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Natália Medeiros, Carlos Ordóñez-Parra, Elise Buisson, Fernando Silveira. Systematic review of field research reveals critical shortfalls for restoration of tropical grassy biomes. *Journal of Applied Ecology*, 2024, 61 (6), pp.1174-1186. 10.1111/1365-2664.14640 . hal-04593821

**HAL Id: hal-04593821**

**<https://hal.science/hal-04593821v1>**

Submitted on 6 Dec 2024

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# Systematic review of field research reveals critical shortfalls for restoration of tropical grassy biomes

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Funding information: Conselho Nacional de Desenvolvimento Científico e Tecnológico; Fundação de Amparo à Pesquisa do Estado de Minas Gerais; Coordenação de Aperfeiçoamento de Pessoal de Nível Superior

## 1 Abstract

1. Scientists and policymakers are becoming aware of the pressing need to
- 2 restore tropical grassy biomes (TGB), which are home to unique biodiversity and
- 3

4 provide essential ecosystem services to hundreds of millions of people. However,  
5 TGB face increasing threats, including the forest- and tree-centric approaches  
6 that promote their degradation, though we still lack a systematic assessment of  
7 where and how TGB restoration research has been done to guide policy and  
8 practice.

9 2. We synthesised knowledge on field restoration experiments by conducting a  
10 systematic literature review to map TGB restoration field studies, examine the  
11 association of restoration techniques and degradations sources, and investigate  
12 the diversity of indicators used to monitor restoration outcomes.

13 3. TGB restoration was concentrated at Brazilian and Australian savannas, with  
14 large blindspots in Asia, Africa, and northern and eastern South America. Studies  
15 were largely context-dependent, with an inconsistent usage of restoration  
16 techniques to different sources of degradation. Less than half of the indicators  
17 evaluated were monitored consistently through time, often using a low-  
18 dimensional approach related to ecosystem functioning. Few studies  
19 manipulated fire, herbivores and soils, the key drivers for the re-establishment of  
20 TGB dynamics. Unfortunately, many studies lacked negative (degraded  
21 ecosystems), positive (reference ecosystems) controls, or both, impairing  
22 attempts to robustly determine restoration outcomes.

23 4. Our overview of field research on TGB restoration highlights that research  
24 needs improvement to refine our ability to assess, plan, implement and monitor  
25 restoration. Severe issues with experimental designs and data reporting are  
26 identified as barriers to find generality and upscale TGB restoration to meet the  
27 goals of the UN Decade on Ecosystem Restoration.

28 5. *Synthesis and implications*: Our synthesis calls for enhanced field experiments,  
29 transparent data reporting, and quantitative syntheses to guide large-scale TGB  
30 restoration policies. The overall lack of knowledge on improving resilience and  
31 measuring outcomes hampers meaningful comparisons between studies and  
32 hinders synthetic views essential for determining appropriate restoration  
33 techniques for different degradation sources and selection of suitable indicators.  
34 To overcome the scarcity of reliable and transparent data supporting TGB  
35 restoration, we propose a simple checklist for minimum research reporting  
36 information and a more complete multilingual standardized guidelines to improve  
37 the experimental design of field experiments.

38

39 **Key-words:** ecological synthesis, grassland, savanna, shrubland, transparent  
40 science, reproducibility, guidelines

## 41        **1. Introduction**

42        The need to restore ecosystems has never been more urgent due to ever  
43        increasing degradation rates. As a response to this trend, the United Nations has  
44        launched the Decade on Ecosystem Restoration 2021-2030, aiming to catalyse  
45        global restoration efforts to reverse ecosystem degradation, protect biodiversity,  
46        mitigate climate change, and support human livelihoods. Our capacity to achieve  
47        such goals relies largely on knowledge built for the different stages of the  
48        restoration process, including assessment, planning, designing, implementing,  
49        management and monitoring (Gann et al., 2019). Such knowledge builds on  
50        multiple sources and field restoration experiments are essential to test the  
51        generality of hypotheses, calibrate and validate models, and to provide realistic  
52        cost-benefit estimates. Moreover, ecological restoration must also move forward  
53        and overcome Biome Awareness Disparity to include all types of biomes (Silveira  
54        et al., 2022; Török et al., 2021). The goals of the United Nations Decade of  
55        Ecosystem Restoration are ambitious but will remain utopic and unfeasible  
56        without truly embracing the diversity of Earth's ecosystems combined with solid  
57        theory, predictive models and accumulated empirical data.

58        Tropical grassy biomes (TGB) encompass the world's ancient tropical and  
59        subtropical megadiverse grasslands, shrublands and savannas. They are  
60        dominated by a continuous herbaceous layer with variable degrees of woody  
61        cover (Bond, 2019). TGB have evolved with fire and large herbivores playing a  
62        major role in their functioning, structure, and dynamics (Buisson et al., 2019;  
63        Veldman et al., 2015). In addition to these two drivers, edaphic factors can also  
64        shape and maintain these naturally open-canopy ecosystems (Buisson et al.,  
65        2019). Despite their megadiversity and provision of vital ecosystem services for

66 hundreds of millions of people (Bengtsson et al., 2019; Lehmann & Parr, 2016),  
67 TGB cover and biodiversity are declining due to multiple pressures, such as  
68 agricultural conversion, livestock production, mining, urbanization, afforestation,  
69 exotic species invasion, novel fire regimes, woody encroachment and climate  
70 change (Bardgett et al., 2021; Veldman et al., 2015).

71         Threats to TGB are not only due to different degradation pressures but  
72 also because of historical misunderstandings, undervaluation, and insufficient  
73 knowledge and protection (Parr et al., 2014; Pausas & Bond, 2019; Pilon et al.,  
74 2023; Silveira et al., 2022; Tölgyesi et al., 2022). Despite covering nearly 40% of  
75 the land (Dinerstein et al., 2017), a restoration policy, science, and practice  
76 framework for TGB is still in their infancy (Silveira et al., 2022) given that clear  
77 definitions of reference ecosystems have emerged only recently (Bond & Parr,  
78 2010; Veldman et al., 2015). For example, despite the long history of TGB  
79 degradation, the first field TGB restoration experiment (Lovera & Cuenca, 1996)  
80 was published nearly a century after Warming's (1895) seminal plant ecology  
81 book based on Neotropical savannas (Fig. 1). This relatively recent restoration  
82 history resulted in misguided actions (Silveira et al., 2022), such as tree-oriented,  
83 and often carbon-based, practices that continuously have been expanding on  
84 TGB (Fagan et al., 2022; Nerlekar et al., 2023). Therefore, TGB are extensively  
85 threatened by multiple degradation pressures, scientific overlooked and  
86 misguided practices.

