

1 **Towards comparability among state-and-transition models:**

2 **A set of generalised templates linked to ecosystem condition**

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80

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82 condition; ecosystem dynamics; environmental accounting; natural capital, nature positive;  
83 reference states; state-and-transition models

## 84 **Abstract**

85 Growing commitments to environmental sustainability and nature conservation by industry,  
86 government and communities globally have led to a pressing need for consistent methods to  
87 characterise and quantify outcomes of land use and ecological restoration. State-and-transition  
88 models (STMs) are widely used to describe and communicate knowledge about ecosystem  
89 dynamics and are increasingly applied in such contexts. However, STMs are usually tailored to  
90 specific ecosystems and questions, resulting in models that vary widely in character and  
91 representation.

92 To support comparability among STMs and facilitate their application to large-scale  
93 environmental initiatives, we collaborated with over 100 ecological scientists, restoration  
94 practitioners, and environmental program managers to design a set of generic STM templates and  
95 guides. These have already assisted the development of 28 STMs for Australia's Nature Repair  
96 Market and other land management programs, enabling iterative testing and improvement.

97 Our templates recognise common patterns of ecosystem modification and restoration across  
98 terrestrial ecosystems. Three primary templates distinguish an ecologically defining layer from  
99 complementary layers, including overstorey versus understorey in forests and woodlands, shrub  
100 versus tree or ground layers in shrublands, and ground versus woody layers in grasslands. The  
101 templates recognise potential for independent modification or recovery gradients in these layers,  
102 leading to a matrix of 16 core ecosystem states, augmented by a set of intensive land-use states.

103 Four secondary templates identify potential finer distinctions within ecological layers.

104 Supporting guides (a) propose a set of attributes for describing states, (b) specify ranges for  
105 ecosystem condition scores to guide user allocation of states to the template, and (c) support  
106 identification of plausible transitions between states.

107 Our templates and guides advance state-and-transition modelling by establishing a consistent yet  
108 flexible foundation for applying STMs in environmental management programs, environmental  
109 accounting, and on-ground ecosystem management. They achieve this by establishing a common  
110 framing of ecosystem states linked to ecosystem condition, and aligning with globally-  
111 established frameworks. While developed in an Australian context, the templates are adaptable to  
112 any terrestrial ecosystem where a historic, climate-adapted or idealised reference state is  
113 identifiable. We propose further development to support Indigenous engagement, systematic  
114 integration of climate change, and representation of landscape and fauna dynamics.

## 115 **INTRODUCTION**

116 New market-based approaches to promote environmental sustainability and counter the global  
117 decline in native biodiversity are gaining momentum, augmenting longer-standing government-  
118 funded natural resource management programs (Luxton et al., 2024). New approaches include  
119 biodiversity certification to create market advantage (e.g. the Global Biodiversity Standard,  
120 Bartholomew et al., 2024), biodiversity trading or credit schemes (e.g. Australian Government,  
121 2025), and regulations linking agricultural imports to land conversion (e.g. Regulation (EU)  
122 2023/1115, 2023). These in turn are facilitated by emerging voluntary initiatives such as the  
123 Taskforce for Nature-related Financial Disclosures, which guides industry in reducing nature-  
124 related risk (TNFD, 2023), and agricultural sustainability frameworks that enable industry and  
125 governments to support agricultural sustainability claims (e.g. McRobert et al., 2023).

126 The growing commitment to these sustainability and nature conservation initiatives has led to a  
127 pressing need for consistent approaches to characterising and quantifying land-use impacts on  
128 ecosystems and biodiversity, and for planning and evaluating ecological management  
129 interventions (e.g. Czuz et al., 2021). State-and-transition models (STMs, Bestelmeyer et al.,

130 2003; Westoby et al., 1989) are powerful tools for synthesising and communicating knowledge  
131 about ecosystem dynamics, that have potential to address this need.

