

# Pinpointing Fragility: Integrating Resilience Indicators into Risk Evaluation

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## ABSTRACT

1  
2 Ecosystems globally are increasingly threatened by climate change and human pressures,  
3 yet current ecosystem risk assessments predominantly emphasize exposure to stressors  
4 while overlooking intrinsic ecosystem resilience—the capacity to absorb and recover from  
5 disturbances. Here, we advocate for an integrated framework that explicitly incorporates  
6 resilience into ecosystem risk assessments and demonstrate its value in the context of  
7 dryland desertification. Through bibliographic analyses of the desertification literature,  
8 we reveal a persistent disconnect between resilience research and desertification risk  
9 assessments. We then propose pathways for integration and illustrate this approach  
10 using a global dataset of dryland sites to show how accounting for resilience reshapes  
11 our understanding of desertification risk. By bridging theoretical resilience science and  
12 applied risk assessment, our framework offers a conceptual and practical foundation for  
13 pinpointing dryland areas most at risk, thereby supporting proactive management in a  
14 warming, drying world.

15 **Keywords:** Resilience, Risk, Vulnerability, Drylands, Desertification, Degradation, Adaptive  
16 capacity

## INTRODUCTION

17

18 The concept of ecological resilience was introduced by Holling (1973) more than fifty years  
19 ago. Ecological resilience refers to a system's capacity to withstand disturbances and  
20 recover to its original state after being perturbed (see Glossary for definitions; Pimm, 1984).  
21 Since Holling's seminal work, our understanding of the resilience of ecological systems  
22 has advanced considerably. For instance, researchers have developed resilience indicators,  
23 referred to as 'early warning signals', which have been applied across a variety of systems  
24 to anticipate critical transitions (Scheffer et al., 2009; Clements and Ozgul, 2018; Arani et al.,  
25 2021) and which have been used to map changes in ecosystem resilience at large scales (*e.g.*  
26 Lenton et al., 2022). Recent studies have also explored the drivers of resilience changes  
27 over broad spatial extents, shedding light on the relative contribution of anthropogenic  
28 and climatic factors (Forzieri et al., 2022; Wang et al., 2024; Zhang et al., 2024). Collectively,  
29 this body of research has significantly deepened our understanding of the spatial and  
30 temporal variability of ecological resilience. Despite these advances, much of the literature  
31 on ecological resilience remains largely theoretical and has yet to be integrated into applied  
32 fields such as risk assessment, which could enhance its utility for ecological management  
33 (Gunderson, 2000; Spears et al., 2015).

34

35 Risk assessments are used in many different contexts such as climate (IPCC, 2022), earthquakes  
36 (Silva et al., 2014), fire (Hernandez-Leal et al., 2006), or floods (Wang et al., 2015). In these  
37 contexts, 'risk' (or 'vulnerability') is usually defined as the integration of the *exposure*

38 of ecosystems to climatic and human disturbances, the *intrinsic resilience* of ecosystems  
39 to those disturbances, and their *adaptive capacity* (Fig. 1; Glossary for definitions). The  
40 latter corresponds to the intrinsic ability of a system to prepare for stresses and change  
41 in advance, or to adjust and respond to the effects caused by the stresses (*sensu* ; Smit  
42 and Wandel, 2006; Folke et al., 2010). There is a large diversity of ways to define risk  
43 indicators for ecosystems depending on the subset of components each study accounts  
44 for and the ways to combine those variables (*e.g.*, Gallopín, 2006; Smit and Wandel, 2006;  
45 Engle, 2011). Although seminal conceptual papers on risk, grounded in socio-ecosystem  
46 theory, explicitly recognized the intrinsic resilience of ecological systems (Turner II et al.,  
47 2003; Gallopín, 2006; Folke et al., 2010), in practice, most contemporary ecosystem risk  
48 assessments overlook this critical dimension (*e.g.*, Réjou-Méchain et al., 2021; Anderegg  
49 et al., 2022; Lecina-Diaz et al., 2024 for forests).

50

51 This disconnect between resilience and risk assessments arises from several persistent  
52 challenges. First, the coexistence of disjointed resilience concepts in the literature (*e.g.*,  
53 engineering vs. ecological) creates implementation challenges because each study needs  
54 to identify and chose resilience indicators among the many that exist (Holling, 1973;  
55 Domínguez-García et al., 2019; Dakos and Kefi, 2022). Second, resilience indicators can  
56 be quantified at different temporal and spatial scales and sometimes provide conflicting  
57 signals, making it difficult to standardize their use across different ecosystems and contexts  
58 (Gsell et al., 2016; Veldhuis et al., 2022). Third, traditional resilience indicators do not  
59 capture an ecosystem's exposure to anthropogenic and climatic stressors (Gallopín, 2006),  
60 limiting their relevance for practical risk evaluation. While integration of resilience into

61 ecosystem risk assessments remains limited and fragmented, a more comprehensive  
62 approach that explicitly links ecosystem resilience with current and projected climate and  
63 human stressors, as well as the adaptive capacity of systems to withstand change, holds  
64 significant promises for the identification of fragile or at-risk areas, ultimately supporting  
65 more effective conservation and management strategies.

66

67 Here, we illustrate the relevance of such an integrated approach for dryland ecosystems.  
68 Drylands, which cover approximately 45% of Earth's terrestrial surface, are defined as  
69 regions where rainfall amounts to less than 65% of the evaporative demand. These  
70 ecosystems are exposed to large disturbances due to pronounced precipitation seasonality  
71 (Wang et al., 2022), frequent extreme drought and wet events (Schumacher et al., 2022),  
72 and significant human disturbances, since nearly three billion people inhabit dryland  
73 regions (IPCC, 2022). Drylands are also especially vulnerable to future changes in climate  
74 dynamics. Projections indicate that increasing aridity could expand the extent of drylands  
75 by 11% to 23% by 2100, depending on the climate scenario considered (Huang et al.,  
76 2016; Mirzabaev et al., 2022), and that large dryland areas are desertifying (Eckert et al.,  
77 2015; Burrell et al., 2020). Recent research also highlights that feedbacks between climate  
78 and vegetation can further drive the expansion of drylands, promoting aridification and  
79 drought even in downwind humid areas (Schumacher et al., 2022; Koppa et al., 2024). Such  
80 profound changes in climatic disturbance regimes are likely to have significant impacts on  
81 dryland ecosystem functioning and resilience, with direct consequences for the millions of  
82 people who depend on these ecosystems for their livelihoods.

