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Combating global grassland degradation

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1 Combatting global grassland degradation

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26 Abstract

27 Grasslands are under severe threat from on-going degradation, undermining their capacity to
 28 support biodiversity, ecosystem services, and human wellbeing. Yet grasslands are largely
 29 ignored in sustainable development agendas. In this Perspective, we examine the current state
 30 of global grasslands and explore the extent and dominant drivers of their degradation. Socio-
 31 ecological solutions are needed to combat degradation and promote restoration. Important
 32 strategies include: increasing recognition of grasslands in global policy; developing
 33 standardised indicators of degradation; using scientific innovation for effective restoration at
 34 regional and landscape scales; and enhancing knowledge transfer and data sharing on
 35 restoration experiences. Stakeholder needs can be balanced through standardised assessment
 36 and shared understanding of the potential ecosystem service trade-offs in degraded and restored
 37 grasslands. The integration of these actions into sustainability policy will aid in halting

38 degradation and enhancing restoration success, and protect the socio-economic, cultural and
39 ecological benefits that grasslands provide.

40

41 **Table of Contents Summary**

42 Grasslands provide key ecosystem services, but their protection is often ignored in sustainable
43 policy. This Perspective describes grassland degradation and sets out the steps needed to
44 protect these systems and promote their restoration.

45

46 **[H1] Introduction**

47 Grasslands, comprising open grassland, grassy shrublands and savannas, cover about
48 40% of the Earth's surface and 69% of Earth's agricultural land area¹⁻³. Grasslands serve as an
49 important global reservoir of biodiversity, including many iconic and endemic species, but also
50 provide a wide range of material and non-material benefits to humans. These benefits include
51 a wide range of ecosystem services, such as food production, water supply and regulation,
52 carbon storage and climate mitigation, pollination, and a host of cultural services¹⁻³. Despite
53 the importance of grassland, its degradation is widespread and accelerating in many parts of
54 the world⁴⁻⁶, with as much as 49% of grassland area globally having been degraded to some
55 extent^{5,7,8}.

56 Grassland degradation poses an enormous threat to the hundreds of millions of people
57 who rely on grasslands for food, fuel, fibre and medicinal products, in addition to cultural
58 values^{9,10}. The global cost of grassland degradation on livestock production has been estimated
59 at \$6.8 billion over the period 2001-2011¹¹, with the resulting impact on human welfare being
60 particularly severe in regions where most the population is below the poverty line. Grassland
61 degradation also creates major environmental problems, as grasslands play a critical role in
62 biodiversity conservation, climate and water regulation, and global biogeochemical cycles^{2,4}.
63 For example, the conversion of tropical grassy biomes to arable cropland poses a threat to
64 biodiversity, given grasslands have vertebrate species richness comparable to forests¹². The
65 expansion of croplands in United States has caused widespread conversion of prairie
66 grasslands, with considerable cost to wildlife⁶. Moreover, the conversion of grasslands to
67 arable cropland and disturbance through overgrazing, fire and invasive species can lead to
68 substantial soil carbon loss¹³.

69 Because of these problems, grassland degradation represents a major global challenge
70 that must be addressed to achieve the key targets of biodiversity agendas, such as the Aichi
71 Biodiversity Targets of the Convention on Biological Diversity (CBD) and the United Nations

72 Sustainable Development Goals (SDGs), including restoration and sustainable use of terrestrial
73 ecosystems, hunger and poverty alleviation, and climate change mitigation. Combating
74 degradation is also central to the UN Decade on Ecosystem Restoration (2021-2030), which
75 puts a firm focus on the urgent need for restoration strategies for degraded ecosystems,
76 including grasslands.

77 There are multiple, co-occurring drivers of grassland degradation, including over-
78 grazing, eutrophication, land conversion to forestry and crops, land abandonment, invasive
79 species, climate extremes and altered fire regimes (Fig. 1). These drivers are also often closely
80 linked to socio-economic drivers, such as spatial expansion of humans, the economics of land
81 use, changes in affluence and dietary preferences, and in land tenure and a lack of enforcement
82 of land use rights⁹. Climate change is further exacerbating grassland degradation, especially
83 through more frequent and intense fires and droughts⁸. Despite the importance of grasslands,
84 there has been little progress in finding solutions to halting and reversing global grassland
85 degradation, which is compromising sustainable development and the ecosystem services
86 grasslands provide.

87 In this Perspective, we consider the current state of and ecosystems service provided by
88 grasslands (open grassland, grassy shrublands, and savanna). The known extent and dominant
89 causes of grassland degradation are reviewed. We then consider the challenges that grassland
90 restoration efforts face, from societal attitudes to practical efforts, and identify actions that are
91 critical to the development of socio-ecological solutions to combat degradation and promote
92 restoration of global grasslands. We argue that progress can only be made through increasing
93 recognition of grasslands in regional and global policy, developing standardised indicators of
94 degradation and restoration, introducing ecological innovation into restoration, and enhancing
95 knowledge transfer and data sharing regarding restoration experiences.

96

97 **[H1] Defining grasslands**

98

99 A key issue in the poor recognition of grassland in policy is a lack of clarity in defining
100 the grassland biome. Indeed, there are many definitions of “grassland” and the boundaries
101 between grasslands and other ecosystems are often poorly delineated, which contributes to
102 variable estimates of their global extent³. For example, some definitions of grassland have a
103 relatively high tree cover of 30% before they become classed as forest¹⁴ and in many regions
104 there is no clear delineation of grasslands, forests and their distinct transition zones, which in

105 Eurasia are called forest-steppes¹⁵. This Perspective uses the common definition of grasslands
106 as areas dominated by grasses or other graminoids, with a low abundance of trees or shrubs^{3,16}.

107 The definition here includes both temperate and tropical grasslands and considers broad
108 grassland types based on a gradient anthropogenic influence, ranging from ‘natural grasslands’
109 that are climatically determined with minimal human interference, to ‘semi-natural grasslands’
110 that have been shaped by centuries of human activity, and ‘intensively managed grasslands’
111 that have been substantially modified for agriculture³. As agriculture has become increasingly
112 intensive over the last century, ‘intensively managed grasslands’ of low plant species diversity
113 now dominate in some parts of the world, characterised by the use of inorganic fertilisers, high
114 stocking densities of productive livestock breeds, and often frequent re-sowing with high-
115 yielding plant varieties. While intensively managed grasslands are valued by some stakeholder
116 groups, here we consider them potentially degraded given that they are fundamentally different
117 from natural and semi-natural grasslands in terms of their biodiversity and the ecosystem
118 services they provide¹⁷.

119 Natural grasslands are often considered the most important grassland type. They are
120 found in both the tropical (namely as savannas, which are extensive in Africa and South
121 America) and temperate (North American prairies, Eurasian steppes and South American
122 pampas) regions of the world. Their extent is largely climatically determined, occurring where
123 the climate and/or soils cannot support woody plant growth, such as above the tree-line or in
124 drylands. However, climatic factors often interact with natural disturbances, such as by fire or
125 wild herbivores, which constrain growth of woody plants and maintain the grasses and
126 associated low-growing plants¹⁸. Indeed, changes in the balance of these interacting factors can
127 trigger radical change. For example, the encroachment of native woody plants into natural
128 grasslands is occurring in many parts of Africa (and elsewhere), which is linked to a decline in
129 burned area and herbivore densities along with warmer and wetter climates¹⁹. In contrast, the
130 Holocene transition from extensive grasslands into the Sahara Desert was likely due to the
131 onset of drier conditions at the end of the African Humid Period²⁰.

132 Semi-natural grasslands, also referred to as secondary grasslands¹⁶, have been created
133 by clearing natural vegetation such as forest and by modifying natural grasslands. They are
134 typically ‘early successional’ systems and would not exist without some human influence³.
135 This type of grassland is of particularly high concern for conservation in Europe, due to their
136 importance as reservoirs for biodiversity²¹ and their historical role in the landscape²². Indeed,
137 semi-natural grasslands have been produced by centuries of human activity, generally by
138 traditional, low-intensity agriculture involving livestock grazing, hay-cutting, and sometimes

139 management with fire, and are often valued for their aesthetics and are related to a sense of
140 identity, place and heritage²².

141 The vegetation of both natural and semi-natural grasslands, while typically dominated
142 by grasses and graminoids, can have a large forb component²³. In terms of species richness,
143 forbs dominate grasslands worldwide, and are often the most species-rich functional group²³.
144 Natural grasslands are grazed by wild herbivores, but large areas are also used for domestic
145 livestock. As such, meat, dairy and other livestock products, such as wool, comprise the most
146 prominent ecosystem services provided by both natural and semi-natural grasslands. Indeed,
147 the livelihoods and cultures of some traditional pastoralist communities revolve almost entirely
148 around their livestock systems²⁴, which in turn maintains the diversity of livestock breeds²⁵.
149 Natural grasslands also support rich biodiversity, hosting numerous species not found in
150 forests^{12,26} and distinct assemblages of native large herbivores and their predators, many of
151 which are threatened by extinction²⁷. Many of these species are charismatic and globally
152 recognized, such as bison, wolves, rhinos and lions, and hence provide cultural services, such
153 as ecotourism²⁸.

154 It is less acknowledged, however, that both natural and semi-natural grasslands provide
155 other ecosystem services, including holding flood waters, providing clean water, regulating
156 soil erosion, and providing wild food and medicines¹⁰. These services and their importance
157 vary geographically in relation to local environments and the demands from people¹⁰. Cultural
158 services include aesthetic value, hunting, heritage values and resources for tourism and
159 recreation, especially where grasslands define the ecology and culture of an area²⁹.

160 The role of grasslands in carbon storage is often overlooked, but could contain 30% of
161 the world's soil carbon stock³⁰, with natural and sparsely grazed grasslands potentially acting
162 as a notable global carbon sink and providing an important climate cooling service³¹. However,
163 there is a global trend of grasslands transitioning towards a net warming effect on climate due
164 to increased greenhouse gas emission associated with higher livestock numbers and
165 management intensification³¹. Natural and sparsely grazed grasslands contain "irrecoverable
166 carbon" that is vulnerable to land use conversion; once lost, this carbon is not recoverable over
167 timescales relevant to climate mitigation³². Nevertheless, there is high potential for increasing
168 soil carbon sequestration in grasslands via improved grazing and by arresting grassland
169 conversion and degradation³³.

170

171 **[H1] Extent and drivers of degradation**

172

173 Globally, estimates suggest that as much as 49% of the total grassland^{5,7,8} and about
174 half of the natural grassland area has been degraded to some extent³⁴. However, specific
175 estimates of the extent of grassland degradation vary greatly. For instance, about 90% of the
176 UK's semi-natural species-rich grasslands have been degraded as result of intensive agriculture
177 and land conversion since the 1940s¹⁷. Up to 90% of the vast grasslands of the Qinghai-Tibetan
178 Plateau have been degraded due to human activities and climate change³⁵. Over 60% of the
179 former grassland area of southern Brazil has been lost to unsuitable management and land use
180 change³⁶.