132 State-and-transition models identify relatively stable manifestations of ecological communities  
133 (**ecosystem states**; see Appendix S1 Glossary for bolded terms), and describe the **transitions**  
134 among these using box and arrow diagrams (Westoby et al., 1989). The models can include  
135 transitions between alternative stable states (Holling, 1973; Lewontin, 1969) that are abrupt or  
136 irreversible, as well as more progressive transitions (Westoby et al., 1989). In this way STMs are  
137 more flexible than traditional models of ecological change founded on concepts of ecological  
138 succession, which assume a single, gradual and potentially reversible transition to a stable  
139 vegetation climax state after disturbance (Clements, 1916; Dyksterhuis, 1949).

140 State-and-transition models have been widely employed by ecological researchers and land  
141 managers globally, to characterise ecological change and build understanding of associated  
142 ecological or social drivers relevant to ecosystem management (e.g. Bestelmeyer et al., 2003;  
143 George et al., 1992; Huntsinger & Bartolome, 1992; Orning et al., 2023, Szetey et al., 2025,  
144 Young et al., 2014). Increasingly, applications are expanding to broader environmental policy  
145 and programs, including ecosystem and natural capital accounting (e.g. Rainsford et al., 2024;  
146 Richards et al., 2023), regional and national land management programs (Bestelmeyer et al.,  
147 2017; Blankenship et al., 2021; Burns et al., 2016; Herrick et al., 2025), and nature markets  
148 (Murphy et al., 2025). In both management and policy contexts, STMs can provide a discerning  
149 framework for characterising diverse values of different ecosystem states, guiding management  
150 interventions towards states that are higher in desired values, and evaluating outcomes.

151 Choices among alternative values to assess ecosystems involve value judgments, so these values  
152 should be made explicit. Potential values include ecosystem services (e.g. carbon storage,

153 recreation, agricultural production), specific biodiversity values such as threatened or culturally  
154 significant species, values associated with broader persistence of biodiversity and integrity of  
155 ecosystems (Richards et al., 2023), and cultural services and well-being of traditional custodians  
156 (Woodward et al., 2023). The values are commonly reflected in measures of **ecosystem**  
157 **condition**, defined by United Nations (2024) as *‘the quality of an ecosystem measured in terms*  
158 *of its abiotic and biotic characteristics. It is assessed with respect to an ecosystem’s composition,*  
159 *structure and function, which, in turn, underpin the integrity of the ecosystem, and support its*  
160 *capacity to supply ecosystem services on an ongoing basis’*. Here we focus on values of  
161 ecosystems for biodiversity captured in the concept of **ecosystem integrity**, defined as *‘the*  
162 *ecosystem’s capacity to maintain characteristic composition, structure, functioning and self-*  
163 *organization over time within a natural range of variability’* (UN, 2024).

164 Ecosystem condition assessed from the perspective of ecological integrity or biodiversity  
165 (hereinafter ‘ecosystem condition’ for brevity) is typically expressed on a scale from 0–1 (e.g.  
166 UN, 2024). However, such one-dimensional scales are inadequate for recognising the varied  
167 outcomes of ecosystem modification. A single ecosystem condition score can reflect a variety of  
168 ecosystem states, each with different characteristics shaped by different ecological drivers, and  
169 with different values for biodiversity and ecosystem services. For example, within tussock  
170 grasslands both loss of palatable grasses and forbs and invasion by woody species (e.g. Aweto,  
171 2024) can lead to similar ecosystem condition scores, although their habitat structure and  
172 ecosystem services differ. Linking ecosystem condition to states in STMs thus enables the  
173 retention of critical ecological information alongside condition scores, including the multiple  
174 characteristics of states and associated ecological drivers.

