IPBES risk definition using species/populations extinction probabilities (Fig. 4B).

Minimizing other classical risk measures as additional signposts for the sustainability track

In real situations, due to the complexity of social-environmental systems, directly minimising the failure probability p_{dt} may be tough, if not impossible. In addition, very large losses (e.g. a large number of casualties or a large monetary loss due to a disaster) may lead to system failure even within the range of acceptable states (e.g. trajectory T4 in Fig. 2). For such cases, the classical approach in risk science is to implement actions that minimise other risk measures implying other—generally simple—functions $f(.)$(Appendix S2). For example, the standard strategy in disaster risk mitigation is to minimise, with suitable actions, risk measures defined according to the negative increment function $f(.) = \delta_s^-(t) = \delta_s(t)I\{\delta_s(t)<0\}$, where $I\{.\}$ is the indicator function and $\delta_s(t) = S_{t+\delta_t} - S_t$. These measures include the expectation $E\left[p\left(\delta_s^-(t)|a\right)\right]$ or the value at risk α corresponding to the probability $P\left(\delta_s^-(t)|a > q_\alpha|a\right)$, where $q_\alpha|a$ refers to the α percentile of the distribution $p\left(\delta_s^-(t)|a\right)$. This clearly shows that applying formal risk management strategies and acting in favour of SDGs fulfilment is essentially equivalent. A practical application is flood risk mitigation using optimal combination of grey and green solutions at the watershed scale, which directly contribute, among others, to SDGs 3, 9, 11 and 13 (Fig. 1).

Broader formulations to mitigate risks related to SDG formulation and monitoring

According to Appendix S1, fulfilling the SDGs implies accounting for a large variety of risks. Keeping the equivalence in our formal framework between risk mitigation and SDG actions is however possible by considering more complex expressions for $f(.)$ and hence, risk measures. For instance, for the risk of inadequacy of the 17 SDGs as a coordinated system to map the evolution of any socio-environmental system, $f(.)$ relates to the discrepancy between a "true" vector space in which the considered system can be described (Appendix S2) and its projection within the space defined by the 17 SDGs (or the 169 targets). Similarly, for risks related to the definition and choice of indicators, $f(.)$ relates to the discrepancy between the vector space defended by the SDGs/targets and its projection within the indicator space (Appendix S2). In both cases, working directly with the algebraic coordinate system defined by the SDGs (respectively the indicators)

[7] Also denoted the death probability of the system, which is acknowledged by the "d" index in the p_{dt} notation.

[8] For a stationary system, the failure probability identifies to the inverse of a return period, T, and a sustainable situation verifies $T >> (t_h - t_o)$.

without considering the (potentially complex) transformation induced by $f(.)$ may result in biassed risk estimates. This may lead to the choice of inappropriate actions, i.e. actions that seem optimal in the space of the analysis (the one of SDGs or of the indicators), but which are not optimal in reality, and which may, in turn, alter the chance of staying in the sustainability range. Hence, keeping socio-environmental systems on sustainable tracks involves a wide range of relevant functions $f(.)$, risk statistics and evaluation methods, and implementing actions that minimise their negative impacts. This may, in practice, be a very tricky problem, which is out of the scope of this analysis to solve. However, the equivalence demonstrated here between mitigation of risks defined in a mathematically broad sense and actions in favour of the sustainability of socio-environmental systems may already be an important starting point. What follows further details benefits for both the risk and sustainability communities of this SDG-risk nexus.