181 A key issue when considering grassland degradation is clarifying what it constitutes,
182 especially since definitions of both grassland and degradation vary. Degradation is broadly
183 defined as a decline in land condition, or more specifically the human-caused processes that
184 drive a persistent decline or loss in biodiversity, ecosystem functions or ecosystem services³⁴.
185 Such a broad definition of grassland degradation can help to inform policy and practice about
186 the level of grassland degradation in a certain region. However, pinpointing what degradation
187 constitutes in specific settings can be less clear because it has both ecological and
188 socioeconomic dimensions³⁷, and different stakeholder groups prioritise different
189 combinations of ecosystems services^{38,39}. As such, the definition of grassland degradation can
190 depend upon the stakeholder and needs to be tailored accordingly.

191 Grassland degradation is defined here from a socio-ecological perspective, where
192 grassland is considered degraded if the supply of multiple ecosystem services falls short of that
193 demanded by grassland stakeholders⁴⁰. In some cases, grassland degradation is apparent to all
194 grassland stakeholders, for instance when overgrazing leads to loss of vegetation, declines in
195 soil organic matter and consequent soil erosion⁴¹, or when natural or semi-natural grassland is
196 converted to another land use. However, in many cases, perceptions of degradation could
197 differ: the increase in plant production but accompanying loss of plant species diversity
198 resulting from fertiliser use might be considered an improvement by pastoralists (due to
199 increased forage production), but degradation by conservationists concerned with biodiversity
200 protection⁴². Hence, defining grassland degradation from a socio-ecological perspective
201 recognises that it alters the supply of multiple ecosystem services from grassland relative to
202 their human demand by different stakeholders⁴⁰. Moreover, a socio-ecological approach
203 provides a framework for guiding the restoration of degraded grasslands as it considers the
204 need to enhance the co-supply of multiple ecosystem services in efforts to meet the needs of
205 all stakeholders^{37,40,43}.

206 Although threats to natural and semi-natural grasslands are present globally (Fig. 1),
207 the tropics face particularly acute threats¹⁸, while degradation of European semi-natural
208 grassland has largely slowed⁴⁴. Human activities are the principal drivers of grassland
209 degradation. For example, increased disturbance from over-grazing or a heightened fire
210 frequency has reduced vegetation cover, increasing susceptibility to soil erosion and
211 desertification⁴⁵. Conversely, the cessation of livestock grazing associated with extensive land
212 abandonment of semi-natural grasslands in Europe during the 20th century has led to grassland
213 degradation due to the expansion of scrub⁴⁶. Nutrient enrichment of natural and semi-natural
214 grasslands from fertiliser use and/or atmospheric nitrogen deposition has led to widespread
215 declines in biodiversity and other ecosystem services^{17,47}. These impacts are especially notable
216 when combined with the sowing of productive cultivars to support heavy grazing and/or silage
217 production in intensively managed grasslands³. The conversion of natural and semi-natural
218 grasslands to other land uses, such as arable farming, built infrastructure and forestry, is also a
219 major driver of grassland degradation worldwide^{36,48}. One immediate land use threat is the
220 planting of trees on natural grasslands, ostensibly to meet afforestation targets for climate
221 change mitigation⁴⁹.

222 Ongoing climate change also poses a threat to all grasslands, as it causes grassland
223 degradation. Projected future climate change will likely combine with human activities to cause
224 increased woody plant encroachment in some areas and desertification in others^{50,51}. For
225 example, natural grasslands in the Americas, Australia and Africa are being degraded due to
226 woody plant encroachment, with the major causes thought to be a combination of higher
227 atmospheric CO₂ concentrations, warmer and wetter conditions, and changes in grazing
228 intensity and timing relative to fire, which is key to episodic tree recruitment⁵². Conversely, in
229 many parts of the world, such as Central Asia and Africa, over-grazing combined with more
230 intense and frequent droughts is exacerbating grassland desertification and degradation⁵³.

231

232 **[H1] Promoting restoration**

233

234 A socio-ecological approach is also key to identifying how restoration of degraded grasslands
235 might be achieved^{37,43}. Five actions are proposed here that should be deployed to develop
236 effective socio-ecological solutions to the halting the degradation and promoting the restoration
237 of global grasslands.

238 **[H2] Policy recognition of grasslands.** National and global policy are needed to recognize the

239 role of grasslands in addressing climate mitigation, food security, biodiversity conservation
240 and poverty alleviation. A major factor contributing to the degradation of grasslands is the lack
241 of representation of grassland in national and international policy. In fact, grasslands are often
242 underappreciated, with the scientific and political focus of global sustainability policy being
243 on ecosystems such as oceans, freshwaters, forests and croplands. Indeed, despite suffering
244 some of the highest rates of degradation of any biome, only 8% of grassland and savanna
245 biomes are protected⁵⁴.

246 The reasons for this neglect of grasslands in sustainability policy are unclear, but it
247 likely relates to historical factors and misconceptions about grasslands. For example, natural
248 grasslands are often erroneously considered to be degraded lands or wastelands, a result of
249 human action, or early successional stages of forest, whereas forests are perceived as more
250 productive, pristine ecosystems that are rich in diversity^{18,55}. Moreover, natural grasslands
251 primarily occur in areas where climatic and soil factors only allow for relatively low economic
252 benefits to land users, whereas their economic value for the provision of ecosystem services
253 has only been fully recognised over the last twenty years⁵⁶. Another reason for this bias might
254 be that worldwide, forests were the first lands to be converted to agriculture, which has
255 contributed to greater awareness of the consequences of deforestation for biodiversity and
256 society. In contrast, most natural and semi-natural grasslands continued to be grazed at low
257 densities by wild herbivores and livestock until technological barriers hindering agricultural
258 improvement of grasslands and land conversion were overcome. As such, the consequences of
259 large-scale grassland degradation, which are also less obvious than cutting down trees, are
260 newly appreciated⁵⁷.

261 Although grasslands are recognised in some national policies on environment and
262 sustainability, such as China's Grassland Law, numerous prominent examples exist where they
263 have been ignored. For example, halting and reversing ecosystem degradation is a central goal
264 of the SDGs (Goal 15), the UN Framework Convention on Climate Change (UNFCCC), and
265 the Convention on Biological Diversity (CBD), but there is no explicit mention of grasslands
266 in any of them. The SDG targets also fail to mention grasslands, whereas forests, oceans and
267 coastal ecosystems are repeatedly referenced in targets and indicators. Further, while around
268 half the world's 234 Centres of Plant Diversity—sites of global botanical importance based on
269 endemism and species richness—are contained in grassland regions, they were not mentioned
270 in the Aichi Biodiversity Targets of the CBD. The European Biodiversity Strategy to 2020 also
271 makes little mention of grasslands relative to forests, which feature heavily. Although the EU
272 Common Agricultural Policy (CAP) does aim to protect grasslands, there has been widespread

273 criticism about the effectiveness of the grassland measures for biodiversity conservation in this
274 policy⁵⁸.

275 Pressures on grasslands have also been accentuated through the unforeseen
276 consequences of global and national environmental and socio-economic policies. In particular,
277 natural grasslands are increasingly targeted in carbon sequestration programs that emphasize
278 tree planting, such as REDD+ and China's Grain-to-Green Project, which often leads to their
279 degradation. The Chinese government, for example, has invested heavily in tree planting, with
280 tree coverage of previously non-forested areas increasing at an average rate of 0.15 million
281 hectares per year over the last 25 years⁵⁹. However, there is major concern that tree planting in
282 arid and semi-arid grasslands with water-demanding trees is exacerbating grassland
283 degradation, reducing plant diversity, damaging soils, and increasing water shortages⁶⁰⁻⁶².

284 Similarly, large tracts of natural grassland in Brazil have been identified as targets for
285 tree planting, posing a major threat to these ancient and highly diverse ecosystems²⁶. An
286 estimated 7.41 million ha of eucalypt and 2.07 million ha of pine plantation already occupy
287 mostly former savannas and grassland, at a rapid rate of 0.4 million ha per year from 2013-
288 2017 (Ref⁶³). Indeed, it has been calculated that meeting land restoration and protection targets
289 would increase global tree cover by 4 million km², often at the expense of grasslands⁶⁴.
290 Furthermore, models of global forest restoration potential have identified natural grasslands as
291 sites for restoration using tree planting, with potential to contribute to carbon sequestration and
292 climate mitigation⁶⁵. The logic of such proposals for climate mitigation, however, is
293 increasingly being challenged on the basis of their damaging impact on natural grasslands and
294 because their carbon sequestration potential is considered inflated^{49,66}.

295 Evidence is mounting that grasslands can be more resilient carbon sinks than forests⁶⁷,
296 and afforestation can cause soil carbon loss^{68,69}, soil acidification and nutrient-depletion⁷⁰,
297 especially when trees are planted in natural grasslands⁶⁸, which can make them prone to carbon
298 loss from fires⁶⁶. Large-scale afforestation also leads to changes in surface albedo, given that
299 forests absorb more short-wave radiation than grasslands, thereby creating a warming effect⁷¹.
300 As such, changes in albedo resulting from afforestation can reduce or even negate benefits of
301 increased carbon capture, potentially leading to a net warming effect of tree planting⁷¹. Another
302 issue is that policies such as REDD+ focus primarily on carbon sequestration in aboveground
303 tree biomass, while healthy and restored grasslands can store comparable amounts of organic
304 carbon as forests, but mainly belowground^{67,72}. Grasslands have also been shown to be more
305 effective than forests in providing soil erosion control and water protection in semi-arid
306 ecosystems⁷³, and in some situations the conversion of grassland to forest, either through

307 natural regeneration or afforestation, can be highly detrimental to people who depend on
308 grasslands for forage, game habitat, water reserves, and cultural services^{66,74,75}.

309 The lack of emphasis on grasslands in international and national policies has a long
310 history. Grasslands in India have been historically undervalued in national policies, and still
311 today they are widely considered to be unproductive wastelands of limited value, leaving them
312 vulnerable to land conversion^{76,77}. In Brazil, major progress has been made in the conservation
313 of forest ecosystems, but non-forest biomes—including the Cerrado and Pampas grasslands—
314 have been largely neglected, despite being among the most species rich grasslands in the
315 world⁷⁸. Similarly, and despite their ancient origin, Asian savannas have been considered
316 degraded forest since colonial times, which has led to inappropriate management and policies
317 that promote savanna degradation and loss^{77,79}. China's grassland law now includes policies to
318 protect healthy and restore degraded grasslands, and progress being made in certain areas⁸⁰,
319 but was not incorporated in the Constitution of the People's Republic of China until 1985.