83 In addition, drylands are particularly prone to non-linear changes in dynamics, driven by

84 strong feedbacks at the soil-vegetation interface (Callaway, 2007; Kéfi et al., 2007a), soil-  
85 atmosphere interactions (Schlesinger et al., 1990; Schumacher et al., 2022), and hydrological  
86 processes (Turnbull et al., 2012). The interplay between escalating external pressures  
87 and these inherent feedback mechanisms significantly increases the risk of abrupt and  
88 potentially irreversible desertification in drylands (Kéfi et al., 2007b; D’Odorico et al., 2013)  
89 -a process defined as the degradation of dryland ecosystems resulting from climate change  
90 and unsustainable land management (UNCCD, 1994; see Glossary).

91 Despite these complexities, current assessments of desertification risk in drylands exclusively  
92 focus on exposure to climatic and human disturbances, largely overlooking the intrinsic  
93 resilience of these ecosystems to disturbances (*e.g.*, Contador et al., 2009; Huang et al.,  
94 2020). For instance, the global dryland vulnerability index proposed by Huang et al. (2020)  
95 is based solely on present climatic and anthropogenic pressures, without accounting for  
96 the ecosystems’ capacity to absorb and recover from disturbances. This gap is also evident  
97 in major policy documents, including reports from the IPCC (Intergovernmental Panel on  
98 Climate Change) and the UNCCD (United Nations Convention to Combat Desertification),  
99 where the integration of resilience and risk assessments remains largely absent (*e.g.*, IPCC,  
100 2022; Reichhuber et al., 2023; Vicente-Serrano et al., 2024).

101 Bridging this divide requires the development of novel approaches that incorporate  
102 the intrinsic resilience of drylands, alongside their vulnerability to current and future  
103 climatic and human-induced changes (Fig. 1). Given that drylands support an increasing  
104 proportion of the global population and of the Earth’s land surface (Huang et al., 2016),  
105 advancing such integrated assessments is both timely and important.

106

107 Our objective is to show how an integrated risk assessment framework that explicitly  
108 incorporates the intrinsic resilience of ecosystems to disturbances can more effectively  
109 pinpoint areas at heightened risk of future ecosystem degradation. We also address  
110 the inclusion of ecosystems' adaptive capacity within such a framework, alongside the  
111 methodological challenges involved. To illustrate these concepts, we use drylands as a  
112 case study. Through a bibliographic analysis, we first highlight the current disconnect  
113 between desertification risk assessments and the resilience literature. We then review  
114 existing methods for assessing desertification risk and summarize key concepts and  
115 metrics of ecological resilience, emphasizing the strengths and limitations of each. Next,  
116 we explore why resilience and risk perspectives are rarely combined, despite their clear  
117 complementarity. Building on emerging examples from other ecosystems where integrating  
118 resilience and risk approaches has improved the detection of vulnerable areas, we outline  
119 how a similar approach can be developed for drylands and illustrate this using a global  
120 dryland dataset. Finally, we conclude by emphasizing the broader importance of incorporating  
121 interactions between ecosystems and human activities to improve the identification and  
122 management of ecosystems at risk of degradation.

## 123 **A DISCONNECT BETWEEN THE RISK AND RESILIENCE**

### 124 **LITERATURES**

125 To determine existing quantitative linkages between the literature on risk and resilience, we  
126 conducted a bibliographic analysis focused on drylands and desertification. We retrieved

127 and filtered all papers on desertification risk and dryland resilience from ecological and  
128 interdisciplinary journals between 2000 and early 2025 from the Web of Science ( $n = 158$   
129 for the final list) and performed a co-citation analysis. This analysis creates a so-called  
130 co-citation network in which nodes are all the papers cited in the publications retrieved  
131 by the Web of Science search and the links connect papers that are cited together in at  
132 least two of the retrieved publications. Articles were clustered into thematic groups using  
133 the Walktrap method, and we investigated the different keywords used in each identified  
134 group to characterize the thematic. We refer to Supplementary method 1 for details on the  
135 request, on the clustering approach and on the sensitivity analyses made.

136

137 Our co-citation network reveals four groups of studies (Fig. 2). One aggregates general  
138 reviews on desertification and vegetation dynamics (pink group in Fig. 2a), another is  
139 mostly focused on assessing the human and climatic drivers of desertification (orange  
140 group). The two others are studies on resilience indicators (blue group) and desertification  
141 risk assessments (green group). As we can see, resilience indicator studies (*e.g.*, Kéfi et al.,  
142 2007a; Scheffer et al., 2009) are well linked to the concept of desertification captured by  
143 studies like Schlesinger et al. (1990); Reynolds et al. (2007); D’Odorico et al. (2013). This  
144 is well emphasized both by the links connecting the blue and orange or red groups in  
145 Fig. 2a, and the presence of “desertification” within the most used keywords of resilience  
146 indicator studies (blue keywords in Fig. 2b). Yet, resilience and risk assessment studies  
147 do not communicate much with one another (green and blue groups in Fig. 2a): most  
148 studies assessing regional risk of desertification do not cite resilience-related studies (and  
149 reciprocally; see Fig. S1). This contrasts with the rest of the literature on the concept of

150 desertification including papers on vegetation dynamics, climate and human disturbances  
151 that are well integrated within the network of co-citations (Figs. 2a, S1).

152 This dichotomy of ways of seeing the desertification concept percolates to keywords used  
153 in the articles (see Fig. S2 for the global network). Most keywords from desertification  
154 risk assessment studies focus on indicators based on soil and climate (green keywords in  
155 Fig. 2b). By contrast, resilience literature focus on indicators based on vegetation spatial  
156 structure and the possibility of abrupt transition due to positive feedbacks, keywords that  
157 are seldom used in risk assessment studies (blue keywords in Fig. 2c).