Usefulness of a risk perspective for sustainability and the 2030 Agenda

Considering risks within sustainability sciences

Transformative changes for sustainable development are now urgently required (e.g. IPBES 2019). Sustainability sciences (e.g. Kates et al. 2001) propose an approach based on systemic thinking, inter- and trans-disciplinarity to identify and follow sustainable trajectories (Visseren-Hamakers et al. 2021). International guidelines regarding sustainability already give an important place to the risk concept (section "Within specific research fields"), but sustainability science research focusses mostly on broader issues (energy transition, climate change, biodiversity conservation, etc., Randers et al. 2018). However, maintaining the sustainability of socio-environmental systems also requires developments that target risks both in a more specific and comprehensive way, as repeatedly emphasized by EU guidelines (Poljanšek et al. 2017; Casajus Valles et al. 2020; DRR Research Agenda Core Group 2021). Main challenges can be summarised as follows: (i) study the evolution of risks and their components over long time frames, (ii) the articulation of the biophysical, social and mathematical dimensions of risks with interdisciplinary developments, (iii) the missing consideration of the entire chain of risks, from prevention to reconstruction, including crisis preparation and management, (iv) work side by side with stakeholders and populations. To address these challenges, concepts and methods from theoretical risk science are required, notably quantitative tools (see below) as well as social science rationales and techniques developed to, e.g., understand risk awareness and behaviour towards risk. Among these, approaches for assessing and accounting for uncertainties may prove particularly useful, notably to anticipate potential pitfalls in the future. They include statistics and probabilities for uncertainty sources that can be practically expressed as probability distributions and, e.g., prospective exercises for those that cannot.

Accounting for all risks linked to the formulation of 2030 Agenda

Most current environmental problems relate to several SDGs and many targets. The IPBES Global assessment concludes that "Taking into consideration that the Sustainable Development Goals are integrated, indivisible, and nationally implemented, current negative trends in biodiversity and ecosystems will undermine progress towards 80% (35 out of 44) of the assessed SDG targets (IPBES 2019)". Hence, not only focussing on one single SDG is insufficient to address most of current environmental problems, but it may also threaten the objective of earth system sustainability as a whole. This confirms that, within our formal framework, the SOS needs to be defined according to the 17 SDGs altogether, and not separately for each SDG. Another specificity of the SDGs is their universal nature, independent of scale and problem-specific considerations, which is appealing but may raise some issues. In parallel, SDG targets are highly heterogeneous in terms, e.g., of broadness and temporal horizon. These sizing/scaling complexities are not necessarily insurmountable. Yet, they point to the risk of having exactly/only 17 SDGs, which, as said before, requires the definition of a first family of complex $f(.)$ functions. Also, inadequate and/or inaccurate indicators may give a biassed vision of what is happening, leading to the fallacious statement that "there is a problem" whereas there is none, or, on the other way round, that we are on the fine track when this is not the case. Such discrepancies may have various origins: for instance, heterogeneity of national indicators that may alter the global picture, availability of data to feed the SDG indicators (Lyytimäki et al. 2020), or insufficient understanding of the dynamics of socio-environmental systems to produce meaningful indicators. All of these results in the discrepancy highlighted in our formal framework between the indicator space and the true space, which may ultimately threaten the chance of reaching SDG targets. Assessment and mitigation of this risk requires the definition of a second family of complex $f(.)$ functions. Even more broadly, risks related to SDG achievements may well largely lay in what is not explicit in the 2030 Agenda. For example, an insufficient adhesion to required transformative changes may make the 2030 Agenda impossible to implement. Also, within our context of quick global transitions, drastic changes in many risks and emergence of new risks challenge the 2030 Agenda. The Covid pandemics was already an extremely serious “unexpected” obstacle in the way (Sachs et al. 2020). Other environmental risks may arise, e.g., related to sea level rise (IPCC 2019), appearance of new pathogens and their likelihood and impact may have been underestimated within the 2030 Agenda. These risks require a third family of complex $f(.)$ functions. All in all, achieving the SDGs will require rigorous and multi-faceted analyses and anticipation of all relevant risks (Appendix S1). We argue that only such an approach may allow a comprehensive adaptive risk management and governance able to cope for “pebbles in the shoe” at any time, giving thus a chance to fulfil the SDGs.