320 If grasslands are to be valued and managed sustainably, then both global and regional
321 policy must change to recognize the value of grasslands as providers of multiple ecosystem
322 services and hotspots for biodiversity, and to establish targets for their protection and
323 sustainable management. Approaches could comprise specific inclusion of natural and semi-
324 natural grasslands in conservation laws and policies and ensuring conservation policies do not
325 have perverse consequences for grasslands, such as promoting fire suppression or afforestation.
326 New policies to promote and fund appropriate management and restoration of grasslands are
327 also needed, including penalties for degrading activities such as overgrazing.

328

329 **[H2] Standardised assessment.** New approaches are needed to enable standardised assessment
330 of grassland condition globally under different situations. These approaches should assess the
331 severity of grassland degradation and its consequences for biodiversity and ecosystem services
332 and evaluate the success of restoration schemes. Currently, restoration efforts are disjointed
333 across regions and carried out by a wide range of organisations, which often leads to
334 incompatible and inaccessible datasets, and a lack of communication about successful
335 methods⁸¹. The diversity of grasslands across and within regions, and the many drivers of
336 degradation, mean a fully uniform set of guidelines is impractical. Yet, standardised
337 approaches are needed to underpin effective decision-making.

338 Progress can be made by defining grassland degradation from a socio-ecological
339 perspective, where the severity of degradation and the relative benefits of different grassland
340 restoration practices can be assessed by combining measures of ecosystem service supply and

341 stakeholder priorities and demands⁴⁰. Such measures can show how alternative restoration
342 options differ in their impacts on ecosystem service supply and in their resulting benefits for
343 different stakeholder groups. We recommend that this goal be achieved via a general five-step
344 approach for standardising the assessment of grassland degradation and restoration (Fig. 2).
345 The results of this approach can also be used to support negotiation over restoration
346 management.

347 The first step is to assess the demand for, and relative priority of, different ecosystem
348 services by multiple stakeholder groups, for instance via social surveys of many stakeholders,
349 or representative community leaders^{38,82} (Fig. 2). It is vital that all major stakeholder groups
350 are represented and the full range of relevant ecosystem services considered, including non-
351 material (cultural) benefits. Otherwise, bad management decisions could result and potential
352 conflict⁸³. Moreover, it is important that potential power imbalances among stakeholders are
353 addressed, for instance by strengthening and enforcing land use rights of pastoralists and agro-
354 pastoralists.

355 Once ecosystem service demand is determined, indicators need to be identified and
356 measured for each of the services (Fig. 2). These should fall into two classes: general indicators,
357 which measure ecosystem services for all stakeholder groups (measured in step two); and
358 specific indicators for services used by a subset of the stakeholder community (measured in
359 step three). The general indicators measured in step two should be inexpensive and easy to
360 measure over large scales, and relate to key regulating functions that underpin all other
361 ecosystem services. Such properties could include the cover and type of vegetation present,
362 aboveground biomass, and soil properties such as organic matter, nutrient content, and pH
363 (Table 1).

364 While the general indicators proposed above provide broadly comparable information
365 on grassland condition, perceptions of grassland degradation differ between stakeholder
366 groups⁸⁴. Therefore, in addition to general indicators, other variables should be identified
367 locally for these context-specific ecosystem services via stakeholder engagement, and
368 developed according to local conditions (step three). In the French Alps, for example, surveys
369 identified that aesthetic value of mountain grasslands was essential to local farmers and
370 tourists, and related not only to flower diversity, but also to the absence of a build-up of plant
371 litter⁸⁵. As another example, the cover of woody species can be used as an indicator of the vital
372 regulating service of shade provision in East African grasslands⁸⁶. Visually estimable
373 indicators can also be employed in such assessments to ensure both relevance and cost-
374 effectiveness.

375 In the fourth step, general and specific measures are combined to calculate an integrated
376 index of grassland condition that can be related to local environmental conditions, management
377 factors, global change drivers and restoration management. The creation of such indices can
378 be achieved by adapting approaches developed for measuring the co-delivery of multiple
379 ecosystem services based on stakeholder preferences^{40,87}, and other participatory multi-criteria
380 analyses of ecosystem services⁸⁸. Both approaches can also be used to weigh the measures
381 included in the calculation of the index, for example by encouraging representatives of different
382 stakeholder groups to assign scores to the ecosystem services considered⁸⁶.

383 In the final step, conclusions from this standardised approach are used to inform
384 management decisions regarding which restoration options should be employed and where.
385 Deciding on which restoration options are employed and where is best resolved in participatory
386 approaches, so that stakeholders share understanding, and conflict is minimised (Fig. 2). The
387 best options for whole communities can be estimated by weighting stakeholder groups equally
388 in a community level metric, or by evaluating which restoration options minimise trade-offs
389 between groups. As a single restoration practice might not benefit all stakeholder groups, the
390 compartmentalisation of the landscape into different restoration options should also be
391 considered (Fig. 2). The approach presented here would not only allow for more detailed
392 examination of grassland condition with regards to local needs, but also a better means of
393 assessing the severity of grassland degradation and restoration success at both local and larger
394 scales (Figures 3 and 4; see Supplementary Material for details on the source of these
395 estimates).

396
397 **[H2] Shared understanding and trade-offs.** When assessing grassland restoration options that
398 best suit different stakeholder groups, there will likely be differences in preferred options (Figs.
399 3 & 4), which might cause disagreement and conflict. To address these differences, there is a
400 need for shared understanding, based on best knowledge and practice and operational
401 constraints, of the potential for different grassland restoration options to supply different
402 ecosystem services^{43,89}, which can be quantified using the same tools as described here for
403 assessing degradation. Such an approach could help identify which restoration option might
404 best deliver the needs of all stakeholder groups, thereby supporting resolution of disagreements
405 and conflict.

406 To illustrate these trade-offs and how they could be resolved, two examples are
407 considered (Figs. 3 and 4). In both, fundamental trade-offs caused by degradation and
408 restoration options prevent the co-supply of all ecosystem services. The first example is taken

409 from permanent agricultural grasslands in Europe (Fig. 3), where extensive management
410 promotes functions related to water and soil carbon storage, which support ecosystem services
411 linked to water and climate regulation. In contrast, intensive management with fertiliser use
412 and high grazing pressures leads to faster rates of nutrient cycling and higher plant productivity,
413 thereby promoting provisioning services^{42,90}. However, intensive management also reduces
414 plant and soil biodiversity and causes soil compaction, which diminishes the supply of several
415 ecosystem services demanded by stakeholders, leading to reduced overall benefits to
416 stakeholder groups (Fig. 3)⁹⁰. To reverse these impacts, restoration to high diversity grassland
417 can enhance the supply of multiple ecosystem services, and therefore provides substantial
418 benefits to all stakeholder groups. Despite these benefits, the abandonment of agricultural
419 management altogether, which leads to woody plant encroachment, could be the best option to
420 provide some of the benefits prioritized by national decision makers, namely water quality and
421 climate regulation. Given these various trade-offs, and depending on European or national
422 objectives, and on regional conditions⁹¹, collective choice would likely favour a mosaic of all
423 three grassland types with the restoration of high diversity grassland, accompanied by the
424 segregation of intensive production and climate regulation into specific regions and
425 landscapes⁹².

426 The second example is taken from natural grasslands in arid and semi-arid regions of
427 Eastern Africa (Fig. 4). Here, nomadic pastoralists favour provisioning services of forage
428 production and natural products from grasslands, while charcoal producers derive their
429 livelihoods from native woody vegetation and, increasingly, from invasive woody species such
430 as *Prosopis juliflora*. Because the invasion of *P. juliflora* transforms grasslands into scrubland
431 with bare soil⁹³, the supply of most ecosystem services demanded by stakeholders is greatly
432 reduced, but fuel wood and charcoal production are promoted⁸⁶. The supply of other services,
433 such as soil carbon storage, is context-dependent; soil conditions are improved when *P.*
434 *juliflora* invades grasslands degraded by overgrazing and other forms of mismanagement.
435 However, if undegraded grassland is invaded, the supply of these services is reduced⁹⁴ and all
436 stakeholders, apart from charcoal producers, lose ecosystem service benefits and so perceive
437 the invasion as degradation. This example also clearly demonstrates that successful restoration
438 depends on stakeholder perspectives as all restoration options benefit the priority services of
439 some groups, while diminishing those of others. These constraints preclude a single win-win-
440 win restoration option. Therefore, regional-scale restoration that establishes a landscape
441 mosaic, including livestock grazing and patches of conserved or abandoned land, is likely to
442 be required for all three stakeholder groups to be satisfied. It should be noted, however, that

443 such a landscape mosaic would require continuous management of *P. juliflora*, otherwise it
444 will re-invade grasslands and conserved land.

445 Identifying the presence and cause of trade-offs is a first step towards management and
446 policy solutions to grassland degradation. We suggest that the approaches presented here could
447 be combined as a decision support tool in ecosystem management⁹⁵. This tool can be used as
448 part of a ‘landscape approach’ to management, which emphasises close collaboration and
449 shared understanding between stakeholder groups to identify and mitigate land management
450 conflicts. Depending on context, this approach could allow for the allocation of different
451 restoration options to different sections of the landscape, as in semi-arid grasslands of Eastern
452 Africa (Figure 4), or the identification of win-win options where a single restoration practice
453 might suit multiple stakeholder groups, such as in European grasslands (Figure 3).

454 These approaches are already considered in existing grassland management
455 approaches, such as the Participatory Rangeland Management (PRM) approach, which has
456 been developed to improve the sustainable management of rangeland resources and their
457 security of access for local rangeland users in arid and semi-arid grasslands⁹⁶. This approach
458 includes a step where stakeholder groups, through extensive meetings, discussions and
459 negotiations, develop a rangeland management agreement that considers the needs of all
460 stakeholder groups involved. This agreement should ultimately become a binding contract
461 document between a representative rangeland management institution and the appropriate
462 government authority. The PRM was initially developed by a consortium including the
463 International Livestock Research Institute in Ethiopia and has been applied in Kenya and
464 Tanzania⁹⁷. A similar approach called Participatory Rangeland Management Planning (PRMP)
465 has been adopted by the International Union for Conservation of Nature (IUCN)⁹⁸.

466 Complex trade-offs might prevent the formulation of simple solutions, and in such
467 situations multi-criteria decision analysis (MCDA) can be used to support deliberation among
468 groups and help steer them towards a compromise where local communities have a voice and
469 multiple perspectives of grassland degradation are accommodated^{99,100}. Advanced MCDA
470 approaches also allow for the incorporation of socio-economic factors, such as access rights
471 and ease, and power relationships between stakeholder groups across scales, which will
472 determine the ultimate benefits of ecosystem services to different groups¹⁰¹. However, to
473 ensure better outcomes from decision tools such as MCDA it is also important to consider
474 optimal allocation and prioritisation of limiting resources to actions¹⁰², especially since funds
475 for grassland restoration are often limited.