175 Increasing application of STMs to broad-scale sustainability and nature conservation initiatives  
176 call for more consistent approaches to developing STMs and linking ecosystem states to  
177 ecosystem condition. Historically, STMs have been developed at local to regional scales towards  
178 varied purposes, resulting in a diversity of STMs with widely differing emphases, designs and  
179 resolutions (i.e. degrees of granularity). For example, at least six different STMs representing  
180 eucalypt woodlands in south-eastern Australia have been published (e.g. McIntyre & Lavorel  
181 2007; Rainsford et al., 2024; Rumpff et al., 2011; Prober et al., 2002; Spooner & Allcock, 2006;  
182 Szetey et al., 2025). These are valuable for their established purposes, but inherent differences  
183 make them difficult to apply at program- or national-scales. Further, Twidwell et al. (2013) found  
184 789 regional-scale models were inconsistent in design and application even though they were  
185 developed towards a national-scale US rangelands program.

186 Given that drivers and outcomes of ecological change exhibit strong commonalities across  
187 ecosystems (e.g. Lu et al., 2024), it should be feasible to capture these shared patterns in  
188 templates and protocols to facilitate consistency in STM development. Such tools would provide  
189 a significant step toward coherent synthesis of ecosystem dynamics across **ecosystem types**, in  
190 turn facilitating a foundation for ecological management and policy and communicating  
191 ecosystem dynamics. At the same time, it is important that any such approach retains the  
192 flexibility to tailor STMs to project objectives (Bestelmeyer et al., 2017).

193 To address this need, we worked with more than 100 ecologists, land managers and decision  
194 makers to develop, trial and refine a set of generic templates and guides to facilitate  
195 comparability among STMs. Here we describe the methods and principles for developing the  
196 templates, and provide the tools in user-ready form, including: (1) a set of ecosystem states  
197 templates for forests and woodlands, shrublands, and grasslands; (2) a set of attributes for

198 describing ecosystem states; (3) ranges for ecosystem condition scores to guide user allocation of  
199 their states to the template; and (4) a guide to assigning plausible transitions between states.

## 200 **METHODS**

201 Establishing the STM tools involved three steps: (1) developing a preliminary template of  
202 ecosystem states and associated attributes list, (2) testing and adapting the preliminary template  
203 for 11 broad ecosystem types at an expert workshop, and (3) follow up synthesis and refinement  
204 facilitated by application in five subsequent STM workshops (Figure 1). These steps are outlined  
205 further below. The workshops and wider project adhered to human ethics procedures (CSIRO  
206 Human Research Ethics approval numbers 248/23 and 046/24).

### 207 **Preliminary template and attribute set**

208 To develop the templates, we focused on identifying generic ecosystem states that are relevant  
209 across terrestrial ecosystem types and can be characterised further when developing an STM for  
210 a specific ecosystem type. Ecosystem states apply to distinct configurations of ecosystem  
211 structure, function and composition that can occur at scales of tens of square metres to many  
212 square kilometres, noting broader landscape contexts (e.g. connectivity) were outside our scope.

213 A preliminary template of ecosystem states for forests and woodlands was progressively  
214 developed by the core project team of 12 ecological scientists (Appendix S2: Figure 1), using the  
215 Vegetation Assets, States and Transitions (VAST) framework (Thackway & Lesslie, 2006) as a  
216 starting point. The VAST framework defines a series of six vegetation categories, that were  
217 established to enable consistent national-scale assessment of vegetation trends. VAST categories  
218 are partitioned based on the degree of post-colonisation human modification, ranging from  
219 'residual' (intact), through modified, transformed, replaced-adventive and replaced-managed, to

220 removed. Key diagnostic criteria in the VAST framework include degree of alteration of  
221 vegetation composition, structure and regenerative capacity. Further development included  
222 trialling at four regional STM development workshops, Appendix S2: Table S1) and refining to  
223 accommodate ecosystem states frequently included in STMs. These included states that do not fit  
224 in a simple linear sequence of change in ecosystem condition, and states with fundamentally  
225 altered ecosystem processes (e.g. affected by rising saline water tables).