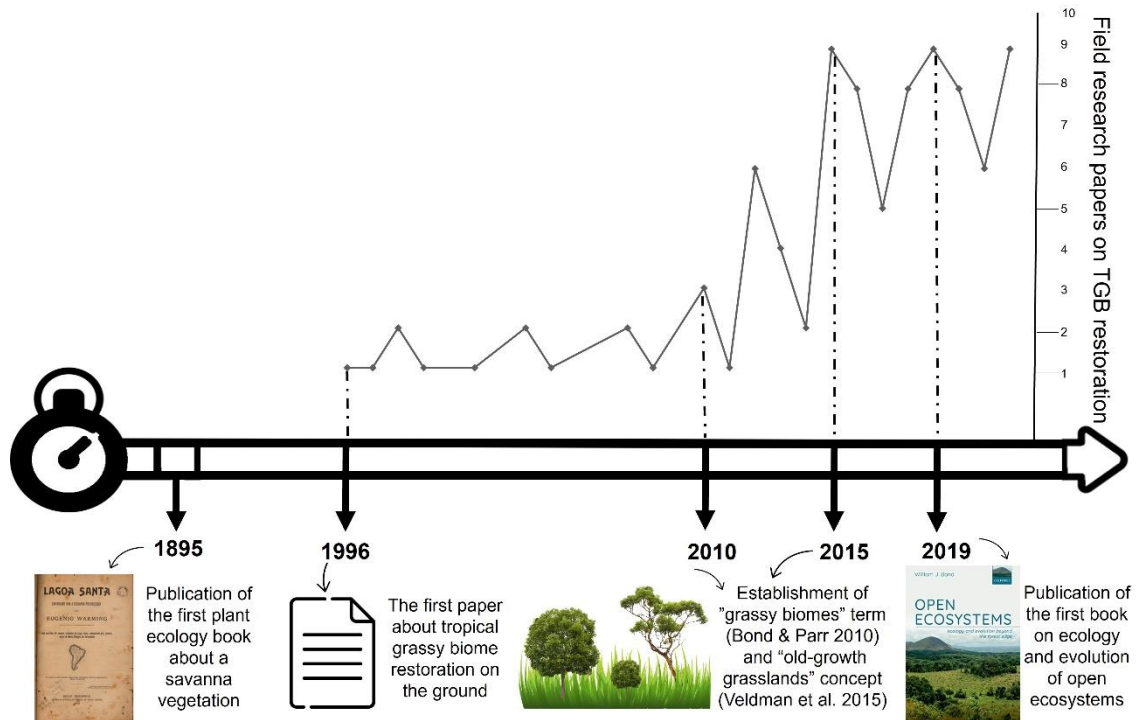
87         Although challenging, recent efforts have attempted to increase the  
88 knowledge underpinning TGB restoration (Buisson et al., 2019). Such studies  
89 have demonstrated the need for active interventions given the extremely slow  
90 recovery rates and natural regeneration of TGB (Nerlekar & Veldman, 2020).

91 Proper management of livestock and wild herbivores, tree and shrub control (i.e.,  
92 removal and cutting), invasive species control and prescribed fires are among the  
93 key strategies to restore TGB (Buisson et al., 2019). The efficiency of such  
94 strategies should be evaluated by long-term monitoring of species composition,  
95 community structure and ecosystem functioning, which should assess the  
96 resilience to endogenous disturbances (Buisson et al., 2019). Nonetheless, TGB  
97 restoration is still constrained by an overall lack of knowledge on how to improve  
98 ecosystem resilience (Buisson et al., 2019, 2022). Therefore, mapping field  
99 restoration experiments is pivotal to precisely identify bottlenecks in TGB  
100 restoration and overcome practical challenges.

101 Several global reviews on restoration research have emerged (see  
102 Atkinson et al., 2022; Wortley et al., 2013) but, in contrast to forests, syntheses  
103 specifically focusing on TGB restoration are beginning to emerge only recently  
104 on a regional scale (Carbutt & Kirkman, 2022; Medeiros et al., 2022; Pilon et al.,  
105 2023). Broad and detailed mapping of field restoration experiments  
106 encompassing sources of degradation, restoration strategies and indicators  
107 usage is needed to support the target agenda for TGB restoration (Buisson et al.,  
108 2021). Such overview will provide the baseline for developing novel and refined  
109 strategies for TGB habitat-tailored interventions. Therefore, here, we aim to fill  
110 this knowledge gap by conducting a systematic literature survey and providing  
111 the first empirical synthesis of TGB restoration research, along with the  
112 techniques and approaches used. Specifically, we mapped restoration field  
113 research, identified the major drivers of habitat loss, evaluated the most used  
114 restoration techniques, and assessed the diversity of monitoring strategies.  
115 Finally, to tackle the remarkable disparity found in data reporting in our database,

116 we provide a Multilanguage checklist of minimum standards for data reporting on  
 117 TGB restoration to foster future research designs and quantitative syntheses.

118



119

120 **Figure 1** – Timeline showing cornerstones in the history of tropical grassy biomes  
 121 (TGB) ecology and restoration. The curve above the timeline shows the recent  
 122 and poorly developed restoration framework with the publication of very few  
 123 papers addressing field restoration papers.

124

## 125 2. Methods

### 126 2.1. Literature review

127 To assess where and how TGB restoration research is being conducted,  
 128 we carried out a systematic literature review of peer-reviewed articles that  
 129 conducted field restoration research. We used both the Web of Science and  
 130 Scopus databases to perform the searches, considering studies published in  
 131 English from January 1945 to December 2022 and using the following keywords:



132 (“grassy biome” OR “grassland” OR “meadow” OR “prairie” OR “rangeland” OR  
133 “savanna\*” OR “steppe” OR “shrubland” OR “cerrado”) AND (“afforestation” OR  
134 “afforested” OR “restoration” OR “restored” OR “recovery” OR “recovered” OR  
135 “reforestation” OR “reforested” OR “rehabilitation” OR “rehabilitated” OR  
136 “revegetation” OR “revegetate”) AND (“tropical” OR “subtropical”). Given the wide  
137 diversity of terms to describe TGB (Bond, 2019) and commonly misused terms,  
138 we used all these words to encompass as much restoration research as possible  
139 (a list of data sources used is provided in S1).

140           Research on ecological restoration should aim to improve the state and/or  
141 functionality of a degraded, damaged, or destroyed ecosystem towards re-  
142 establishing the native ecosystem (Gann et al., 2019). The initial state of  
143 degradation is key for dictating the possibility of restoration as well as the most  
144 appropriate approach to be undertaken. In some cases, a novel ecosystem needs  
145 to be created due to high levels of degradation (Hobbs et al., 2009). We  
146 considered an ecosystem as degraded or damaged when it experienced  
147 deleterious impacts that reduced biodiversity and ecosystem functioning (Gann  
148 et al., 2019) due to exogenous disturbances or shifts in endogenous disturbance  
149 regimes. We assessed degradation as quantitatively (time-zero data) or  
150 qualitatively self-reported. In the last case, the site targeted for restoration must  
151 have had some anthropogenic impact (e.g., oil spill, mechanical clearance,  
152 human-induced fire, etc.) or previous land use (e.g., mining, livestock production,  
153 farming, etc.) that explicitly resulted in degradation. Therefore, degraded sites did  
154 not necessarily imply having a negative control. We considered that research had  
155 a negative control when restoration outcomes were compared with data collected  
156 at a time-zero, at a degraded site without interventions or undergoing

157 degradation. Furthermore, we considered that research had a positive control  
158 when studies compared restoration outcomes to a target reference ecosystem.