476

477 **[H2] Knowledge sharing in grassland restoration.** Evidence of success or failure of grassland
478 restoration programmes is scant^{103,104}. Accordingly, there is a need for standardised and
479 accessible reporting of restoration successes and failures, and ongoing monitoring of grassland
480 restoration programmes and their outcomes in different parts of the world. Restoration
481 knowledge must be shared to achieve this goal, which requires the formation of networks of
482 scientists and practitioners that exchange knowledge on successful, but also unsuccessful,
483 restoration efforts. Examples of platforms that provide information on successes and failures
484 of grassland restoration programmes are beginning to emerge. The Society for Ecological
485 Restoration (SER) launched their Restoration Resource Centre in 2017, an online, publicly
486 accessible platform for exchanging knowledge and experience through ecological restoration
487 projects, publications, and other resources from around the world. The World Overview of
488 Conservation Approaches and Technologies (WOCAT) database provides a format and a
489 platform for knowledge exchange regarding Sustainable Land Management (SLM)
490 technologies and approaches and is recognized as the primary recommended database by
491 UNCCD. The Global Landscape Forum (GLF), led by the Centre for International Forestry
492 Research (CIFOR) and supported by the UN and World Bank, provides a mobile platform for
493 discussions leading to action on sustainable land use, including land restoration.

494 While grasslands are currently underrepresented within these databases, which are still
495 under development and continually being expanded, they demonstrate the potential for user-
496 driven platforms to provide valuable insight into effective restoration practices in different
497 parts of the world (Box 1 Fig. 1). To be effective, such platforms should include a wide range
498 of restoration programmes, both local and regional, and small and large scale. They should also
499 include less successful programmes and identify why they have not reached their objectives.
500 Moreover, grassland restoration projects should identify clear aims of restoration and an
501 inventory before restoration starts to be able to evaluate restoration success¹⁰⁵. By comparing
502 case studies, it is possible to understand how the effectiveness of specific restoration methods
503 differ geographically and depending on the degree of degradation and socio-ecological context,
504 the first step towards finding general rules, both social and ecological, for successful
505 restoration. They could also illustrate the successful translation of research into improved
506 restoration and management, which should include the co-creation and co-implementation of
507 technical solutions to grassland restoration, and the political and socio-economic conditions
508 that made them possible.

509 Case studies reporting technical solutions to grassland degradation at scales of hundreds
510 to thousands of hectares are particularly scarce, especially for developing countries in semi-

511 arid and arid regions of the world. However, previous efforts indicate that grassland restoration
512 is feasible, at least starting from low levels of degradation, and that technical and socio-
513 ecological solutions often need to be combined to achieve long-term management goals (Box
514 1). For example, steppe grasslands in Inner Mongolia are challenged with a diverse set of
515 stakeholder demands, including the need for environmental services, such as increased soil
516 carbon storage, the local herders' wish to retain traditional livelihoods while increasing their
517 income, and an increasing demand for red meat by the wider population in China and
518 elsewhere⁸⁰. To address these demands of various stakeholder groups, a grassland management
519 system was developed that built on optimizing income from livestock production per unit area,
520 which was achieved by increasing animal growth rates (and thus reaching marketable size
521 earlier) by decreasing livestock numbers by approximately 50%⁸⁰. Thus, the system created a
522 win-win situation by improving local herders' income and enabling the recovery of steppe and
523 associated ecosystem services (Box 1).

524 In northern Ethiopia, several years of excluding livestock from degraded communal
525 grazing lands led to the recovery of plant species richness, forage and wood production, and
526 soil health, and thus helped to improve the supply of services prioritised by local
527 stakeholders^{106,107}. However, the uptake of technical solutions for restoring degraded
528 grasslands depends on socio-economic factors, including reconciliation with traditional land-
529 tenure systems, well-established communication pathways, and supporting institutional
530 settings and policies (Box 1. For example, implementation of sustainable grassland
531 management in Inner Mongolia benefits from efforts of the Chinese government to emphasize
532 sustainable grassland management in agricultural policies¹⁰⁸. The success of the grazing
533 enclosure programme in northern Ethiopia will depend on successful communication and
534 negotiations between local stakeholder groups and policy, and among local stakeholders to
535 ensure land use enforcement and sharing of management responsibilities and harvesting
536 benefits¹⁰⁹.

537

538

539 **[H2] Research innovation:** Innovations in environmental research need to be developed and
540 employed to improve the assessment of grassland degradation and provide novel solutions to
541 restoration and sustainable grassland management. At a global and regional scale,
542 developments in remote sensing offer potential to evaluate both the extent and status of
543 grasslands and inform the spatial targeting of large-scale restoration efforts. For example, maps
544 of general degradation indicators, such as primary productivity, standing biomass, soil

545 moisture, phenology, soil organic carbon¹¹⁰⁻¹¹², could be combined with spatial information on
546 climate, edaphic and socio-economic data to identify national and global patterns of grassland
547 degradation and pin-point locations where restoration efforts could have the greatest impact.
548 Although current global maps of primary productivity and biomass carbon still need
549 improvement, they offer a means to monitor the dynamics of grassland aboveground biomass
550 and evaluate the degradation of global grasslands^{113,114}.

551 There has been a boom in research directed at grassland management for sustainable
552 agroecosystems since the turn of the 21st Century, leading to improved grazing and fertiliser
553 management, and reduced reliance on external inputs, nutrient losses and emissions of
554 greenhouse gases¹¹⁵. However, new ecological understanding could also facilitate grassland
555 restoration. For example, new research could enable landscape and regional scale restoration
556 of inter-connected grasslands in regions where semi-natural grassland remnants are fragmented
557 and persist within a matrix of forested or intensive agriculture land uses. Indeed, there is
558 increasing evidence that grassland dynamics and function are enhanced by connectivity that
559 encourages flows of species and biogeochemical processes^{116,117}. In theory, such spatial
560 networks have improved resilience to perturbations, such as climate extremes, and the ability
561 to adapt to a changing environment¹¹⁸. These emerging concepts on landscape design could
562 also be applied to the restoration of ecological flows of species and processes within
563 landscapes^{119,120}, and at a practical level, there is already considerable opportunity to trial these
564 approaches in large-scale restoration programmes¹²¹. Such approaches also require improved
565 understanding of the tele-coupling of different landscape elements, whereby human-induced
566 processes in one area impact on distant areas. For example, pastoralists in arid regions depend
567 on grazing areas along major water bodies, which are also of interest to other stakeholders for
568 crop production or biodiversity conservation¹²². Loss of such grazing areas forces pastoralists
569 to overgraze rain-fed grasslands elsewhere, leading grassland degradation¹²³.

570 Another fast-developing area of ecological research that could assist grassland
571 restoration programmes concerns the application of knowledge of aboveground-belowground
572 interactions^{124,125}. A wealth of studies show that high grassland plant diversity can enhance
573 multiple ecosystem functions, both above- and belowground, and increase the resistance of
574 plant production to environmental perturbations, such as climate extremes¹²⁶⁻¹²⁸; such
575 knowledge could be applied to degraded grassland to restore ecosystem functions and their
576 resilience to environmental change^{129,130}. Benefits can also be realised through informed
577 selection of plant species based on functional traits, especially root traits, which has been
578 shown to be an effective way of enhancing grassland multifunctionality¹³¹ and the physical

579 properties of degraded soils¹³². Research points to the potential of soil inoculation and plant
580 translocation from donor sites to enhance the recovery of degraded ecosystems and steer plant
581 community development^{133,134}. Further, there is increasing awareness that diversifying
582 livestock promotes plant diversity and grassland multifunctionality¹³⁵, especially at moderate
583 levels of grazing¹³⁶, and that interventions can facilitate robust multi-trophic interactions in
584 restored ecosystems could benefit restoration¹³⁷.

585 A potential hurdle to the adoption of new research innovation is that the majority of
586 scientific knowledge underpinning grassland restoration comes from studies done at a local
587 scale and in a handful of regions, especially North America, Australasia and Europe. As such,
588 there is a need for new, long-term research to underpin approaches to large-scale restoration of
589 degraded grasslands, especially in Asia, Africa and South America where grassland
590 degradation is widespread¹³⁸. One solution to these geographic gaps might be the use of meta-
591 level analyses¹³⁹⁻¹⁴⁰ and data collection using standardised methodology from globally
592 distributed grassland studies such as the Nutrient Network¹⁴¹ and HerbDivNet¹⁴². These can
593 help to identify generalisable impacts of biotic and environmental drivers and disturbances,
594 such as grazing and nutrient enrichment, on grassland diversity and function, that could be
595 transferred to regions where data is lacking. However, that large gaps in environmental and
596 management conditions still need to be filled, and the ecological context will affect the specific
597 applicability of any generalisations¹⁴³. At all scales, new technology and practices need to be
598 embedded within socio-ecological approaches to grassland restoration to ensure empowerment
599 of local people and best outcomes for their quality of life.

600

601 **[H1] Summary and future perspectives**

602

603 Despite progress in understanding the causes and consequences of grassland degradation, and
604 in developing restoration techniques, there remain many barriers to halting grassland
605 degradation and effective restoration. Here, we have argued that overcoming these barriers
606 requires an integrated socio-ecological approach to grassland degradation and restoration,
607 which not only demands greater recognition of grasslands in global policy, but standardised
608 approaches for assessing grassland degradation and restoration success. It also requires the
609 adoption of innovations in environmental science for detecting grassland degradation and
610 enhancing restoration success, along with enhanced knowledge transfer and data sharing
611 regarding restoration experiences.

612 Many examples exist of national and international sustainability policies that have
613 ignored grasslands, including the SDGs and CBD. Giving due attention in sustainability policy
614 to grasslands and the ecosystem services they provide, on a par with other biomes such as
615 forests, is therefore essential for the future protection of healthy grasslands and restoration of
616 those that are degraded. The UN Decade on Ecosystem Restoration (2021-2030) and CBD
617 post-2020 global biodiversity framework provides an opportunity to set future targets for the
618 protection, sustainable management and restoration of grasslands, and prevent damaging
619 practices such as the planting of trees in natural grasslands¹⁴⁴. Put simply, if grasslands are to
620 be managed sustainably, then both global and regional policy must be revised to recognize the
621 value of grasslands for multiple ecosystem services and establish targets for their protection,
622 restoration and sustainable management.

623 There is hope in some initiatives, though. The Worldwide Fund for Nature launched a
624 ‘Global Grassland & Savannah Dialogue Platform’ in 2020, with the aim to “develop
625 consensus around human and biological importance of these ecosystems”. The UN Decade on
626 Ecosystem Restoration (2021-2030) has added ‘grasslands, shrubland and savannahs’ to their
627 set of focal ecosystems. Furthermore, while the Aichi targets of the CBD largely ignored
628 grasslands, and the draft of its post-2020 framework lacks specificity, the most recent synthesis
629 of the proposals of the parties includes mentions of grasslands (albeit other ecosystems such as
630 forest and wetlands are discussed more frequently).