Better quantifying all SDG-related risks

Whereas system dynamics is already largely used to foster sustainability and resilience of complex socio-environmental systems (Doyen et al. 2013; Rougé et al. 2015), a formal assessment of related risks remains largely absent, at least in an explicit way. We therefore argue that our approach could be a solid starting point to popularise the use, within the integrated approach required by the SDGs implementation, of recent developments in risk science, notably those adapted to spatio-temporal non-stationary, multivariate and/or extreme value cases (e.g. Coles et al. 2001; Banerjee et al. 2003). This would complement the research conducted on, e.g., the resilience of socio-environmental systems and fit the various types of risks faced within the SDG context: e.g. gradual or abrupt risks, and increasing or emerging risks, notably within future projections and their uncertainties. Such analyses may help design sustainable solutions at different spatial scales and at various temporal horizons. For instance, recent refinements related to interconnected risks were arguably driven by the emphasis given by the SDGs on systemic and holistic environmental issues (Renn et al. 2020). As tools which are still under development, they remain in practice little used explicitly so far within research communities focussing on the SDG and/or environmental risks, but they have clearly huge potential to fit the challenges of our times (e.g. Zscheischler et al. 2018).

Benefiting from an increasing risk awareness as a leverage for action

It is difficult to quantify in an objective way different types of risks, the associated damages/costs and their evolution over time. Nevertheless, sectoral and/or local data are available (WMO 2021) and a clear trend towards an increase in the cost of disasters is well established, as well as the preponderant weight of social inequalities in vulnerability to these disasters (Wallemacq and House 2018). This exacerbation of environmental risks and its causal linkage to rapid socio-environmental transitions is almost universally known. For instance, in the 2020 Future Earth (2020) survey, risks related to climate and weather extremes were the first source of concern. Also, whereas 15 years ago, the World Economic Forum was primarily concerned by risks of economic collapse and war, in 2020 it pointed out first to the risks linked to climate change and weather extremes (World Economic Forum 2020). And even in the (post-)Covid pandemics context, the failure of climate change mitigation strategies remains placed almost at the same level as the pandemic risk in terms of impact (World Economic Forum 2021). This knowledge and perception is largely shared by a wide public and the demand for safety of modern societies, whose aversion to risks is well known, is very strong. Arguably, this risk awareness may be a very powerful leverage for action, and notably a justification to undertake the efforts required to fulfil SDGs.

Usefulness of SDGs and sustainability for environmental risks assessment and mitigation

Better accounting for complexity and interconnexions in risk assessment

As established by our review (section “Environmental risks and their relations to SDGs”), risks are currently clearly assessed in situations where procedures for risk assessment already exist such as national regulatory frameworks developed in many application fields, e.g. EIA regulations (Bond et al. 2017). Despite some exceptions, these procedures generally focus on only one single risk or impact, e.g. chemical risk or flood risk. This ignores the concept of cumulative impacts and goes against the fact that environmental risks are increasingly complex and interconnected with far-reaching consequences. For example, risks that food production encounters (or agriculture generates) are currently not evaluated in a coordinated fashion (OECD 2014; Rockström and Sukhdev 2016). Also, whereas biodiversity conservation increasingly considers biodiversity loss in an explicit risk assessment framework, side effects such as loss of ecosystem services and protection against natural hazards (floods, wildfires, etc.) are for now weakly considered. Due to their integrated nature, 2030 Agenda and SDGs may lead to paradigm shifts in the way risks are assessed and mitigated, from sectoral assessment to approaches that account for such interconnections. In parallel, even for risks that are already very well accounted for, a more integrated perspective should be beneficial. For example, better mitigating flood risk using green solutions which promote biodiversity or identifying and addressing the different underlying drivers of human health are appealing (e. g. Venter et al. 2020). We argue that SDGs should allow tackling/mitigating such risks with a new (and hopefully more efficient) perspective by proposing a systematic framework usable whatever the system/problem. To this aim, innovative developments to assess risks within models for complex dynamics fed by massive amounts of data of various nature are needed. Developments should also consider risks related to data imperfection, error propagation and sensitivity analyses (Saltelli et al. 2006). For example, approaches to identify and quantify cumulative impacts on, e.g., biodiversity loss (IPBES 2019) are largely lacking. Existing suitable frameworks include hierarchical Bayesian Models (Banerjee et al. 2003), graphical models that account for long-term dependencies in physical and social processes (Giacona et al. 2019), the recent frameworks related to multi-risks (Curt 2020), and, for choosing the best paths, viability theory (Aubin et al. 2011), decision theory (Berger et al. 1985) and optimal control (Rougé et al. 2015). The work to be done largely consists in bridging these different schools of thoughts within a framework based on SDGs. We hope that our work provides a first cornerstone in this direction, and will foster research in risk science promoting more comprehensive risk assessments that account for complexity and interconnections in a consistent manner.