158

159 We conclude that the concept of resilience is absent from assessments of risk of desertification,  
160 and that inversely, resilience studies have yet to include dryland exposure to current and  
161 future climatic and human disturbances. It is noteworthy that in the resilience literature,  
162 these disturbances are generally treated as potential drivers of resilience losses or gains  
163 (*e.g.*, (Zhang et al., 2024; Kéfi et al., 2024)), and not as complementary information on  
164 desertification risk. Conversely, current risk assessments generally account for the diversity  
165 of disturbances that dryland areas face, but fall short accounting for the differences in  
166 responses and resilience between different dryland areas.

167 This review of the literature highlights that there are two subsets of the literature aiming at  
168 evaluating the risk of desertification of ecosystems, largely disconnected from one another,  
169 ultimately limiting our ability to pinpoint the most fragile dryland areas. This dichotomy  
170 in views of the desertification process contrasts with seminal conceptual frameworks on  
171 the concept of risk emphasizing that resilience and exposure are intertwined (Turner II  
172 et al., 2003; Gallopín, 2006; Miller et al., 2010). We next review each of the subsets of the

173 desertification risk assessment and resilience literature before discussing opportunity for  
174 combining them.

## 175 CURRENT DESERTIFICATION RISK ASSESSMENTS

### 176 *How is current desertification risk assessed?*

177 The first global-scale and comparable assessment of desertification was made by the US  
178 Department of Agriculture by combining soil climate and soil classification information  
179 (Eswaran and Reich, 1998). At that time, risk assessment studies mainly focused on the  
180 exposure component of dryland risk and identified human pressure (“man-made deserts”)  
181 and climate as the two main causes driving desertification (Reynolds and Stafford Smith,  
182 2002; Asner et al., 2004; Geist and Lambin, 2004). Desertification is however a complex  
183 phenomenon that involves changes in soil composition and stoichiometry, community  
184 composition, and vegetation productivity (Berdugo et al., 2020; Mirzabaev et al., 2022;  
185 Berdugo et al., 2022).

186 The Mediterranean Desertification and Land Use framework illustrates well this vegetation,  
187 soil and climate nexus (Contador et al., 2009). This framework proposes to average soil  
188 characteristics (*e.g.*, depth, texture, drainage capacity), static vegetation characteristics  
189 such as plant cover, and the type of land-use (*e.g.*, cropland, pasture, forest) with climate  
190 exposure variables (*e.g.*, aridity, rainfall, fire risk, drought). Such combined human-climate-  
191 soil-vegetation indicators were applied at the regional or national scale (Salvati et al., 2009;  
192 Prăvălie et al., 2017), such as in Iran (Jafari and Bakhshandehmehr, 2016) or in Mongolia

193 (Meng et al., 2021) with the aim to identify the most threatened areas. Desertification  
194 risk assessment studies have thus integrated a static vegetation component (*e.g.*, cover  
195 or type of vegetation) in their desertification risk indicators using field data or remote  
196 sensing products, which has allowed accounting for the different components of the strong  
197 feedbacks between the vegetation, the soil, and the atmosphere (D’Odorico et al., 2013).

### 198 *Shortcomings of current risk indices*

199 There is still no generally accepted framework for building a risk index. Key questions  
200 remain regarding which climatic, vegetation, or soil variables should be included, how  
201 they should be weighted, and how the resulting indices can be validated (Hagenlocher  
202 et al., 2019; Lecina-Diaz et al., 2021). This partly explains the large discrepancy of variables  
203 included in studies assessing regional risk of desertification. This lack of standardization  
204 has made it difficult to quantitatively compare different regions and their relative fragility.  
205 To address this issue, Huang et al. (2020) recently proposed a desertification risk index  
206 based on the exposure of drylands to human (*e.g.*, CO<sub>2</sub> emissions, population density) and  
207 climatic (*e.g.*, average of temperature anomaly, aridity index) pressures as well as their  
208 productivity (with the leaf area index). This desertification index represents an interesting  
209 framework to compare dryland areas across the globe solely based on remote sensing  
210 vegetation, and both climatic and human pressures. Yet, this index does not account for  
211 the dynamics and resilience of the vegetation in response to disturbances, as well as how  
212 climate and human disturbances could change in the near future (dynamic vegetation  
213 component; Fig. 1).

## QUANTIFYING DRYLAND RESILIENCE

The concept of resilience has been associated with alternative stable states. Mathematically, resilience can be quantified using the width of the *basin of attraction* of a ecosystem's stable state. The basin of attraction is the region of the system's state space where the system tends to return to a specific stable state after a disturbance. When the disturbance is large and displace the system beyond its basin of attraction, there can be abrupt transition between stable states (Scheffer et al., 2001). For drylands, while there are uncertainties about whether such alternative states may exist (Lenton et al., 2023), some theory (Kéfi et al., 2007b; D'Odorico et al., 2007) and data about dryland functioning (Berdugo et al., 2017a; Kéfi et al., 2024) or grassland-shrubland transition (Ratajczak et al., 2014; Collins et al., 2021) provide evidence that such alternative states may exist. As such, monitoring and comparing the resilience of drylands has been a focus of many studies, which used both temporal and spatial data.

### *Resilience using temporal data*

Theory suggests that drylands undergoing desertification will experience critical slowing-down characterized by for example increasing temporal variance (variability of fluctuations) and autocorrelation (system's memory ; Wissel, 1984; Scheffer et al., 2009). These temporal indicators (also called early warning signals of transitions) therefore serve as proxies of the changes of resilience of a system in time and provide information about whether and which dryland areas are losing or not resilience (*i.e.*, moving toward or opposite to abrupt

234 transition respectively). This has for example been applied to tropical drylands (Saatchi  
235 et al., 2021), and in the context of the desertification of the "green Sahara" about 5,500 years  
236 ago (Dakos et al., 2008). Temporal indicators of resilience are therefore complementary to  
237 static indices based on vegetation cover or vegetation type since they track recent losses  
238 and gains of resilience.