631 Whilst we demonstrate how our five-step approach can be applied using specific case
632 studies, future research is needed to test this approach in different contexts and at local and
633 larger scales. Research is also needed to better understand different societal perceptions of
634 grasslands and the reasons why they have been neglected in sustainability policy, to develop
635 and test promising new ways of assessing grassland degradation and restoration, and to harness
636 ecological knowledge for restoration success. This aim will require ambitious, interdisciplinary
637 national and international research programmes of the kind that could be facilitated by major
638 research and innovation schemes targeted at achieving Sustainable Development Goals. We
639 hope the approach we present provides a basis for such future research aimed at the assessment
640 of grassland degradation and restoration in the context of stakeholder needs.

641 The actions we raise for developing effective socio-ecological solutions to the
642 degradation and restoration of global grasslands are not exhaustive and many challenges
643 remain. Nevertheless, we hope that they provide a guide to future research and policy needs
644 for halting grassland degradation and achieving restoration success. We also hope that they
645 serve to raise awareness of the plight of global grasslands and the need for urgent action to halt

646 grassland degradation and enhance restoration success, thereby conserving the many socio-
647 economic, cultural and ecological benefits that grasslands provide.

648

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650

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1039 **Author contributions**

1040 R.D.B. conceived the idea and gained funding with input from N.O. R.D.B wrote the paper
1041 with significant input from J.M.B, P.M., U.S. and S.L. G.L.P and P.M. designed the figures.
1042 All authors contributed to the development of ideas and writing of the paper.

1043 **Competing interests**

1044 The authors declare no competing interests.

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Table 1. Common ecosystem services of grasslands and indicators of associated ecosystem structure and function parameters

Ecosystem services	Ecosystem structure / function	Common indicators	Scale and means of measurement
Forage production (quantity)	Annual aboveground biomass production	Net primary productivity (NPP)	NDVI (remote sensing) at a landscape scale
		Aboveground biomass	Direct harvesting at a local scale
Forage production (quality)	Protein content and digestibility	Leaf N content	Remote sensing at a landscape scale
		Presence of species of nutritional importance	Direct measures at a local scale
Forage reliability	Interannual variation in aboveground biomass production	NPP	Remote sensing at a landscape scale
		Species composition	
Other grassland products (medicinal, food, hunting)	Species of particular interest	Species presence and/or abundance	Field survey at a local scale
Biofuels	Woody species of interest	Cover or biomass of species of interest	Direct field measures or remote sensing
	Grass species of particular interest (including flammable or high yielding species)		
Species of cultural value	Presence of species of cultural interest	Species presence	Local direct measures and records
			Regional surveys
Aesthetic value	Plant community composition and phenology	Flower and flower colour, and presence of 'unattractive' species	Direct surveys
		Flowering phenology	Species list and external databases for phenology
Biodiversity conservation value	Plant and animal (vertebrate and invertebrate) species	Presence and abundance of species of conservation value	Global Biodiversity Information Facility (GBIF) and national monitoring schemes

			at larger scales
			Direct surveys at a local scale
Regulation of invasive exotics and other undesired species	Invasive exotic species Species of negative pastoral or cultural value	Presence and abundance of undesired species	GBIF and national monitoring schemes at a larger scale Direct surveys at a local scale
Global climate regulation	Carbon stocks and carbon cycling processes	Soil respiration and carbon stocks Woody species biomass and vegetation carbon stocks Litter mass and depth	Remote sensing for aboveground stocks Soil sampling and interpolation for belowground carbon stocks and fluxes
Maintenance of soil fertility	Nutrient stocks and nutrient cycling processes	Soil nutrient and carbon content Litter mass Soil enzyme activities	Soil sampling and interpolation to required scales
Maintenance of soil stability and regulation of erosion	Soil stability in the root profile Erosive flows	Evidence for erosion, bare ground cover and soil organic matter (SOM), and measures of soil loss and erosive flows Soil aggregate stability, bulk density, and water holding capacity Plant rooting profile	Field observations or remote sensing to detect erosion Direct sampling and measurement of multiple indicators
Regulation of hydrological flows	Soil water retention and flows	Soil texture and bulk density, and SOM content Soil electrical and hydraulic conductivity)	Direct survey and interpolation Rapid assessment methods

Regulation of water quality	Retention and transformation of pollutants in soil	Soil properties including texture, pH, CEC, salinity and water table depth	Direct sampling of soil and water
		SOM content and available water capacity.	
		Nutrient and pollutant concentrations in freshwater bodies	

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1063 Figure legends

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Figure 1. Degraded grasslands. The extent of degraded grasslands worldwide with examples of paired non-degraded (left) and degraded (right) grasslands. Grassland classification follows the UN FAO Land Cover Classification System (LCCS) (data downloaded at <https://lcviewer.vito.be/2015>¹⁴⁵ with tundra ecosystems excluded). Degradation is measured as greenness changes, as measured by rain use efficiency (RUE) adjusted Sum Normalized Differential Vegetation Index (NDVI) between (1981-2015)¹⁴⁶ with regions showing a reduction in greenness of 0.01 being classed as degraded. Therefore, much degradation involving vegetation change is not shown. Degradation is caused by many factors, including overgrazing, fertilization, tree planting, and invasive species. Image credits: United States (L. Brudvig), United Kingdom (L. Hulmes), India (S.K. Chengappa), and Australia (S. Prober). Map © Copernicus Service Information year of publication [2015]

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Figure 2. Standardised assessment of grassland degradation and restoration. Included are the steps required to assess grassland condition and select restoration options. These include the assessment of demand for different ecosystem services by stakeholders (step 1) and identification of universal (step 2) and specific (step 3) ecosystem service, the evaluation of grassland restoration and identification of restoration options (step 4), and the shared selection and implementation of restoration strategy (step 5). The relationship between this approach

1084 and the other strategies described in this Perspective are shown on the side panel. For specific
1085 and quantitative examples of steps 1 and 4, see Figures 3 and 4. For steps 2 and 3, which relate
1086 to identifying indicators, see Table 1.

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1088 **Figure 3. Assessing ecosystem service trade-offs in degraded and restored European**
1089 **grasslands.** Steps 1 and 4 from Figure 2 are shown in greater detail so that the quantitative
1090 methods can be demonstrated. In this system, degradation caused by intensive agriculture
1091 reduces plant and soil biodiversity and causes soil compaction. This degradation diminishes
1092 the supply (SD) of ecosystem services demanded (D, represented for each group as D followed
1093 by a number) by stakeholders, resulting in a low multifunctionality (MF) for all stakeholder
1094 groups (D x SD). Restoration to high diversity grassland (SR1: Conservation) enhances the
1095 supply of multiple ecosystem services, though only moderately for fodder production and
1096 climate regulation through carbon storage. Thus, it provides the greatest multifunctionality to
1097 all stakeholder groups among restoration options. Restored high diversity grassland also
1098 provides the best option for priority ecosystem services (PR) for conservationists (see the D1
1099 x SR1 circle), and for local farmers given their demand for organically-maintained soil fertility
1100 and cultural identity (D2 x SR2), which could compensate for lower fodder production than
1101 intensive grassland (as in SR2: Livestock grazing). However, abandonment of agricultural
1102 management (SR3: Abandoned grassland) could be seen as favourable by some national
1103 decision makers due to their prioritization of water quality and climate regulation (D3 x SR3
1104 circle). All MF and PR scores are scaled between zero and one to provide a comparable metric
1105 and check marks (+, ++) indicate the restoration option with the highest MF or PR.

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1110 **Figure 4. Assessing ecosystem service trade-offs in degraded and restored grasslands in**
1111 **arid and semi-arid Eastern Africa.** Steps 1 and 4 from Figure 2 are shown in greater detail
1112 so that the quantitative methods can be demonstrated. In these regions, invasion of alien woody
1113 plants such as *Prosopis juliflora* transforms grasslands into scrubland with bare soil. While the
1114 supply (SD) of most ecosystem services (ES) demanded (D) by stakeholders is greatly reduced
1115 by this invasion, fuel wood and charcoal production are promoted (as in D2). The supply of
1116 other services, such as soil carbon storage, is context-dependent; if grassland previously
1117 degraded by overgrazing and other forms of mismanagement is invaded, then soil conditions

1118 are improved. However, if healthy grassland is invaded, the supply of these services is reduced.
 1119 All stakeholders, apart from charcoal producers, lose ecosystem service benefits (D2 x SD) if
 1120 undegraded grasslands are invaded by *P. juliflora*, and so perceive it as degradation.
 1121 Restoration options have differing impacts on stakeholder groups. Sustainable livestock
 1122 grazing (SR2) requires fencing off or access restriction but promotes ES supply more than
 1123 conservation (SR1) and supports the greatest multifunctionality (MF) from the perspective of
 1124 all the considered groups. Abandonment does not restore the supply of any ES and even incurs
 1125 ES losses (SR3), because *P. juliflora* consumes substantial amounts of groundwater. However,
 1126 considering economic priorities towards only the priority ES (PR) of fodder for pastoralists,
 1127 wood products for charcoal producers and ecotourism for tourists would lead these
 1128 stakeholders to respectively favour livestock production, abandonment or conservation as best
 1129 restoration options (highest respective PR scores). All MF and PR scores are scaled between
 1130 zero and one to provide a comparable metric and check marks (+, ++) indicate the restoration
 1131 option with the highest MF or PR.

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1139 **Box 1** | Case studies of successful grassland restoration.

1140

1141

1142 **[bH1] Ethiopia (Tigray & Amhara region)**

1143 Ref¹⁴⁷⁻¹⁴⁸

1144

1145 **[bH2] Restoration - Needs and Actions**

1146 [b1] Drivers of degradation: overgrazing

1147 [b1] People's needs: fodder, wood and water

1148 [b1] Restoration goal: promote soil fertility, herbaceous layer and tree growth, increase water
 1149 retention

1150 [b1] Actions: time series of area exclosures (5-20 years) protected by community bylaws and
 1151 /or hired guards.

1152

1153 **[bH2] Outcomes (+/-)**

1154 [b1] 2 to 3-fold increase in plant species richness, compared to areas outside exclosures

1155 [b1] 2 to 3-fold increase in vegetation cover

1156 [b1] Increased soil nitrogen, available phosphorus and cation exchange capacity

1157 [b1] Erosion and flood perceived to be highly reduced and soil moisture increased

1158 [b1] Improved provision of fodder for stall-fed livestock

1159 [b1] No published information on the economic benefits for local livelihoods.

1160

1161 ***[bH2] Opportunities and challenges***

1162

1163 [b1] Opportunities: government- and NGO-provided incentives including food for work and
1164 payments for the protection of exclosures

1165 [b1] Challenges: government has stopped paying incentives in some areas; membership to
1166 exclosures and distribution of benefits unclear; decision processes and forms of collaboration
1167 need clarification; limited participation by women in decision processes.