159         In the first screening, we checked the paper title and abstract to exclude  
160 studies focusing on improving site conditions with objectives unrelated to  
161 ecological restoration, such as crop planting and pastureland for livestock. We  
162 also exclude studies done under laboratory and greenhouse conditions. To refine  
163 our database, we ran a second screening evaluating the full text of remaining  
164 papers to assess whether studies (1) were conducted in tropical or subtropical  
165 grassy biomes; (2) disclosed information on degradation, and (3) applied at least  
166 one restoration technique aiming for ecological restoration. To match the first  
167 criterion, research must have been done within 30 to -30° latitude and should be  
168 classified as a grassland, shrubland or savanna biome (Dinerstein et al., 2017).  
169 We decided to exclude wetlands and ecotones even if located within the  
170 boundaries of TGB due to their unique characteristics, functioning and restoration  
171 needs. To match the second criterion, research must have been done on a  
172 degraded site and should not have been restricted to the management of native  
173 areas (e.g., fire management inside a savanna protected area). Thus, we  
174 included papers reporting perturbations in the fire/grazing regime but excluded  
175 those aiming to understand the role of herbivores and fire in TGB dynamics even  
176 if they provide knowledge support to guide future restoration and conservation  
177 management (e.g., Alvarado et al., 2018; Pilon et al., 2021). In the end, we only  
178 included 15 papers that clearly provided enough information on changes in fire  
179 regime as a degradation source (Table 5 in S1) and 27 papers that reported  
180 grazing pressure due to livestock as a degradation source (Table 6 in S1). Finally,  
181 to match the third criterion, research should have been carried out an intervention

182 within the restoration *continuum* (Gann et al., 2019) ultimately aiming to  
183 (re)establishing a native TGB.

184

## 185 2.2. *Data collection and analyses*

186 To map TGB restoration, we retrieved geographic coordinates, biome type  
187 and sources of degradation for each site from eligible papers. We plotted the  
188 geographic coordinates of each field experiment using QGIS and classified biome  
189 types as savanna, grassland, or shrubland based on original descriptions. We  
190 plotted the geographical coordinate of the restoration site into a global biome map  
191 (Dinerstein et al., 2017) for 28% of the cases in which the reference ecosystem  
192 was unspecified and upon the use of ambiguous terms (i.e. open forest). Despite  
193 inconsistencies with more precise, local-scale maps, we chose Dinerstein et al.  
194 (2017) as a source of mapping because it uses a hierarchical classification and  
195 is a widely used system for biome classification worldwide allowing our study to  
196 be comparable to others. Coordinates falling outside the area covered by TGB  
197 were excluded. Papers for which we were unable to identify the reference  
198 ecosystems (i.e. used ambiguous terms with no geographical coordinates) were  
199 also excluded.

200 We classified the sources of degradation into few categories even if they  
201 often involve multiple drivers of loss of biodiversity and ecosystem functioning.  
202 For example, crop plantation often involves soil disturbance, fertilization, and  
203 invasive species. Hence, despite the diversity of disturbance histories, we  
204 operationally classified sources of disturbance into the following categories:  
205 afforestation, agriculture, exotic species, fire, livestock, and mining, or classified

206 studies as having two and three sources of degradation (more details in Table 2  
207 in S1). Furthermore, we were unable to classify three studies that did not provide  
208 clear causes of degradation even after contacting corresponding authors.

209 We recorded the degradation and restoration time length based on data  
210 provided by the original studies. To identify the most common strategies for TGB  
211 restoration, we extracted information on manipulation of the main drivers (fire,  
212 herbivores and soil), and the restoration techniques provided in the original  
213 papers (natural regeneration, seed sowing, planting, topsoil transfer, etc., or a  
214 combination – see Table 4 in S1 for detailed information). We considered natural  
215 regeneration as a technique of passive restoration in cases where the  
216 regeneration process started after the cessation of an exogenous disturbance  
217 that has caused degradation. Hence, resilience after endogenous disturbances  
218 (i.e. fire and grazing) was not considered as a restoration technique, because, in  
219 this case, disturbances are part of TGB functioning rather than a source of  
220 degradation. Finally, we examined the diversity of indicators used to measure  
221 restoration success (e.g., Prach et al., 2019; Ruiz-Jaen & Aide, 2005; Wortley et  
222 al., 2013), the frequency intervals and length of monitoring. To accommodate the  
223 diversity of indicators into workable categories, we classified all indicators into the  
224 six attributes or categories use by the Society for Ecological Restoration (SER):  
225 absence of threats, ecosystem function, external changes, physical conditions,  
226 species composition and structural diversity (Gann et al., 2019).

227 Because some papers assessed restoration outcomes in more than one  
228 degraded area and/or applied more than one restoration treatment, we  
229 considered each independent restoration experiment as our sample unit.  
230 However, because papers employed the same indicators to measure restoration