Bridging the gap between risk and sustainability sciences with a systemic vision

Due to the now almost total imbrication of natural systems and societies, it is rather universally accepted that environmental risks must be understood holistically (e.g. Pörtner et al. 2021), and a systemic vision is mandatory to address the related challenges. Clearly, a sustainability science perspective may contribute to reinforce the importance of inter- and trans-disciplinary approaches in risks, so as to associate to the most accurate developments used for long in risk science (i) knowledge from all the relevant application fields and, (ii) co-construction with stakeholders and the wide public to design risk management tools efficient and widely accepted. Also, a sustainability science perspective points to the importance of accounting for risks which are generally not considered in risk science, e.g., in the SDG case, risks related to indicators, to SDGs and targets definition or to institutional failure. An example of the latter is that, in many countries, SDGs and related progresses are mainly the responsibility of one single ministry. Although, in theory, SDGs apply to all policies, this makes them, in practice, not that much considered by other ministries. This absence of coherent political strategy to reach the overall ambition of the 2030 Agenda puts at risk not only individual SDGs, but also exacerbates the risks related to linkages and trade-offs among SDGs. Hence, a sustainability science perspective broadens the scope of risk research, pointing to the necessity of a systemic vision of the whole chain of risk management, from prevention to resilience, and the 2030 Agenda, may be the right and timely instrument for that. In fine, if the benefit of risk science to sustainability science is clear, the other way round is true as well, even beyond the sole question of better consideration of complexity in risk assessment and mitigation, and both fields definitely need to make a step towards each other.

CONCLUSION AND OUTLOOKS

Main outcomes of the work

SDGs and their targets constitute a framework that is intended to be operational for the management of all socio-environmental systems. Fulfilling these goals is supposed to keep any system (and hence the whole earth system) within its Safe Operating Space, granting that only sustainable trajectories can be followed. We argue that this is true only when the framework is accompanied with a proper risk assessment/mitigation. Hence, if 2030 Agenda is the “Yin”, risks may well be the “Yang”, and considering jointly SDGs and risks is mandatory to design sustainability paths. This statement, however, holds only if the risk concept is expanded with regard to its “traditional” sectorial acceptations and econometric formulations, so as to encompass within a unique assessment and a broad mathematical definition all aspects of environmental management/policies targeted by SDGs.

A wide SDG-related risk concept, even if appealing, is arguably even more ambiguous and difficult to formalize than a sector-specific application. As a step towards clarification, we showed (i) the equivalence between acting to fulfill SDGs and mitigating risks for socio-environmental systems and, (ii) the usefulness of this broad perspective from both the SDG and environmental risk perspectives. We indeed see a large potential to further develop and apply risk assessment, management and governance-relevant aspects related to SDGs, their associated targets and their implementation in most environmental problems raised by the issue of a sustainable future. In parallel, communities in the areas of insurance, finance or disaster mitigation work routinely within a risk framework but they generally lack a holistic perspective, so that a greater use of the implementation of SDGs may be useful for them as well. Hence, even if the SDGs have already attracted rich and diverse research (e.g. Nilsson et al. 2016), our analysis points to the crucial need of a better integration of the risk perspective in this research. For example, for administrations and financiers, SDGs already represent quality and responsibility criteria (Riaño et al. 2021), but how to account for related risks in a proper way remains to be investigated. We therefore expect our findings to be relevant, and the proposed SDG-risk perspective useful, for the broad range of communities and publics that try to contribute to the overall effort towards sustainability, from research to the practical implementation of environmental policies.