1168

1169 **[bH1] Brazil (Cerrado Region)**

1170 Refs ^{134,149}

1171

1172 ***[bH2] Restoration - Needs and Actions***

1173 [b1] Drivers of degradation: pine plantations (afforestation) and invasions

1174 [b1] People's needs: water

1175 [b1] Restoration goal: recovery of herbaceous layer; increase habitat for grassland fauna
1176 threatened by land conversion and woody encroachment

1177 [b1] Actions: cutting pines, prescribed burns, transplanting native grasses, controlling re-
1178 invasion by pines and exotic grasses

1179 ***[bH2] Outcomes (+/-)***

1180 [b1] Within two years, recovery of 70% the ground cover and 55% plant species relative to
1181 reference ecosystem.

1182 [b1] 65 plant species recorded after two years

1183 [b1] Increase of grassland area in the protected area by 5%

1184 [b1] Rise in the water table in a cleared watershed

1185 [b1] Economic benefits not expected nor quantified

1186

1187 ***[bH2] Opportunities and challenges***

1188

1189 [b1] Opportunities: eradication of pines mandatory in protected areas; companies obliged to
1190 mitigate environmental damage by carrying out restoration work experiments provide
1191 scientific support for the practices applied

1192 [b1] Challenges: tendency for woody encroachment and re-invasion by pines from the
1193 neighbourhood; fire management would be an important tool but there are legal constraints in
1194 restored ecosystems; invasion by exotic grasses is a permanent threat.

1195

1196 **[bH1] China (Inner Mongolia)**

1197 Ref ^{80,150,151,152,153,154}

1198

1199 ***[bH2] Restoration - Needs and Actions***

1200 [b1] Drivers of degradation: overgrazing

1201 [b1] People's needs: increased revenue from livestock

1202 [b1] Restoration goal: mutually beneficial outcome for environmental health and household
1203 income

1204 [b1] Actions: reduced stocking rates since 2004; optimization of management practices (such
1205 as the increased use of feed supplement in winter and spring, and retaining the most
1206 productive animals) to increase efficiency.

1207 ***[bH2] Outcomes (+/-)***

1208 [b1] Reduction in stocking rate increased aboveground and below-ground biomass, species
 1209 diversity, C sequestration and storage, and net sustainable livestock carrying capacities of
 1210 desert grassland in China

1211 [b1] Light and moderate grazing led to greater ecosystem stability

1212 [b1] Low stocking rate, reducing number of old animals and other optimization practices
 1213 increased net household income and alleviated grazing pressure.

1214 ***[bH2] Opportunities and challenges***

1215 [b1] adoption of policies for poverty alleviation and grassland restoration, including
 1216 environmental payment schemes, hiring of supervisors to protect grassland ecosystems, or
 1217 funding of warm sheds; adoption of an energy-balance/market-based approach to reduce
 1218 livestock numbers; increased demand for meat in China

1219 [b1] Challenges: uptake of practices of reducing animal numbers and optimizing livestock
 1220 management by pastoralists.

1221

1222

1223 **[bH1] China (Qinghai Tibetan Plateau)**

1224 Ref¹⁵⁵⁻¹⁵⁸

1225 ***[bH2] Restoration - Needs and Actions***

1226 [b1] Drivers of degradation: human disturbance (overgrazing, excessive exploitation), climate
 1227 change, rodent damage as secondary cause

1228 [b1] People's needs: reasonable income, sustainable grassland management, water
 1229 conservation

1230 [b1] Restoration goal: promote herbaceous layer; restore soil health; reduce area of 'black
 1231 soil' degraded grassland

1232 [b1] Actions: planting artificial or semi-artificial grasslands; reducing grazing pressure;
 1233 establishing protected areas.

1234 ***[bH2] Outcomes (+/-)***

1235 [b1] Continued degradation in grassland has initially been stopped

1236 [b1] In a 17-year chronosequence, grassland restoration increased plant biodiversity and
 1237 vegetation cover; soil total nitrogen sequestration improved by 25%–40%

1238 [b1] Water supply capacity of watersheds has increased

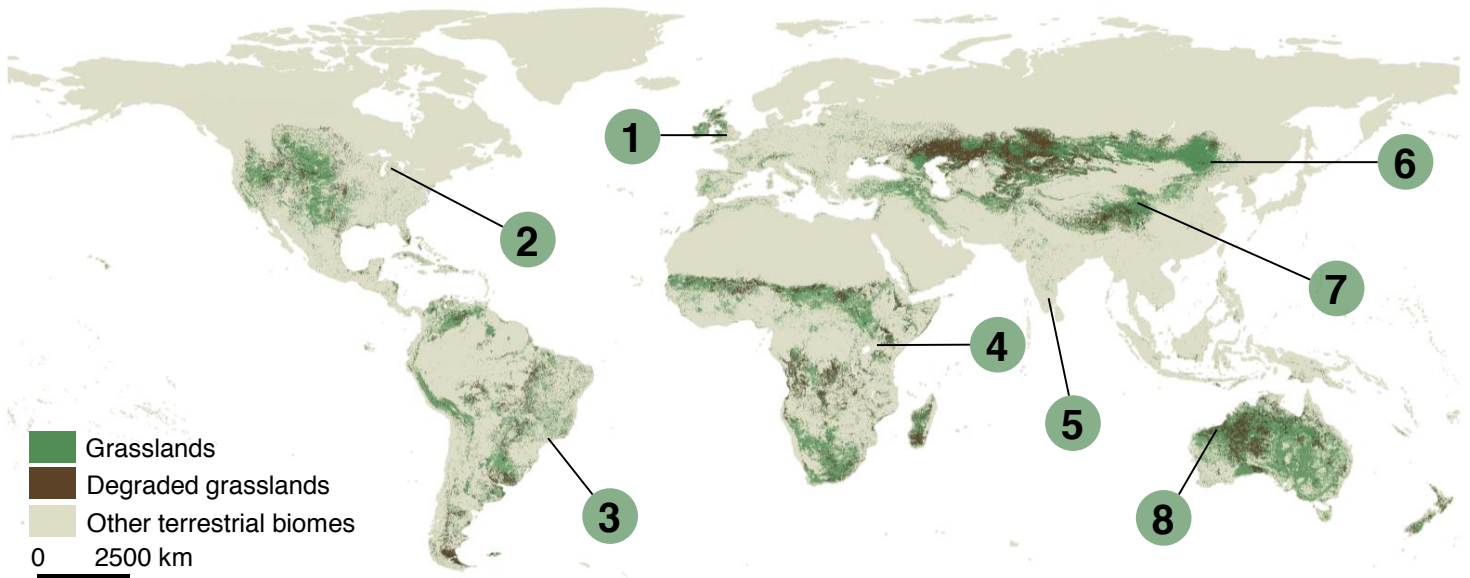
1239 [b1] No significant change in economic profit along restoration chronosequence

1240 ***[bH2] Opportunities and challenges***

1241 [b1] Opportunities: increased awareness that grassland degradation is not only a threat to
 1242 pastoral livelihoods, but also to ecological stability of the region and to people living in other
 1243 regions implementation of environmental payment schemes; government provided funding for
 1244 an ecological conservation and restoration project in the Three-River Source Region

1245 [b1] Challenges: could affect livelihoods because it restricts access to grazing areas; change in
 1246 grazing system can require high input costs (stalls, new feed sources); collaboration among
 1247 farmers, local officials and extension workers required for technology transfer and policy
 1248 implementation.

Global grassland degradation



1



United Kingdom

Ploughing, reseeding and fertilisation has transformed species-rich chalk grasslands into 'improved' grasslands with higher fertility, lower species richness and lower levels of many cultural ecosystem services.

2



United States

Reseeding and fertilisation of tallgrass prairie has transformed species-rich prairie grasslands with a mixture of native C3 and C4 grasses, sedges and forbs, to species-poor grassland dominated by Eurasian C3 grasses.

3



Brazil

Soil tillage and fertilisation for cultivation of Cerrado grasslands destroy underground plant structures and soil aggregates, severely lowering resilience of these ancient and highly diverse ecosystems.

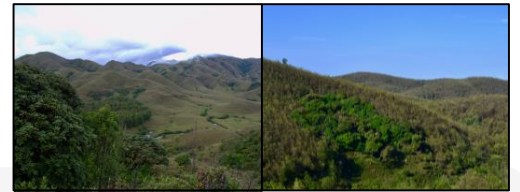
4



Kenya

Decades of overgrazing by cattle and sheep of lowland grassland in Kenya has caused excessive soil erosion, and loss of biodiversity and ecosystem services.

5



India

Invasion by exotic woody species, primarily *Acacia Mearnsii*, poses a major threat to ancient shola-grassland mosaics in the upper reaches of the Nilgiri Biosphere Reserve, Western Ghats.

6



Inner Mongolia, China

Planting of pine trees in semi-arid grasslands can reduce plant diversity, damages soils, and increase water shortages.

7



Qinghai-Tibetan Plateau, China

Extensive overgrazing and the increase in rodent population have caused widespread degradation of alpine grasslands, causing soil erosion and loss of biodiversity and ecosystem services.

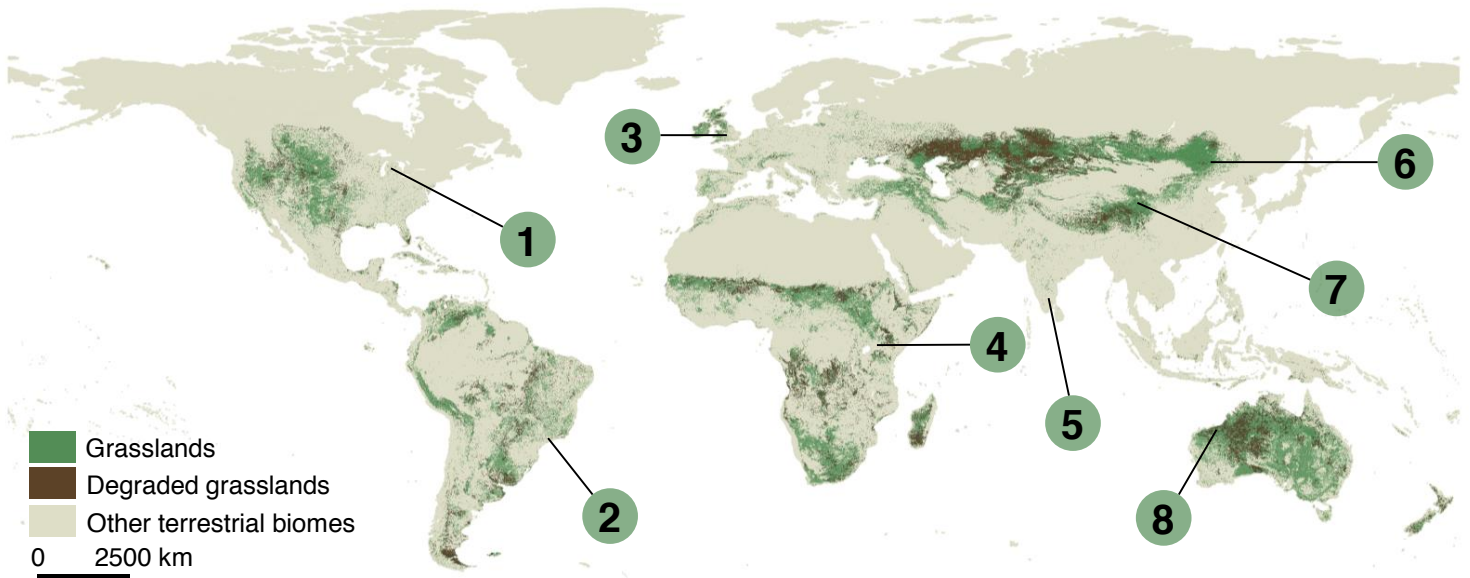
8



Australia

In many parts of Australia, livestock grazing can quickly break down *Themeda* swards and promote invasion by exotic species.