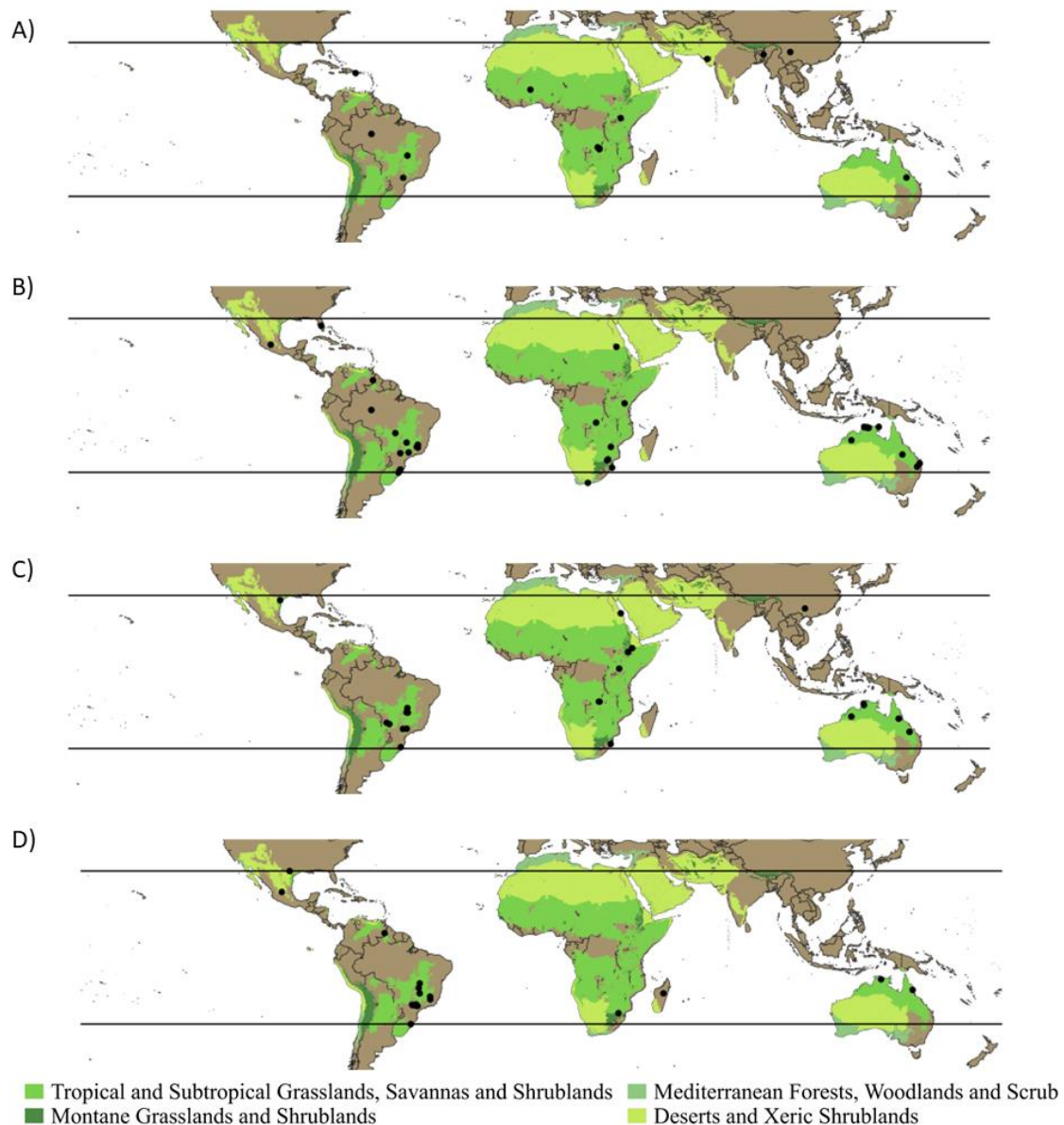
231 success for monitoring analyses, we considered the paper as our sample unit to  
232 avoid inflating our database. We built alluvial diagrams connecting the sources of  
233 degradation to restoration techniques when both data were available. Moreover,  
234 we explored the overlap in the use of the six SER attributes using Venn diagrams.  
235 All analyses and figures were made using R and Inkscape software.

236

### 237 **3. Results**

238 After excluding duplicates, we retrieved 1,256 papers, but only 90 papers  
239 matched our inclusion criteria (Fig.1 - S1). The first paper on TGB restoration was  
240 published in 1996 and despite a recent increase on average publication/year, the  
241 total number of papers was never above 10/year (Fig. 1). These 90 papers  
242 generated 155 TGB field restoration experiments. Most experiments were  
243 concentrated in Brazil (50%), Australia (17%), South Africa (6%) and USA (6%),  
244 with the other 13 countries accounting for less than 5% each (Fig. 2). We noticed  
245 large unstudied TGB in Asia, sub-Saharan Africa, and North-western South  
246 America. Furthermore, most restoration research aimed at restoring savannas  
247 (61%), followed by grasslands (32%) and shrublands (8%). The Brazilian Cerrado  
248 was the most commonly biome target for restoration, whereas other biomes  
249 appeared only rarely in the database.

250 Restoration experiments were implemented in areas with a broad diversity  
251 of degradation sources. Forty-one percent of restoration sites were degraded by  
252 multiple sources, with the combination of livestock and exotic species (25%)



253

254 **Figure 2** – Systematic mapping of tropical and sub-tropical grassy biome (TGB)  
 255 restoration. Each field restoration experiment conducted at different biomes  
 256 (*sensu* Dinerstein et al., 2017) are represented according to their restoration  
 257 control: (a) both positive and negative controls; (b) only positive control (reference  
 258 TGB site); (c) only negative control (degraded site without restoration  
 259 intervention); (d) no restoration control (neither positive nor negative controls).

260

261 appearing as the most frequent degradation cause. Additional degradation  
262 causes included mining (14%), livestock (10%), agriculture (8%), exotic species  
263 (6%), perturbation of fire regimes (6%), combination of agriculture, livestock and  
264 exotic species (5%), and afforestation (4%). Other minor causes (1-3% of cases)  
265 include woody encroachment, desertification, oil spill, urban development, and  
266 diverse combinations of degradation sources (Tables 1 and 2 in S1). Three  
267 papers provided equivocal causes creating bare soils and were classified as  
268 unknown causes.

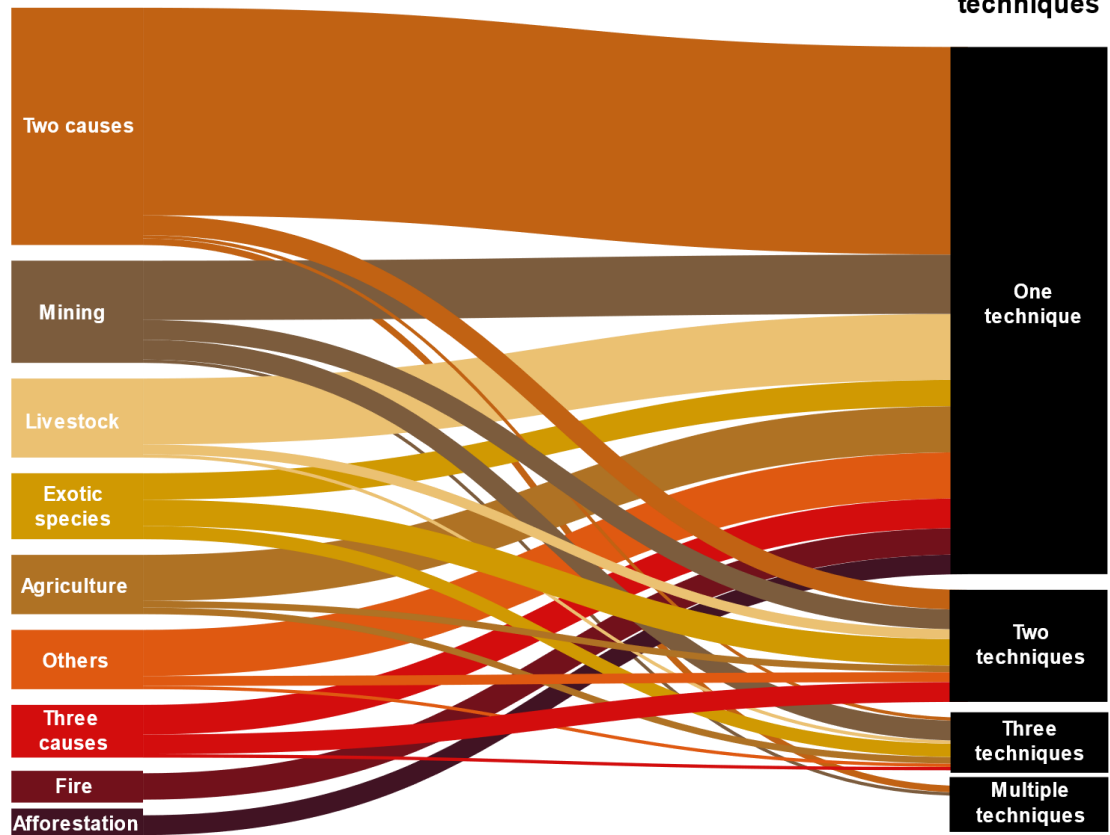
269         Only 29% of studies quantified degradation state of time-zero and the  
270 remaining provided qualitatively assessments of degradation. Eleven papers with  
271 sites degraded by fire qualitatively assessed changes in at least one dimension  
272 of fire regime (severity, frequency or, seasonality) while only four fire-related  
273 papers support the degradation by fire quantitatively. Those fire degraded papers  
274 encompassed 23 sites from which 13 were restored using natural regeneration  
275 while only five sites applied some fire management. Regarding the grazing  
276 pressure, 19 out of 27 papers qualitatively reported livestock as a degradation  
277 source, and eight papers quantified the effects of overgrazing. Furthermore, we  
278 also evaluated how long sites had been under degradation and for how long  
279 restoration experiments had been implemented. Degradation time ranged from a  
280 year to more than a century, but 67% of the papers did not disclose this  
281 information precisely. Restoration experiments were relatively recent with more  
282 than half of the cases occurring from one to 10 years (59%), and 12% spanned  
283 more than 30 years of intervention. Unfortunately, 29% of the experiments did not  
284 provide precise data on the onset of the experiments.