226 We drew on the globally-established Society for Ecological Restoration (SER) Recovery Wheel  
227 and associated ‘Five-star system sub-attributes table’ described in Gann et al. (2024) (hereinafter  
228 SER five-star system), and other sources (Eyre et al., 2017; Parkes et al., 2003), to (1) guide  
229 development of a preliminary attributes list for characterising ecosystem states (Appendix S3),  
230 and (2) inform allocation of ecosystem condition scores to conceptual ecosystem states in the  
231 template. The SER five-star system defines a set of attributes for describing ecological  
232 characteristics of restoration projects, on a scale from zero to five stars compared against a **high**  
233 **integrity reference state**. While the SER five-star system was developed with a focus on  
234 outcomes of ecological restoration, it is equally relevant to paths of modification away from  
235 reference. Eyre et al., (2017) and Parkes et al., (2003) underpin established methods for  
236 assessment of ecosystem condition by State governments in Australia.

### 237 **STM templates expert workshop**

238 We held a two-day face-to-face workshop in February 2025 involving 54 ecological scientists,  
239 restoration practitioners, and environmental program managers. The workshop aimed to (1)  
240 refine the preliminary STM template and attributes list and extend them to apply across a broader  
241 set of ecosystem types and contexts, and (2) explore how ecosystem states in the template could  
242 be related to ecosystem condition. Participants worked in six groups, each assigned one or two of

243 11 terrestrial ecosystem types representing vegetation groups aggregated from Australia's  
244 National Vegetation Information System (Department of Climate Change, Energy, the  
245 Environment and Water, DCCEEW, 2025). The ecosystem types were: (1) rainforests; (2)  
246 eucalypt, (3) casuarina, (4) *Melaleuca*, (5) *Callitris*, and (6) *Acacia* forests and woodlands; (7)  
247 mallee (multi-stemmed) eucalypt woodlands; (8) chenopod shrublands; (9) heathlands; (10)  
248 tussock grasslands; and (11) hummock (*Triodia* spp.) grasslands (Appendices S2, S4: Section 1).

249 Template refinement proceeded in two stages. First, each group tested and adapted their  
250 preliminary template, retaining a similar level of granularity (e.g. groups could remove irrelevant  
251 states or add new ones but could not subdivide states beyond the detail of the original template).  
252 Second, to accommodate greater ecological complexity, groups were encouraged to develop  
253 secondary templates incorporating finer distinctions among states. Template development aimed  
254 for a balance between adequately capturing common and distinct patterns of ecosystem structure,  
255 function, and composition, whilst favouring simplicity through fewer states and fewer templates.

256 Participants also trialled and refined the preliminary set of attributes (variables used to describe  
257 the characteristics of each ecosystem state), and used a group consensus approach to rank  
258 ecosystem states by their relative ecosystem condition for each ecosystem type. Further  
259 information on participant selection and workshop sessions is provided in Appendix S2.

## 260 **Synthesis and refinement of templates and guides**

261 Following the templates workshop, information was synthesised by the core project team into a  
262 set of tools—a draft set of STM templates, an ecosystem condition score guide and an attributes  
263 table. This was followed by two parallel steps: (1) elicitation and incorporation of feedback from  
264 workshop attendees and other experts, and (2) deployment of the tools at six further STM  
265 workshops (involving development of 16 regional-scale STMs and identifying plausible

266 transitions for four generic shrubland types, Appendix S2: Table 1). These steps facilitated  
267 further refinement of the templates and associated condition score ranges, and informed  
268 development of a guide for assigning transitions among ecosystem states.  
269 Specific deliberations around points of difference among workshop groups in the development of  
270 templates, and associated decisions, are documented in Appendix S2. The following sections  
271 describe each of the outputs and how they can be applied to develop STMs.

## 272 **ECOSYSTEM STATES TEMPLATES**

273 Three generic ecosystem states templates were developed to represent the broad structural  
274 variation across terrestrial ecosystems — one for forests and woodlands, one for shrublands and  
275 one for grasslands (or other largely herbaceous terrestrial ecosystems, Figures 2,3; Appendix S4:  
276 Section 2) (Appendix S4: Section 1). Sparsely vegetated ecosystems, marine ecosystems, tidal  
277 wetlands and inland waters (including wetlands) were outside our scope. Four optional, higher-  
278 resolution '*secondary*' templates were added to account for further detail in specific layers of the  
279 primary templates (Figure 4).