Global grassland degradation



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2



Brazil

Cultivation and abandonment of Cerrado grasslands poses a major threat to these ancient and highly diverse ecosystems.

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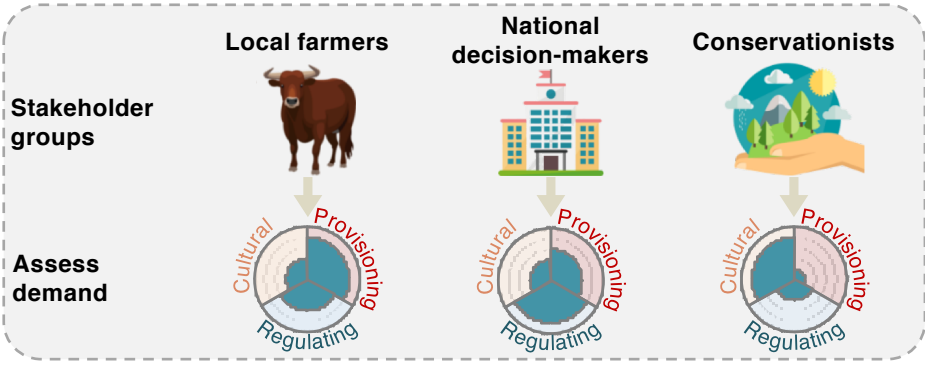
8



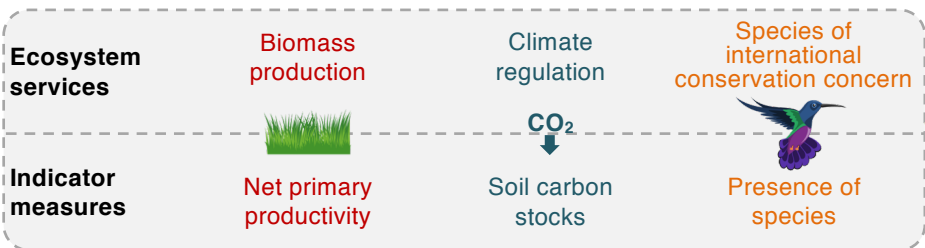
Australia

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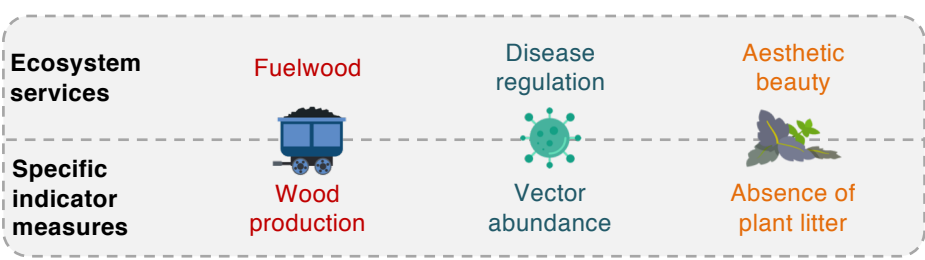
1 Assess demand for different ecosystem services by multiple stakeholder groups



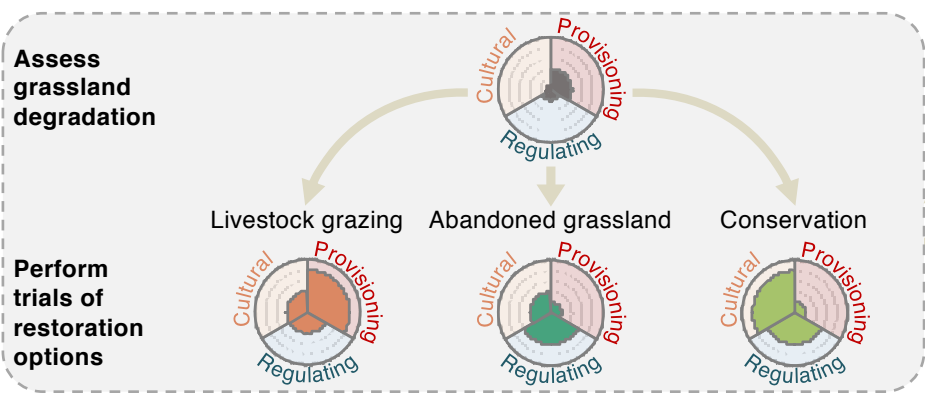
2 Identify universal ecosystem service indicators



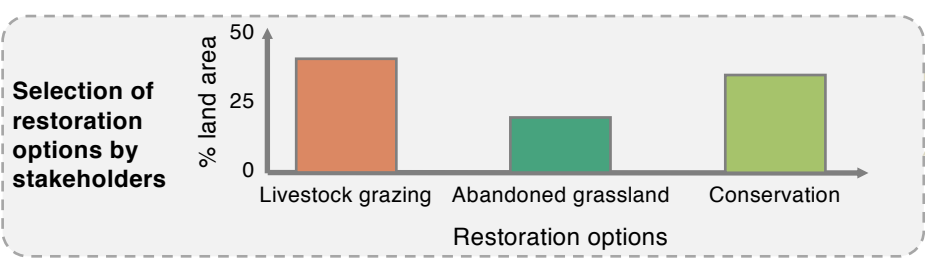
3 Identify indicators for specific ecosystem services