285 Despite most TGB restoration experiments conducted in sites with multiple  
286 degradation sources, 73% applied a single restoration technique (Fig. 3A).  
287 Natural regeneration (22.3%) and fire management (21.8%) were the most  
288 commonly used techniques, followed by physical interventions (9.5%), planting  
289 or seed sowing species (9.1%), chemical interventions (4.5%), gradual livestock  
290 removal (3.2%), and the combination of chemical intervention with physical  
291 intervention and planting or seed sowing (3.2%). Other less used techniques  
292 include translocation, hay transfer, topsoil spreading and the combination of  
293 different techniques (Tables 3 and 4 in S1). When we explored the relationship  
294 between the different combinations of degradation sources and restoration  
295 techniques applied, we found the same general pattern: the dominant usage of  
296 one technique for different types of degradation scenarios (Fig. 3B). Surprisingly,  
297 40% of restoration experiments did not manipulate any driver of TGB distribution.  
298 Currently, 28% of restoration experiments managed soil properties, 23%  
299 managed fire, and 4% managed large herbivores. Some studies manipulated fire  
300 and soil simultaneously (3%) whereas others manipulated both fire and  
301 herbivores (2%).

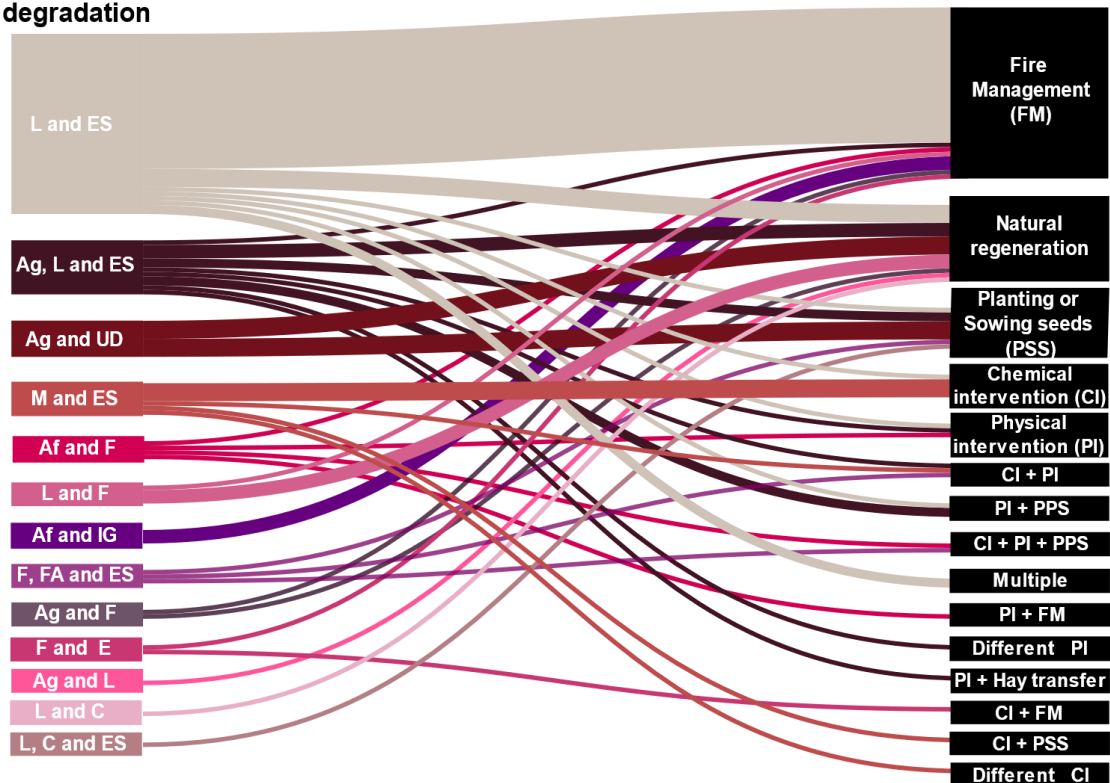
302 We assessed aspects regarding evaluation of restoration outcomes and  
303 surprisingly found that 32% of experiments lacked either a positive control (native  
304 reference ecosystem) or a negative control (degraded site with no intervention or  
305 undergoing degradation). Only 12% of cases implemented both controls, while  
306 37% compared the restoration site to a positive control and 19% compared to a  
307 negative control (Fig. 2). Studies used 1019 indicators to measure restoration  
308 success, encompassing a wide range of measurements. Unfortunately, most  
309 indicators were not monitored through time or information in the original papers