280 All templates retain the general concept introduced in the VAST framework (Thackway &  
281 Lesslie, 2006) of four non-intensive land-use categories (VAST categories I–IV) partitioned  
282 along an ecosystem condition gradient, and a set of intensive land-use states. As in the VAST  
283 framework, these categories often involve pragmatic divisions along a continuum.

284 We made two changes to the VAST framework to suit the needs of state-and-transition  
285 modelling. First, we tailored the conceptualisation and terminology of VAST categories I–IV to  
286 accommodate commonly encountered ecosystem states. This resulted in the categories *Close to*  
287 *reference* through *Modified* and *Highly modified* to *Collapsed/transformer*, spanning the

288 condition gradient (Table 1). Second, we expanded the classification from a one-dimensional  
289 gradient to a two-dimensional matrix, allow independent recognition of ecosystem modification  
290 in different **ecological layers** (i.e. the biotic assemblages and ecological processes associated  
291 with defined strata of an ecosystem).

## 292 **Concepts of reference and the *Close to reference* category**

293 The *Close to reference* category aligns with the VAST ‘Residual’ category I (Table 1). This aligns  
294 with reference concepts in the System for Environmental Economic Accounting Ecosystem  
295 Accounting (SEEA EA; UN, 2024), where reference refers to characteristics against which ‘*past,*  
296 *present or future ecosystems are compared in order to measure relative change over time*’ (Keith,  
297 Czúcz et al., 2020). In the context of the STM templates, a **reference state** has characteristics  
298 reflecting highest ecosystem condition of the ecological community of interest.

299 We emphasise that in our context, the term *Close to reference* is used in conjunction with the  
300 concept of a **High integrity reference**; that is, an ecosystem that maintains “*its characteristic*  
301 *composition, structure, functioning and self-organization over time within a natural range of*  
302 *variability*” (Parrish et al., 2023; UN, 2024). A *High integrity reference* thus has the highest  
303 ecosystem condition score of 1.0 or 100%. *Close to reference* encompasses a broader range in  
304 ecosystem condition, including the *High integrity reference*, but typically exhibiting some  
305 modification of ecosystem attributes. This category is used for pragmatic reasons—to reduce  
306 complexity in STMs (with fewer, more broadly-defined states), and for practical assessment of  
307 reference where the *High integrity reference* is no longer present and not well understood.

308 Aligned with the concept of ‘natural range of variability’ included in definitions of ecosystem  
309 integrity (Parrish et al., 2003; UN, 2024), we propose that the templates employ a dynamic  
310 concept of reference (Richards et al., 2020; Robert, 2024). This can be achieved using the

311 approach outlined in the **Australian Ecosystem Models Framework** (Richards et al., 2020).  
312 Here, a *High integrity reference*’ can be described using an ‘**archetype** model’ that comprises a  
313 set of ‘**ecosystem expressions**’ connected by pathways associated with natural disturbance and  
314 recovery processes (including long-standing indigenous land management). For example, an  
315 archetype model for an Australian mallee ecosystem type includes mature expressions with  
316 multi-stemmed trees, that are converted by fire to expressions characterised by dead above-  
317 ground woody stems and basal resprouting. Over time and without additional disturbance, this  
318 resprouting expression develops into a mature expression (e.g. Richards et al., 2020).  
319 Recognising such variation nested within ecosystem states is critical to avoid erroneous  
320 interpretation of transient expressions as altered states with poorer ecosystem condition.  
321 The term ‘natural’ employed in the definition of ecosystem integrity also requires clarification.  
322 Here, we use the term natural to include Indigenous human-environment relationships that have  
323 evolved over many millennia. This is consistent with concepts of reciprocal contributions  
324 between people and nature (Ojeda et al., 2022), and contrasts with the rapidly escalating human-  
325 mediated decline in biodiversity observed since industrialisation (Robert, 2024).  
326 Naturalness or ecosystem condition can be measured in terms of departure from a reference (UN,  
327 2024). The conceptual framework for reference sites put forward by McNellie et al. (2020)  
328 highlights potential to choose from a number of framings against which ‘natural’ characteristics  
329 and dynamics may be defined. A common choice of reference is an Indigenous cultural  
330 reference, reflecting the characteristics and dynamics of ecosystems prior to colonization of  
331 Indigenous cultures by Colombian, Roman, European or other colonizers, including Indigenous-  
332 driven ecosystem management (e.g. use of fire). This is the typical application of reference in  
333 Australia for example, where the Indigenous cultural reference reflects ecosystems prior to