239 Since the stability of ecological systems is multifaced (Pimm, 1984; Donohue et al., 2013;  
240 Dom'inguez-Garc'ia et al., 2019), many indicators have been proposed to quantify vegetation  
241 response to disturbance, which can provide a more complete description of the stability of  
242 dryland ecosystems. As such, temporal indicators of resilience can include their ability to  
243 withstand disturbances (resistance; *e.g.*, Li et al., 2020; Liu et al., 2022), their recovery time  
244 (*e.g.*, Schwalm et al., 2017; Smith et al., 2022), and their invariability (temporal stability;  
245 *e.g.*, Garc'ia-Palacios et al., 2018). Interestingly these indicators are complementary and  
246 characterize different dimensions of dryland stability and resilience (Runge et al., 2025).  
247 While temporal indicators of resilience are promising to pinpoint potential losses of  
248 vegetation productivity (Liu et al., 2019) or tree mortality (Anderegg et al., 2019) of a  
249 specific ecosystem area, applying these early warning signals to large scale areas (*e.g.*,  
250 global drylands) comes with some limitations. Changes of resilience indicators can be  
251 attributed to other factors. For example, Bernardino et al. (2025) found that abrupt changes  
252 in rain-use efficiency are not always preceded by an increase in autocorrelation in the  
253 timeseries. Quantitatively, resilience measures are also contingent on the type of data  
254 (Smith and Boers, 2023; Blaschke et al., 2024) and indicator used (Gsell et al., 2016; Smith  
255 et al., 2022). In practice, these approaches are not comparable across systems having  
256 different climatic conditions and types of vegetation. This has been well shown in theory

257 (Zhang et al., 2022), and can be explained by the fact that the different local conditions  
258 change the underlying dynamics of each system and the potential threshold at which they  
259 may tip (van Nes and Scheffer, 2005; Villa Martín et al., 2015; Ratajczak et al., 2017a). Hence,  
260 even if two sites are similar in temporal variance and autocorrelation, they may have a  
261 different threshold beyond which they switch to another state. For example, in the context  
262 of the rapid desert transition of the western Sahara about 5,500 years ago, Bathiany et al.  
263 (2012) used a vegetation-climate model to show how atmospheric variability influenced the  
264 timing and location of the transition, which can ultimately change the temporal indicators  
265 of resilience. As reviewed in other papers (*e.g.*, Hastings and Wysham, 2010; Kéfi et al.,  
266 2013; Clements and Ozgul, 2018), temporal indicators of resilience are also prone to type  
267 I and II errors meaning that they sometimes fail to indicate future abrupt transitions or  
268 that they indicate abrupt transitions for systems ongoing gradual changes. Because these  
269 limitations caution against a quantitative interpretation of large-scale mapping of temporal  
270 resilience indicators, a more prudent approach can be taken by qualitatively mapping areas  
271 with increasing trends of both variance and autocorrelation (as done in Smith et al., 2022).  
272 Such semi-quantitative resilience assessment can easily be incorporated into a general risk  
273 assessment accounting for potential gains and losses of resilience.

274

### *Resilience using spatial data*

275 Drylands are areas of low productivity, generally with a vegetation that does not fully  
276 cover the landscape. Because of the facilitative interactions among some plants in drylands  
277 (Callaway, 2007), plants aggregate into patches that are separated by bare areas (Rietkerk,

278 2004). The ability of dryland vegetation to self-organize into vegetation patches through  
279 facilitative interactions has been suggested to increase as stress increases (Rietkerk et al.,  
280 2021; Kéfi et al., 2024). Spatial patterning of the vegetation represents therefore an ability  
281 of the vegetation to buffer against disturbances.

282 In fact, the spatial structure of the vegetation has been shown to reflect the level of stress  
283 experienced by a given dryland ecosystem (von Hardenberg et al., 2001; Rietkerk, 2004; Kéfi  
284 et al., 2007a, 2011). Paralleling temporal indicators of resilience, multiple spatial indicators,  
285 such as the spatial variance, autocorrelation (Guttal and Jayaprakash, 2009; Dakos et al.,  
286 2010) or indicators derived from the patch-size distribution (Kéfi et al., 2011) have been  
287 developed to follow changes in the spatial structure of the vegetation as desertification is  
288 approached (Kéfi et al., 2014). For example, studies have found that lower precipitation or  
289 higher aridity are associated with the loss of the largest patches ("spanning clusters") and  
290 a higher spatial aggregation of the vegetation (Eby et al., 2017; Kéfi et al., 2024). Similarly,  
291 in the context of the grassland to shrubland transition, increasing spatial variance of  
292 grasses has been shown to indicate the progressive encroachment of grasslands (Ratajczak  
293 et al., 2017b). The way vegetation is organized in space has also been associated with the  
294 redistribution of water and nutrients across the landscape (Turnbull et al., 2010; Mayor  
295 et al., 2019). Altogether, because the vegetation spatial structure has been shown to be a  
296 good indicator of multiple dryland processes (erosion, functioning; Tongway and Ludwig,  
297 1994; Bautista et al., 2007; Berdugo et al., 2017a) and their resilience, recent approaches  
298 were developed to pinpoint the least resilient areas among a collection of snapshots of  
299 their spatial structure (Pichon et al., 2024a).

300

301 There are limitations associated with the use of these spatial indicators of resilience, just like  
302 there are for temporal resilience indicators. Spatial indicators can provide conflicting results  
303 about resilience (Rindi et al., 2018; Kéfi et al., 2024; Pichon et al., 2024a). If spatial patterns  
304 emerge from existing spatial heterogeneity of the soil, then, these spatial patterns do not  
305 necessarily reflect the resilience of the system (Nijp et al., 2019; Rodriguez-Iturbe et al.,  
306 2019) and comparing spatial indicators across different levels of soil spatial heterogeneity  
307 may lead to false positives in the detection of least resilient areas. Spatial indicators are also  
308 sensitive to the type of disturbances, such as grazing pressure *versus* drought for instance,  
309 which can provide biased signal of ongoing desertification (*i.e.*, type II errors; Schneider  
310 and Kéfi, 2016; Génin et al., 2018). The field study conducted by Oñatibia et al. (2023) is  
311 a good illustration of this as they found that dryland sites under high grazing pressure  
312 displayed the largest vegetation patches, contrary to what is expected for desertification  
313 caused by higher aridity, and that this was caused by unpalatable shrub invasion (Oñatibia  
314 and Aguiar, 2023, see also Pichon et al., 2025).