A)  
Sources of degradation



B)  
Two or three sources of degradation



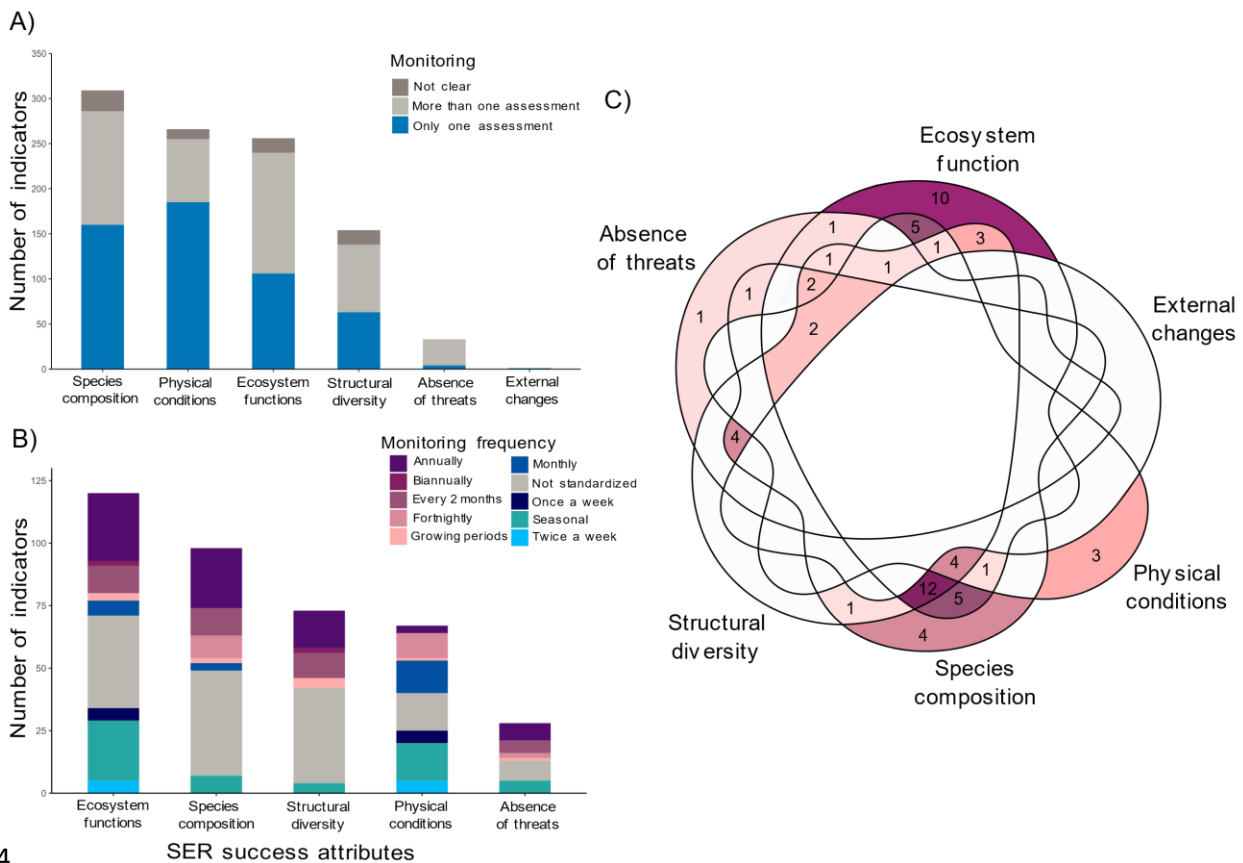
311 **Figure 3** – A poor match between different sources of degradation (left) to  
 312 restoration technique (right) applied to tropical grassy biomes. The general  
 313 pattern is presented in figure 3A and the degradation sources combinations are  
 314 presented in detail in figure 3B as the following: livestock (L), exotic species (ES);  
 315 agriculture (Ag), urban development (UD), mining (M), afforestation (Af), fire (F),  
 316 feral animals (FA), invasive grass (IG), encroachment (E), chopping (C). In both  
 317 figures (A and B), the width of lines linking the source of degradation and  
 318 restoration technique indicates how many times each type of technique was  
 319 applied for the same degradation context.

320

321

322

323



324

325 **Figure 4** – Monitoring interval frequency for indicators of restoration success in  
 326 tropical grassy biomes (A-B). Indicators were classified into SER success  
 327 attribute categories and monitoring restoration success has been historically  
 328 done mostly with low-dimensional approaches as shown by low overlap at all six  
 329 SER success attributes for the 51 papers that applied monitoring (B).

330

331 was not clearly provided (Fig. 4A). As a result, only 501 indicators were monitored  
332 temporally with monitoring lengths ranging from weeks to years. Despite a wide  
333 diversity of attempts to evaluate restoration success over time (Fig. 4B),  
334 monitoring was not consistent through time, suggesting opportunistically  
335 assessments. Indicators used to monitor restoration success were mostly  
336 concentrated in ecosystem functioning (150 indicators) and species composition  
337 (150). Structural diversity (91), physical conditions (81) and absence of threats  
338 (29) were less monitored whereas 'external changes' was the only attribute  
339 without temporal assessment. Unfortunately, no study evaluated all six SER  
340 attributes simultaneously over time, with most cases (85%) of monitoring using  
341 from one to three attributes (Fig. 4C). The combination of species composition,  
342 structural diversity and ecosystem function attributes was the most frequent  
343 approach in TGB restoration experiments.

344

## 345 **Discussion**

346 Our synthesis of TGB restoration highlights multiple methodological  
347 shortfalls, incomplete data reporting and several blindspots preventing overall  
348 assessments on restoration outcomes. Key knowledge improvements identified  
349 were the incorporation of the ecosystem functioning drivers (Buisson et al., 2019)  
350 into field experimental settings and the establishment minimum standards of data  
351 reporting to evaluate outcomes. Context-dependency identified in TGB  
352 experiments prevents assessment of overall recommendations of restoration  
353 techniques and monitoring. Identifying the source of degradation is key for  
354 developing appropriate restoration strategies (Holl et al., 2023), however, one  
355 third of restoration experiments applied natural regeneration as a single

356 restoration technique regardless of the degradation source. Whenever sites were  
357 monitored, length was shorter than recommended for TGB (Nerlekar & Veldman,  
358 2020). Hence, ecologically-sound restoration and monitoring frameworks should  
359 be implemented in future restoration studies.

360         Incorporating TGB functioning into restoration practice is imperative for  
361 enhancing ecosystem resilience (Coutinho et al., 2023). Despite TGB having  
362 evolved with endogenous disturbances and specific edaphic conditions (Buisson  
363 et al., 2019; Veldman et al., 2015), only 55% of the experiments manipulated fire,  
364 herbivores, or soils, and only 5% simultaneously manipulate two drivers.  
365 Excluding disturbances in TGB has been proven unwarranted (Alvarado et al.,  
366 2018) and restoration of disturbance regimes are proposed as a critical  
367 restoration tool (Buisson et al., 2019). Soil chemical, physical and biological  
368 properties are key to prevent biological invasion and should be targeted for  
369 recovering TGB functionality. We thus highlight that restoration frameworks in  
370 TGB must abandon forest-centric paradigms to focus on re-establishing  
371 resilience to endogenous disturbances and the edaphic properties (Gerrits et al.,  
372 2023; Lira-Martins et al., 2022), otherwise, restored TGB are unlikely to deliver  
373 positive long-term outcomes (Giles et al., 2022).