4 Evaluate grassland degradation and identify restoration options



5 Select and implement restoration strategy via participatory approaches

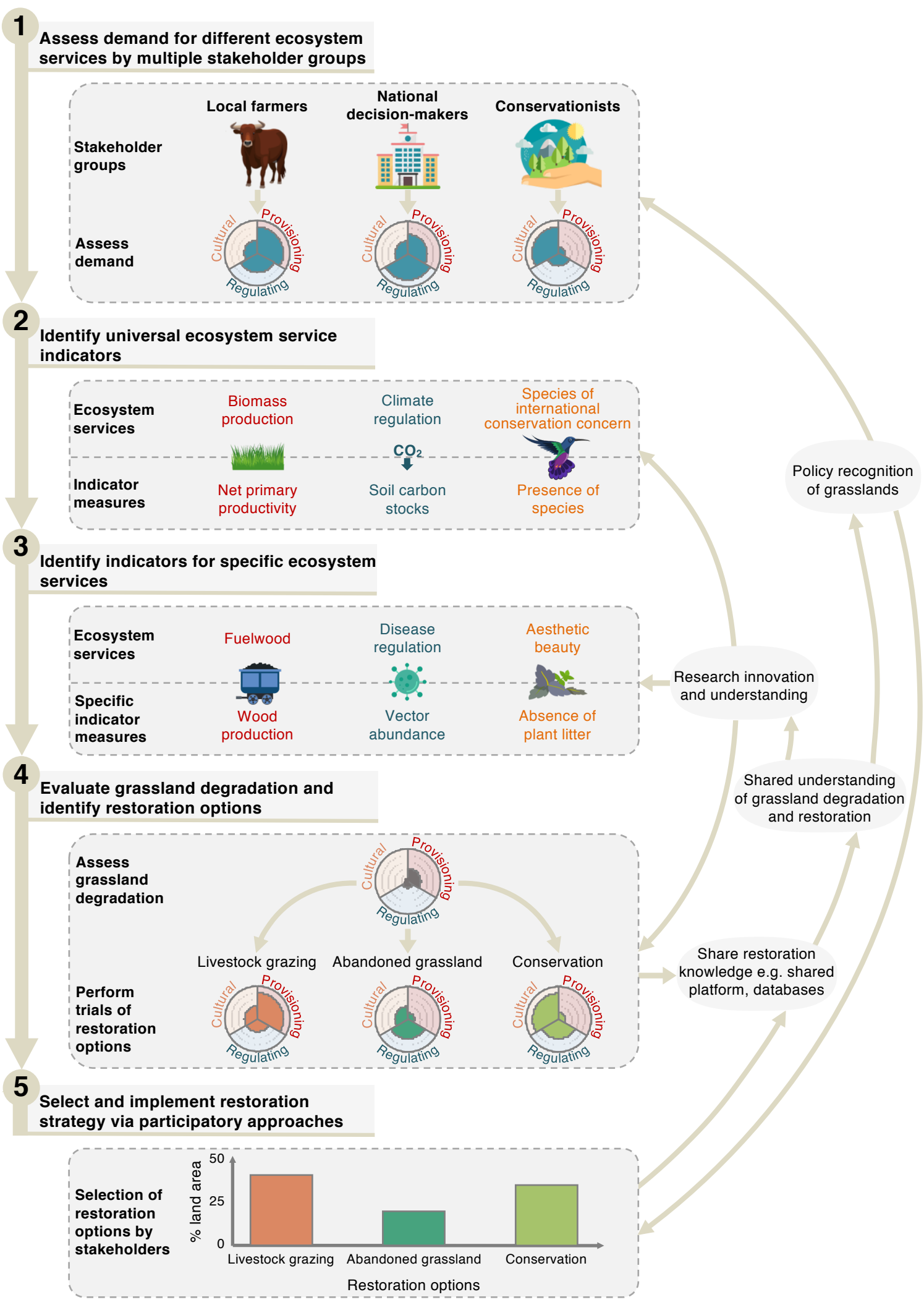


Policy recognition of grasslands

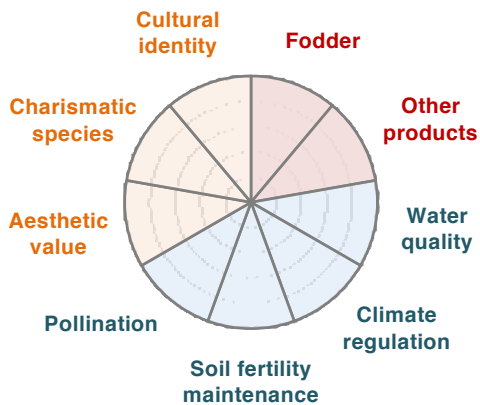
Research innovation and understanding

Shared understanding of grassland degradation and restoration

Share restoration knowledge e.g. shared platform, databases



Ecosystem services



Stakeholder groups

Conservationist



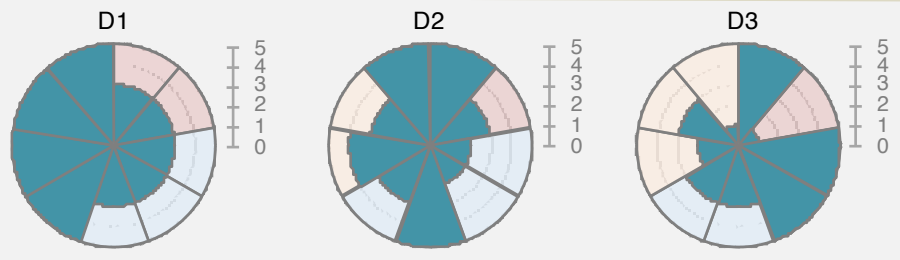
Local farmer



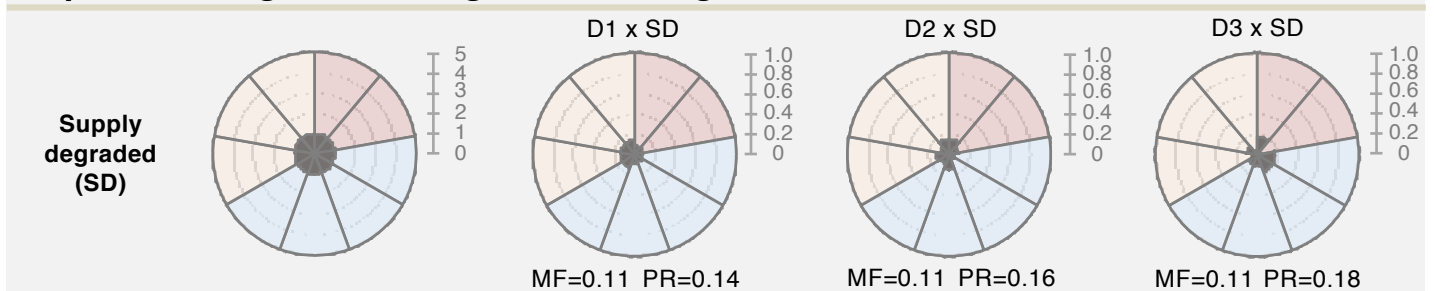
National decision-maker



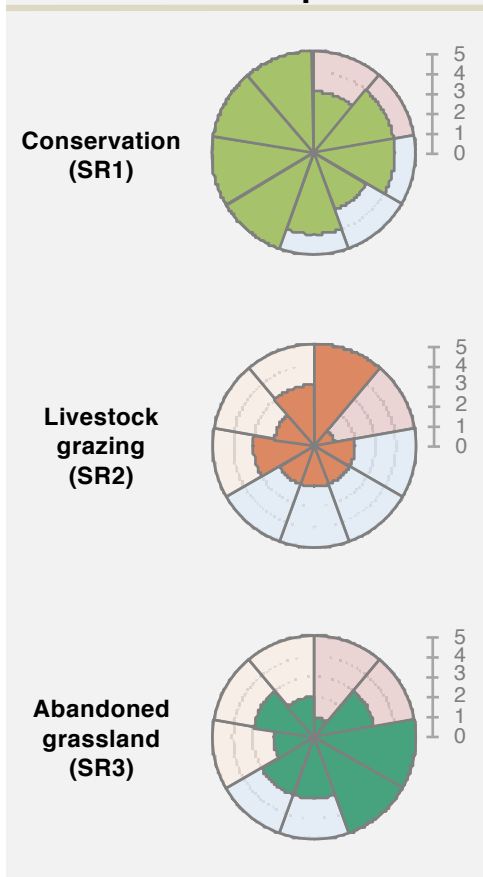
Step 1: Assess demand for different ecosystem services



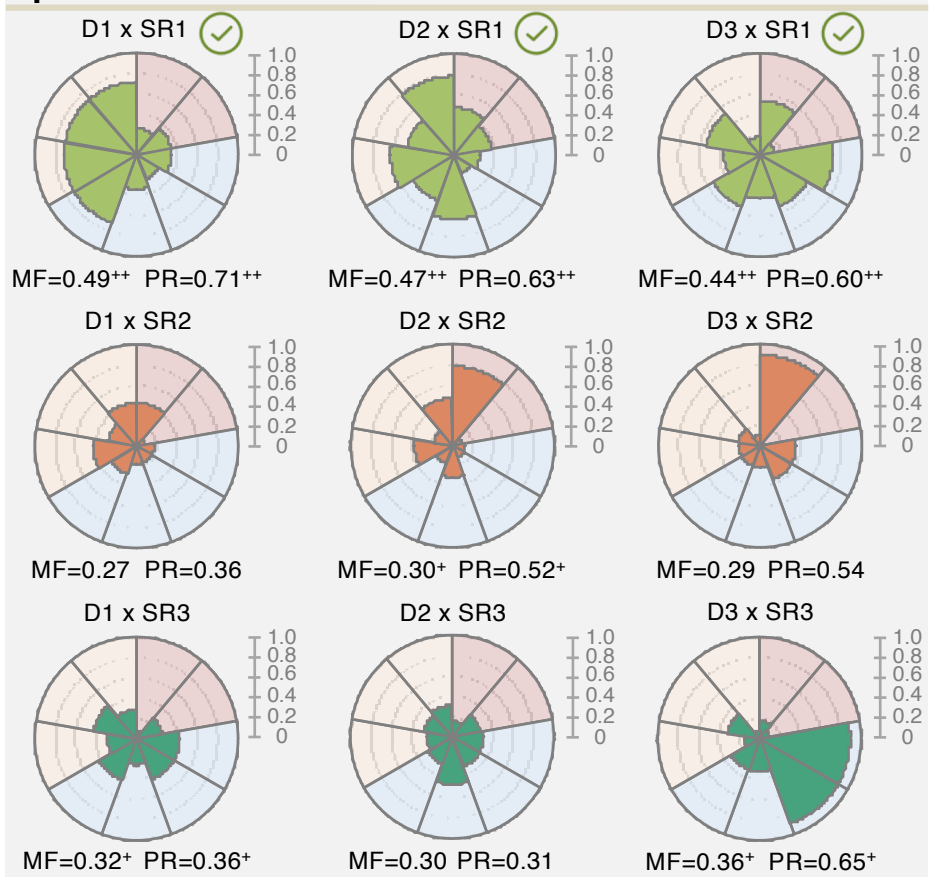
Step 2: Assess grassland degradation using identified indicators



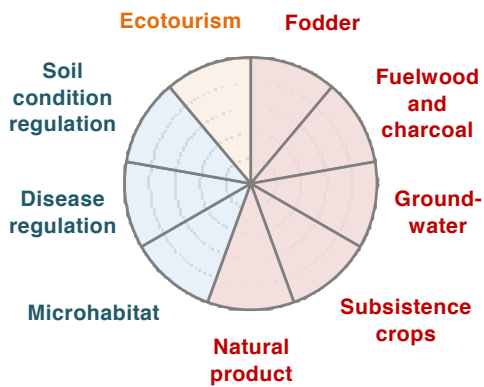
Step 3: Measure supply gain from restoration options



Step 4: Assess stakeholder benefits from restoration options



Ecosystem services



Stakeholder groups

Pastoralist



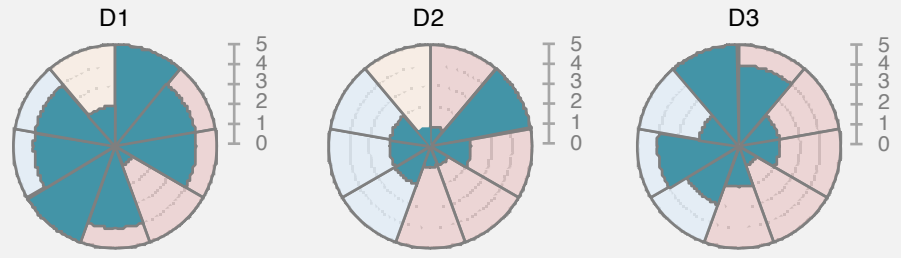
Charcoal producer



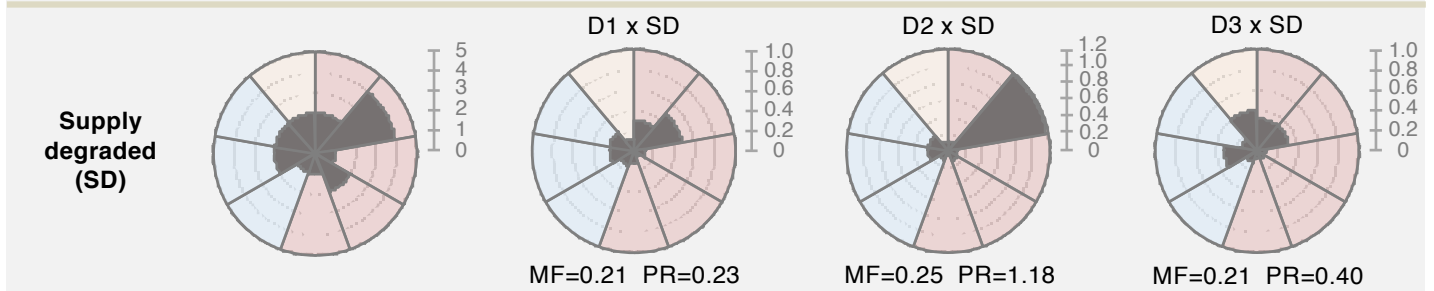
Tourist



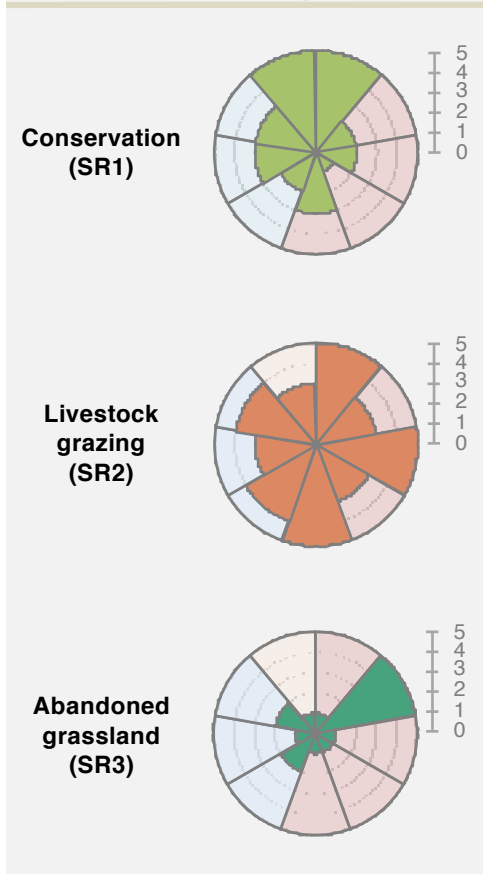
Step 1: Assess demand for different ecosystem services



Step 2: Assess grassland degradation using identified indicators



Step 3: Measure supply gain from restoration options



Step 4: Assess stakeholder benefits from restoration options