## 315 ON THE IMPORTANCE OF INTEGRATION

### 316 *Why? Reasons to expand desertification risk assessments*

317 One may argue that accounting for changes in ecosystem resilience only adds another  
318 layer of complexity into risk assessment. We outline below two reasons motivating the  
319 inclusion of these two components in a general risk assessment in the case of dryland  
320 ecosystems.

321

322 First, traditional desertification risk assessments, based on climate and human pressure,  
323 assume that drylands respond gradually to these pressures. However, dryland dynamics  
324 are driven by feedbacks at multiple scales (Schlesinger et al., 1990; D’Odorico et al., 2013),  
325 meaning that increased pressure does not always lead to gradual ecosystem changes  
326 (Berdugo et al., 2022; Sun et al., 2023). Non-linear ecosystem responses in drylands are  
327 often linked to abrupt transition (Demenocal et al., 2000; Xu et al., 2020; Lenton et al., 2023).  
328 Theoretical models have explored the conditions for abrupt changes in dryland vegetation  
329 cover (Kéfi et al., 2007b; Okin et al., 2009) or community composition (Bera et al., 2021;  
330 Pichon et al., 2024b), demonstrating that strong plant-soil, plant-atmospheric, or plant-  
331 plant feedbacks can trigger rapid changes (Kéfi et al., 2016; Berdugo et al., 2020). Specifically,  
332 studies on the abrupt desertification of the Sahara during the early Young Dryas indicate  
333 that such events can only be replicated in coupled vegetation-climate models when  
334 accounting for feedback between vegetation and ocean temperature (Demenocal et al.,  
335 2000).

336 Moving beyond previous risk assessment indices is therefore an opportunity to embrace the  
337 risk of non-linear and threshold dynamics in drylands. Indeed, anticipating potential non-  
338 linear changes the ability of drylands to provide ecosystem services has major implications  
339 for the socio-economic sustainability of human societies in drylands (IPCC, 2022; Reichhuber  
340 et al., 2023), because abrupt dynamics can be associated with high social costs. As such,  
341 from a decision-making perspective, accounting for such extreme-case scenarios allows  
342 making more robust decisions and can foster conservation efforts. In climate science for  
343 instance, emerging literature acknowledges the need to consider extreme climatic scenarios

344 to foster climate adaptation (Kemp et al., 2022).

345

346 An integrated risk assessment of drylands is also an opportunity to account for the  
347 adaptive capacity of dryland vegetation, a risk component omitted from desertification  
348 risk assessments (Fig. 1; Levin, 1998; Smit and Wandel, 2006; Engle, 2011). In drylands, the  
349 adaptive capacity can be related to different levels of organization of plant communities.  
350 This includes (i) the presence of facilitative interactions among plant species (Soliveres  
351 et al., 2015; Valiente-Banuet and Verdú, 2013), and as such, their ability to self-organize  
352 into vegetation patches (Rietkerk et al., 2021; Kéfi et al., 2024), (ii) species strategies or traits  
353 to cope with the lack of water (Song et al., 2024; Yan et al., 2025) or herbivory pressure  
354 (Blumenthal et al., 2020), and to adapt to changing pressures (Griffin-Nolan et al., 2019;  
355 Kramp et al., 2022). We consider the adaptive capacity of drylands as the *static* attributes  
356 of plant communities that enhance their resilience or their resistance (buffering ability) to  
357 disturbances (traits, facilitative interactions, etc.). By contrast, the resilience is the *dynamical*  
358 component of the vegetation, and complements the adaptive capacity (Fig. 1).

### 359 *How? Insights from other ecosystems*

360 Embedding of resilience indicators into an integrated risk assessment with exposure,  
361 resilience and adaptive capacity has been emerging very recently (Fig. 1). In a study about  
362 the Amazon, Flores et al. (2024) coupled information about (i) the intrinsic resilience of the  
363 Amazonian forest (meaning whether a region is in the forest state or has an alternative  
364 savannah state), (ii) the frequency of extreme climatic events, (iii) temperature projections,

365 and (iv) the protection status of Amazonian areas. Specifically, they considered the  
366 current protected areas and the land attributed to indigenous in the Amazon basin to  
367 account for the adaptive capacity of forest areas. They weighted all variables such that  
368 they had a similar importance and summed them to build an integrated index of the  
369 relative vulnerability of the Amazonian region. While their index cannot be quantitatively  
370 interpreted since (i) it aggregates very different axes of Amazonian forest vulnerability  
371 and (ii) different weights or subsets of variables would give different outcomes, it is  
372 an interesting approach to identify areas that are most at risk according to the selected  
373 variables. Moreover, it is, to our knowledge, the first risk assessment of an ecosystems,  
374 which explicitly includes ecosystem resilience.

375 Another interesting study in tropical forests combined information about climatic pressures,  
376 with temporal changes in biomass, primary production, or evapotranspiration, which  
377 allowed building tropical risk indices according to each of these ecosystem functions  
378 (Saatchi et al., 2021, see also Abel et al., 2020 for a similar risk assessment in tropical  
379 drylands that includes the economic status of countries). These studies highlighted that  
380 when assessing risk using different ecosystem functions, a given tropical area might be  
381 vulnerable based on a given function but resilient based on another one.

382 Aside from these two recent examples, other ecosystems also suffer from the lack of  
383 inclusion of resilience and adaptive capacities into risk analysis. In that sense, our  
384 perspective also applies to other ecosystem where resilience indicators are similar, and for  
385 which adaptive capacity variables have to be defined (Lecina-Diaz et al., 2021).