374         TGB restoration should address the multiple degradation sources that  
375 threaten their conservation and resilience (Bardgett et al., 2021). Multiple active  
376 restoration techniques are required to restore TGB under multiple degradation  
377 sources (Pilon et al., 2023) since they can produce profound impacts, such as  
378 complete removal of soils and subsoils as well as legacies of fertilizers and  
379 herbicides (Török et al., 2021; Wolfsdorf et al., 2021). Nevertheless, 73% of TGB  
380 restoration experiments have applied a single technique, mostly natural

381 regeneration and fire management, regardless of the degradation source. This is  
382 problematic because restoration techniques should be linked to degradation  
383 sources (Holl et al., 2023) which have lasting influence on biodiversity recovery  
384 (Atkinson et al., 2022). Moreover, natural regeneration has a limited capacity to  
385 restore some TGB (Cava et al., 2018; Nerlekar & Veldman, 2020) and likely  
386 results in pronounced recovery debts (Moreno-Mateos et al., 2017). Fire  
387 management, on the other hand, is a recommended technique for TGB  
388 restoration as it represents the reintroduction of a natural endogenous  
389 disturbance driver. However, caution should be taken because benefits largely  
390 outweigh potential negative effects of fire reintroduction (DAWE 2022).  
391 Therefore, we recommend the implementation of multiple active techniques that  
392 have proven positive effects on TGB restoration such as fire management and  
393 topsoil translocation (Gerrits et al., 2023; Lira-Martins et al., 2022).

394 Inconsistent methods to evaluate TGB restoration represent another  
395 barrier to support decision-making and adjusting legislation. Monitoring was  
396 mostly restricted to two or three attributes, with no study addressing the six  
397 attributes recommended by SER (Gann et al., 2019). This result aligns with  
398 previous reviews (Ruiz-Jean & Aide, 2005; Wortley et al., 2013) of restoration  
399 outcomes. Furthermore, monitoring had no consistent intervals and spanned very  
400 short periods of time (69% of studies <5 years), which is insufficient to determine  
401 restoration trajectories in TGB (Nerlekar & Veldman, 2020). The first steps  
402 towards adequate assessments of TGB restoration are clearly to determine the  
403 reference ecosystem, report time-zero data and to establish control sites (Gann  
404 et al., 2019). Issues concerning the reference ecosystem have already emerged  
405 (Ruiz-Jean & Aide, 2005; Wortley et al., 2013), highlighting the need for a clear

406 reference site and the need to establish at least two sites to capture the target  
407 ecosystem variance. We had to exclude 27 papers for not reporting the reference  
408 ecosystem, while a third of experiments lacked any control site and most of them  
409 lacked data to confirm the degradation state. Therefore, we recommend  
410 experiments to report time-zero data as well as clearly determine the reference  
411 ecosystem and to include both positive and negative controls to provide a broad  
412 understanding of restoration trajectories through monitoring.

413         The lack of time-zero reporting is especially concerning in cases of novel  
414 fire regimes and grazing pressure because those are endogenous disturbance in  
415 TGB. In such cases, it is imperative the report of historical data of fire and  
416 herbivore regimes instead of qualitative reports. Changes in fire regime patterns  
417 can have different impacts depending on the changes in fire components (i.e.,  
418 intensity, frequency, seasonality, and type) and characteristics (i.e., severity,  
419 extent, patchiness, ignition type). Fire events can either promote growth of many  
420 TGB species and inhibit woody plant encroachment or do the opposite (DAWE  
421 2022). Understanding how fire and herbivores affect vegetation structure as well  
422 as species composition and ecosystem resilience is vital to select adequate  
423 restoration techniques. TGB restoration experiments in sites degraded by  
424 perturbations in fire regime and overgrazing must include historical data of fire  
425 and herbivore regimes and, for fire degradation, it should clearly discriminate  
426 which fire component and characteristic changed.

427         Future TGB restoration experiments should be expanded throughout the  
428 tropics since research were geographically concentrated in Brazilian and  
429 Australian savannas. The relative high concentration of studies in Brazil is  
430 explained by increasing land use change in the Cerrado, the most biodiverse

431 savanna in the world (Strassbourg et al., 2017). On the other hand, montane  
432 grasslands and shrublands have been also increasingly threatened (Christmann  
433 & Menor, 2021), but were significant blindspots in our review. These biomes have  
434 high diversity, endemism (Madriñan et al., 2013) and provide many ecosystem  
435 services (Mengist et al., 2020), but still remain poorly studied (Christmann &  
436 Menor, 2021). Moreover, we also found absence of research studies in African  
437 and Indian TGB, regions where biodiversity studies have been raising only  
438 recently (Nerlekar et al., 2022; Rabarivola et al., 2019) but where open  
439 ecosystems are increasingly threatened by agriculture and afforestation  
440 (Nerlekar et al., 2023). The misinterpretation of African and Asian savannas as  
441 wastelands with low conservation value has been pointed as a legacy of colonial  
442 forestry (Lahiri et al., 2023; Nerlekar et al., 2022), though old-growth grasslands  
443 and savannas are recognized at least one million years BP (Ratnam et al., 2016).  
444 Such biodiversity knowledge shortfall and misguided policies undermine TGB  
445 restoration efforts. We thus reinforce the need of a better assessment of montane  
446 grasslands and shrublands as well as African (Nsikani et al., 2023) and Indian  
447 TGB restoration efforts (Lahiri et al., 2023).

448         Our review highlights the idiosyncratic essence of TGB restoration and the  
449 need to enhance field experiments to support quantitative syntheses and meta-  
450 analyses guiding large-scale restoration policy and practice (e.g., Gerrits et al.,  
451 2023; Pilon et al., 2023). We also show that TGB restoration is still constrained  
452 by an overall lack of knowledge on how to improve ecosystem resilience and how  
453 to measure restoration success in ecologically and functionally meaningful ways.  
454 Both the effectiveness of restoration techniques and the transparent details of  
455 monitoring practices are not fully comparable among studies, preventing us to

456 synthesize practical knowledge that is essential to determine appropriate  
457 restoration techniques for different degradation sources.

458         To overcome methodological shortcomings, incomplete data reporting and  
459 context-dependency key recommendations include incorporating ecosystem  
460 functioning drivers into experimental settings, establishing minimum data  
461 reporting standards, and considering the source of degradation for effective  
462 restoration strategies to allow tracking restoration outcomes beyond the focused  
463 experiment. Concerns arose about the lack of reporting historical data for novel  
464 fire regimes and grazing pressure, emphasizing the need to understand the  
465 impacts of endogenous disturbances on TGB. The geographical biases towards  
466 Brazilian and Australian savannas urges the expansion of restoration, particularly  
467 in montane grasslands in African and Indian TGB. These studies need to  
468 incorporate TGB drivers, use of active techniques to accelerate natural  
469 regeneration and carefully select suitable set of multidimensional indicators  
470 based on SER recommendations (Gann et al., 2019).