Risks and sustainability paths were implicitly tightly linked within the seminal work of the Club of Rome (Meadows et al. 1972), but our analysis shows that this imbrication was largely lost along the way since then. This divergence may be a heuristic bias, as standard research projects are about risks only, or consider risks at the end of the day in a "risks and solutions" item only, but not as a true constitutive element of the whole problem (Renn 2020). Also, risk conceptualisations and development have traditionally been theory-driven. However, the pendulum is now coming back, with the convergence highlighted by our analysis between all environmental policies related to sustainability issues and risks now on the right track (Figs. 4, 5), an, for instance, SDGs which foster the development of more systemic and policy-driven approaches. By treating both the risk and sustainability path concepts on equal foots and providing a formal link between them, our approach makes a further step forward towards bridging the gaps between communities and disciplines. This is even more required while considering that we are in fact already half way towards the expiration date of 2030 Agenda. Also, the increasingly alarming state of the environment makes a renewed and increased effort towards more inclusion of sustainability issues in every aspect of life on earth each day more mandatory. Hence, not only our analysis could provide some guidelines for implementing the second half of the road towards 2030, but it could also timely contribute to the design of a "2050 Agenda" that eventually explicitly includes a holistic risk assessment/mitigation dimension.

Put the framework at work to foster solutions

A current limitation of our work is that it remains arguably rather theoretical. Moving towards sustainability requires quantitative projections of the state of socio-environmental systems at various temporal horizons, assessment of how policies and management strategies may affect these, and assessment of related uncertainty levels. This is the basis for assessing future risks, taking decisions that maximize the chance of staying on sustainable tracks and communicating on these decisions (what do we know, with which degree of confidence) at global and/or territorial scales (TWI2050 2018). Hence, the challenge is now to put our framework at work so as to benefit from its added value in various operational contexts. Main interests may include (i) risk identification, categorization and reduction in a SDG context, (ii) the understanding of existing monitoring, anticipatory and governance systems, and the design of evaluation methods adapted to an efficient monitoring of SDG fulfilment, (iii) to shed light on interlinkages between SDGs, or (iv) to study how risk reduction/prevention in one area/SDG has synergies/trade-offs/undesirable effects with other areas/SDGs. Potential applications concern a range of scales, and encompass local impacts to broad implications, but important efforts are especially required at the global scale, so as to address the habitability of the whole Earth system. However, the challenge of formalizing and quantifying all risks as defined in this work and integrating these developments within such quantitative projections remains enormous, especially at the global scale (e.g. Rovenskaya et al. 2021). To this aim, the seldom existing sectoral global risk models should be (i) unified under a joint conceptual and mechanistic framework, (ii) merged in a holistic sustainability science perspective (with the modelling options discussed in Section "Better quantifying all SDG-related risks" or others), and (iii) fed with quantitative data as comprehensive as possible. This would make possible the design of projections of the state of socio-environmental systems under various management strategies usable in large-scale environmental policies. This is obviously a tremendously difficult task that will require the mobilization of a wide and diverse research community.

Acknowledgements All participants (meetings workshops, etc.) of the Tackling and managing Risks with SDGs (PEER-TRISD) initiative are warmly thanked for their inputs that contributed to raise the ideas behind this paper. Also, C. Rios Rojas is thanked for useful comments on the manuscript. The authors are grateful to two anonymous referees and to Bo Söderström whose insightful comments helped produce a better paper. INRAE is member of Labex OSUG.

Funding Authors acknowledge support from PEER consortium to the TRISD project. N. Eckert was further supported by the French National Research Agency through the Statistical modelling for the assessment and mitigation of mountain risks in a changing environment—SMARTEN program under Grant Agreement ANR- 20-Tremplin-ERC8-0001.

Declarations

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

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