### *A minimal working example*

386

387 We illustrate some of these ideas using a global dryland dataset comprising 148 dryland  
388 sites sampled across the globe (Berdugo et al., 2017b). On each site, three images of the  
389 spatial structure of the vegetation were collected using satellite data and complemented  
390 by productivity timeseries. We refer to Supplementary Methods 2 for details on the data  
391 extraction.

392 Using the images of vegetation spatial structure, we computed the spatial autocorrelation  
393 of vegetation on the images, which served as the spatial indicator of resilience (Dakos  
394 et al., 2010). Using productivity timeseries, we computed the temporal autocorrelation  
395 of vegetation productivity (Scheffer et al., 2009). These spatial and temporal measures of  
396 resilience were then related with the exposure of drylands to new climatic conditions using  
397 the expected changes in precipitation by 2100 under a business as usual scenario. This  
398 allows building a risk assessment of dryland sites using spatial and temporal indicators of  
399 resilience, and their exposure (Fig. 3). Some sites can show low resilience (in space or in  
400 time) and are expected to change drastically in terms of precipitations (brown points in  
401 Fig. 3). They are therefore more at risk than other sites that are more resilient and expected  
402 to undergo relatively less change in climate (blue points; Fig. 3). Importantly, we see from  
403 this minimal example that resilience indicators alone are not sufficient to identify the most  
404 fragile sites, since many sites have similar resilience levels but are not expected to undergo  
405 similar changes in precipitation regimes in the next decades. From this representation, the  
406 next step is to build a risk index, which we discuss below.

## PERSPECTIVES FOR GLOBAL ASSESSMENT

407  
408 Scaling up ecosystem risk assessments to a global level requires integrating temporal and  
409 spatial indicators of ecosystem resilience alongside current and projected stressors, such as  
410 those arising from land use changes and climate variability (Fig. 1). While Fig. 3 presents a  
411 possible example of application for drylands, identifying the most relevant variables related  
412 to climate disturbances, human pressures, resilience metrics, and adaptive capacity of  
413 ecosystems remains complex (Hagenlocher et al., 2019; Lecina-Diaz et al., 2021). Moreover,  
414 how to best combine these components —whether by additive, multiplicative, or other  
415 integrative approaches— continues to be an open question. For example, depending on  
416 the indicators used for resilience using temporal and spatial information, or the exposure  
417 variables, the risk assessment of the collection of dryland sites used in the previous  
418 minimal example changes (Fig S4 and see Fig. S3 for another possible risk assessment of  
419 the dryland sites). Data availability also differs among components; for example, exposure  
420 and resilience indicators can often be derived from globally accessible remote sensing  
421 and climate data, whereas adaptive capacity assessment frequently requires field-based  
422 ecological and socio-economic data (see Table S1-S3 for details about possible variables  
423 for the resilience, exposure and adaptive capacity components of dryland risk and their  
424 availability at large scale).

425

426 Incorporating socio-economic indicators alongside ecological risk indices offers promising  
427 avenues to capture feedbacks between human activities and ecosystem dynamics (Reynolds

428 et al., 2007; Fraser et al., 2011). For instance, vegetation state changes such as shrub  
429 encroachment in drylands (Van Auken, 2000; D’Odorico et al., 2012; Bestelmeyer et al.,  
430 2018) are linked to socio-economic outcomes like livestock productivity loss (Anadón  
431 et al., 2014), which in turn affect local livelihoods. Similarly, increasing aridity in drylands  
432 poses risks not only to ecosystem functioning but also to water availability for agriculture  
433 and human use. Such integrative assessments are supported by extensive literature  
434 identifying socio-economic vulnerabilities and their interplay with environmental change  
435 (see dedicated reviews for desertification, *e.g.*, Fraser et al., 2011; Reid et al., 2014; Barbier  
436 and Hochard, 2018).

## 437 CONCLUSION

438 In ecological research, there is often a clear divide between studies focused on risk  
439 assessments and those addressing ecosystem resilience. Our bibliographic analysis highlights  
440 this ongoing dichotomy for dryland ecosystems and their desertification. While risk  
441 assessments commonly quantify vulnerability using static environmental indicators —such  
442 as climate variables, soil conditions, and vegetation cover at specific points in time—,  
443 resilience research emphasizes dynamic indicators derived from time series or spatial  
444 patterns that capture ecosystem responses over time. We argue that integrating resilience  
445 metrics into ecosystem risk assessments offers substantial benefits in an ever changing  
446 world.

447 Incorporating resilience indices enables a more comprehensive understanding of ecosystem  
448 dynamics across multiple timescales, particularly for ecosystems prone to non-linear

449 behaviors and abrupt state changes. Moving beyond traditional climate-based and  
450 human-induced degradation frameworks requires identifying the key drivers of ecosystem  
451 dynamics, resilience, and adaptive capacity to better anticipate and manage future disturbances.  
452 Emerging advances made in ecosystems beyond drylands provide valuable pathways  
453 for such integrative approaches. Using drylands as a case study, we demonstrate how  
454 this integrated framework can enhance the identification of vulnerable areas globally.  
455 Ultimately, applying this approach across ecosystems will be critical to improving the  
456 detection and management of fragile landscapes in a changing environment.



## GLOSSARY

- **Adaptive capacity** = ability of an ecological system to withstand and adapt to the changing pressures through its community composition and traits, the type of interactions between species, the functioning of the soil (Engle, 2011). This has also been called the adaptability of ecosystems (*e.g.*, in Flores et al., 2024).
- **Desertification** = According to the UNCCD (1994), it corresponds to land degradation in arid, semiarid, and dry sub-humid areas resulting from various factors, including climatic variation and human activities. In the literature, this has been proxied by changes in plant spatial patterns, soil carbon and nutrient availability, decrease in productivity, or species turnovers with shrub encroachment (see Main text).
- **Exposure** = the extent, intensity, and frequency to which drylands are exposed to climate and human disturbances, as well as how these disturbances are expected to change in the future (*e.g.*, due to increasing aridity, temperature, or droughts).
- **Resilience** = capacity of an ecological system to recover from a disturbance. It encompasses both the recovery time to bounce back to the state before the disturbance (local resilience; May, 1972), but also the ability of the system to withstand against strong disturbance without shifting to a possible alternative state (Holling resilience; Holling, 1973).
- **Resistance** = ability of an ecological system to withstand against a disturbance, often measured as the inverse of the deviation induced by the disturbance (*e.g.*, in Liu et al., 2022).
- **Self-organization** = Ability of the dryland vegetation to spatially aggregate into spatial vegetation patterns without underlying soil and resource spatial heterogeneity.