471

472 **Practical guidelines with minimum standards for data reporting and**  
473 **enhanced experimental settings**

474         Emerging frameworks in restoration science and practice are expected  
475 under the United Nations Decade on Ecosystem Restoration (2021-2030) (e.g.,  
476 Copeland et al., 2021). However, persistent knowledge gaps prevent us from  
477 synthesizing knowledge on TGB restoration to inform future policy and practice.  
478 Our review clearly points out the urgent need of additional field restoration  
479 experiments in TGB and the need to overcome critical issues in primary research



480 that preclude comparability and reproducibility, which dictates the reliability and  
 481 generality of methods and results (Powers & Hampton, 2019). Hence, we  
 482 propose a simple checklist (Table 1) and a multilingual practical guideline for  
 483 minimum standards of data reporting and enhancement of field TGB restoration  
 484 experiment designs.

485 Table 1 – Elementary restoration research information at site level

<b>Site:</b>		
<b>Reference site:</b>		
<b>Degradation source(s):</b>		
<b>Restoration technique(s):</b>		
<b>Restoration management:</b>		
<b>Attributes:</b>	Star recovery	Monitoring measurement
Absence of threats		
Physical conditions		
Species composition		
Structural diversity		
Ecosystem function		
External changes		
★ Extremely low recovery★★ Low recovery★★★ Intermediate recovery★★★★ Great recovery★★★★★ Highly similar to reference ecosystem		

486

487 Global quantitative comparisons among TGB restoration experiments are  
 488 prevented due to poor data reporting and a wide variation of degradation sources,  
 489 restoration techniques and selection of monitoring indicators. Restoration science  
 490 is often context-dependent and cross-studies comparisons are not always  
 491 possible (Gerstner et al., 2017). Nevertheless, clear, detailed, and transparent  
 492 data reporting has the potential to provide support for overcoming challenges in  
 493 restoration outcome predictions (Brudvig & Catano, 2021; Gerstner et al., 2017).  
 494 For example, predictive relative recovery trajectories over time allowed for model  
 495 building in forest restoration (Poorter et al., 2021) but this step is currently  
 496 unachievable for TGB due to the paucity of empirical data and poor data  
 497 reporting. Failure to report methods, code, and results in sufficient detail to allow

498 correct interpretation, replicability, and data extraction, severely compromises  
499 cross-studies comparisons and attempts to synthesize applicable ecological  
500 knowledge (Gerstner et al., 2017).

501         We proposed a step back focusing on improving transparent data  
502 reporting because standardizing field experiment reporting has the potential to  
503 enhance our capacity to understand generalities and develop new theories based  
504 on empirical and functional relationships across spatial and temporal scales  
505 (McCleery et al., 2023). Our guidelines consist of a multilingual checklist  
506 (supplementary material – S2) that can be easily implemented in ecological  
507 restoration research. The guidelines can also be used in sites where new  
508 ecosystems will be created and/or interventions have other goals within the  
509 restorative *continuum* (Gann et al., 2019). Our guideline is a tool for restoration  
510 practitioners, scientists and decisions-makers aiming to increase the value of  
511 scientific evidence and moving TGB restoration experiments towards a more  
512 open, reliable, and transparent science (McCleery et al., 2023; O’Dea et al.,  
513 2021). Below we discussed the main issues regarding data reporting and  
514 provided suggestions for minimum standards for data reporting and experimental  
515 designs with a full checklist in the Supplementary Material (S2).

516         First, providing clear and transparent information on the study site is  
517 mandatory. We were unable to determine the reference ecosystem for 209  
518 restoration sites and to overcome such failures in disclosing detailed information  
519 on the reference ecosystem, we plotted the geographical coordinates into a  
520 global biome map (Dinerstein et al., 2017). However, we acknowledge that our  
521 approach is scale-dependent and cannot be used as a panacea. We also suggest  
522 that a standardised nomenclature should be sought while confusing terms must

523 be avoided. Recently, a critical review of common terms and concepts used in  
524 forest landscape restoration was done (Stanturf et al., 2023), and available  
525 frameworks for open biomes (Bond, 2019; Copeland et al., 2021) can work as a  
526 starting point.

527         A second issue refers to the clarification on degradation history, which  
528 includes information relative to exogenous disturbances and perturbations of  
529 endogenous disturbances regimes. TGB restoration experiments were  
530 implemented in sites under multiple degradation sources and sometimes multiple  
531 interventions were applied. In such cases, information was not transparent  
532 enough to allow data retrieval. For instance, it was challenging to determine the  
533 effectiveness of each technique and for different degradation contexts.  
534 Moreover, identifying degradation history can be tricky since there are no  
535 universally applicable indicators for ecosystem degradation and restoration  
536 (Bardgett et al., 2021). Consequently, quantification of fire and grazing impacts  
537 is needed to allow cross-studies comparisons. Thus, we suggest that a full  
538 diagnostic assessment of the physical, chemical and biological conditions of the  
539 degraded site should be reported along with a clear disclose whether there has  
540 been any perturbation in the natural disturbance regimes (Keeley & Pausas,  
541 2019). Refined, precise and detailed information of initial conditions before  
542 restoration should be more useful for identifying trends and conclusions among  
543 different studies.

544         The third major issue is the description of the restoration setting. Basic  
545 information concerning the methods and results must be systematically and  
546 transparently reported to allow comparisons (Gerstner et al., 2017). A third of  
547 experiments provided no information on restoration controls, while 10% did not

548 provide enough information on the number and composition of species planted  
549 or seeded. To overcome these limitations, we suggest minimum standards for  
550 setting restoration experiments that include detailed information on the  
551 restoration controls, restoration strategies and monitoring indicators (see  
552 supplementary material – S2).

553

## 554 **Conclusions**

555 Our review provides a synthesis of the state of knowledge of field  
556 experiments on TGB restoration research allowing us to identify critical  
557 shortcomings and future priorities. We found knowledge gaps and poor data  
558 reporting in TGB restoration research as well as a need to incorporate TGB  
559 drivers in restoration and to better evaluate outcomes. Severe issues in primary  
560 data report prevented us to integrate field experiments and provide more refined  
561 recommendations for future TGB restoration research and management.  
562 However, to overcome this issue, we provide a guideline to enhance data  
563 reporting which would allow broader quantitative assessments to support  
564 decision-making across different ecological contexts. The implementation of our  
565 proposed checklist is expected to support future TGB restoration projects by  
566 allowing standardizing terminology, methodology and data reporting. We hope  
567 that our synthesis contributes effectively to the UN Decade on Ecosystem  
568 Restoration moving TGB restoration to the forefront and enhancing our abilities  
569 to restore these megadiverse yet overlooked ecosystems.

570

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## 807 **Data sources**

808 The list of data sources (all peer-reviewed papers selected) used in the study is  
809 provided in the Data sources section of the S1.

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