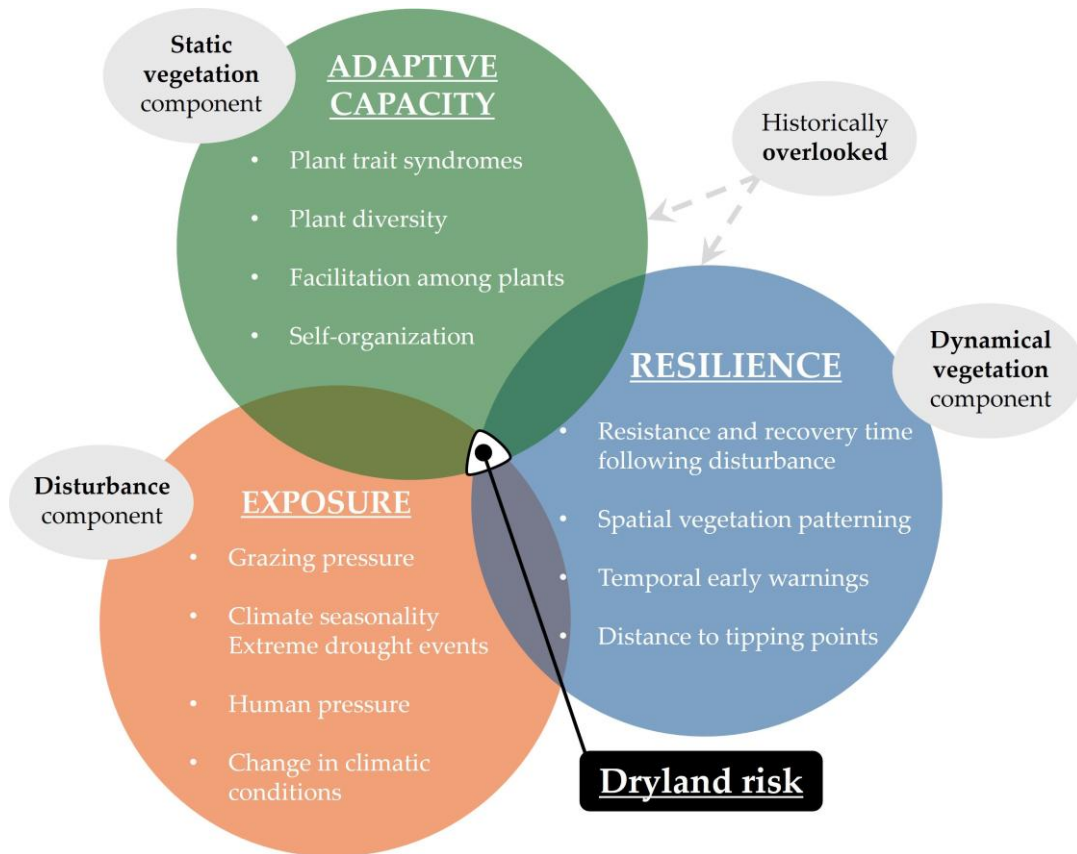
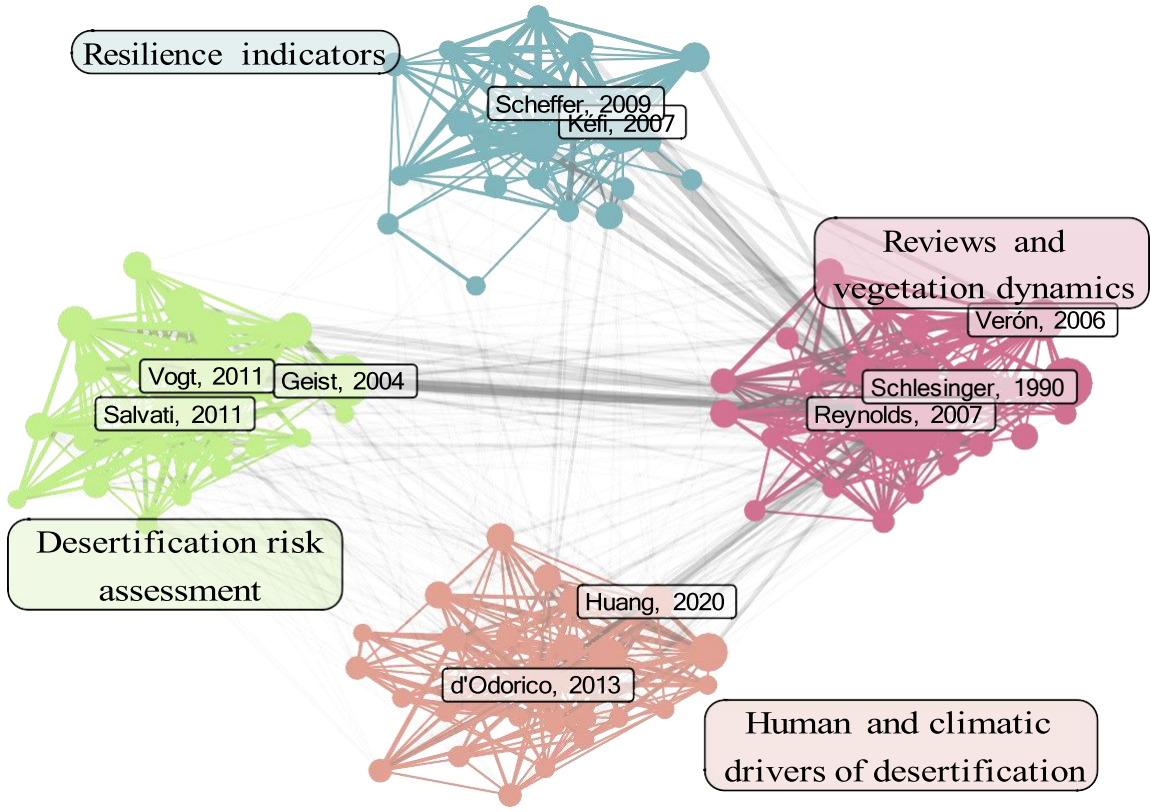


Figure 1: The three components of desertification risk, namely adaptive capacity, resilience and exposure to climatic and human disturbances.

# Co-Citation network of articles

a



# Main keywords

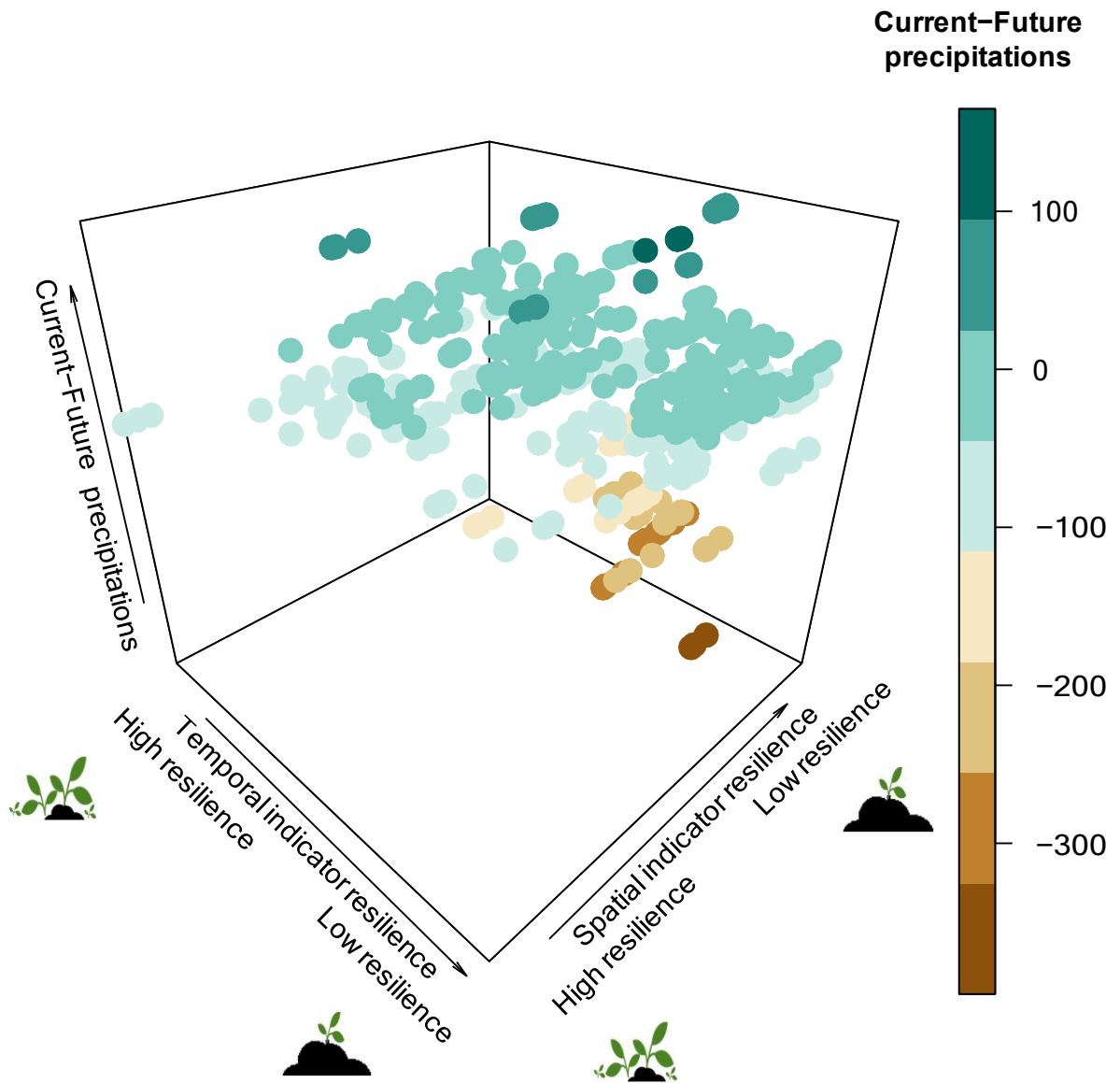
b



28  
Figure 2

458 **Caption for Fig. 2: Bibliographic analysis of resilience and desertification risk in drylands.**

459 (a) Co-citation network of the 100 most cited papers. Each node is an article that is linked to other  
460 articles if they have been co-cited in one of the retrieved publications. The width of the links is  
461 proportional to the number of times articles have been co-cited. The colors refer to the different  
462 clusters identified using a clustering algorithm (see Supplementary Method 1). (b) Frequency of  
463 occurrence of the keywords of the surveyed articles for each cluster identified in panel (a). The  
464 size and the intensity of the color of the words are proportional to their number of occurrences.  
465 We refer to Fig S5, S6 for smaller and larger versions of this co-citation network respectively made,  
466 which shows similar results. The network of keywords co-occurrence is given in Fig.S2. Detailed  
467 methods associated to this figure are available in Supplementary Method 1.



**Figure 3: Minimal example of desertification risk assessment combining dryland resilience and exposure to new climatic conditions.**

For 148 dryland sites, we combined temporal and spatial resilience indicators (here autocorrelation), and how mean annual precipitations will change by 2100 on each of those sites. This allows identifying the most fragile dryland sites, with low resilience and that will likely undergo drier conditions in the next decades (brown points in the bottom-right corner of the plot). Other versions with different exposure and resilience variables are available in Fig. S3.

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