334 European colonization in 1770 (commonly defined as pre-1750), and also aligns with other  
335 reference framings. These include pre-industrial and pre-intensification references (i.e. prior to  
336 accelerated rates of ecological change attributed to human disturbance, McNellie et al., 2020),  
337 and pre-Homogenocene (prior to organisms being widely exchanged around the globe, resulting  
338 in increasing homogenization of the Earth's biological and cultural heritage; Curnutt, 2000).

339 While identifying pre-colonization ecosystem characteristics can be challenging, in more-  
340 recently colonized continents such as North America and Australia it is often feasible through  
341 careful combination of historical records, Indigenous Ecological Knowledge, expert knowledge,  
342 data from contemporary remnant ecosystems, ecological reasoning and ecological modelling  
343 (e.g. McNellie et al., 2020; Richards et al., 2020; Wurtzebach & Schultz, 2016). Where culturally  
344 appropriate, participation of Indigenous experts should be particularly supported given strong  
345 connections to cultural land management. On continents or in regions where characterization of a  
346 reference is more difficult (e.g. Europe), or where ecosystems reflecting historic states are  
347 unlikely to persist (e.g. due to climate change), standardised guidance for determining ecological  
348 reference states is needed (Robert, 2024). Such guidance, that aims to support local and regional  
349 biodiversity in four different 'reference contexts', is in development (M. Grace pers. comm. on  
350 behalf of Accounting for Nature, June 13, 2025).

351 We acknowledge that alternative reference characterization may reflect a pragmatic compromise  
352 from a biodiversity perspective when a pre-colonization or pre-intensification reference is not  
353 identifiable. Regardless of reference frame, the approach adopted should be clearly described and  
354 justified, including the values and objectives informing its selection (e.g. Raymond et al., 2023).  
355 Choice of reference frame also affects the assessment of biodiversity gains, as differing frames  
356 limit comparability among restoration activities or programs. Regardless of the reference chosen,

357 we emphasise that characterising a reference state does not imply that this should be the goal of  
358 ecological management (e.g. McNellie et al., 2020; Robert, 2024). Rather, a reference provides  
359 an anchor point for understanding ecosystem dynamics, assessing ecosystem attributes, and  
360 setting realistic targets (consistent with Gann et al., 2024; UN, 2024).

### 361 **Ecosystem collapse and the collapsed/transformer categories**

362 We redefined the VAST “Replaced-Adventive” category IV to explicitly represent states of  
363 ecosystem **collapse**, characterised by failure of key ecosystem processes, potentially including  
364 invasion by **transformer species**. We adapted the definition of ecosystem collapse from Keith et  
365 al. (2013) for application to different ecological layers at site scales, as follows:

366 *Collapse of an ecosystem across one or more ecological layers involves a transformation of*  
367 *identity with loss of defining features, potentially including complete loss of layers or their*  
368 *replacement by novel elements, such that characteristic native biota are no longer sustained.*  
369 *Further, this ‘collapse’ is associated with failure or transformation of one or more ecosystem*  
370 *processes such that recovery is unlikely without extreme intervention to restore those processes.*

371 Examples of ‘collapsed’ layers include extensive mortality of woody species in mulga (*Acacia*  
372 *aneura* sens. lat.) woodlands or chenopod shrublands due to erosion and disruption of  
373 hydrological processes in semi-arid rangelands (O’Donnell et al., 2025), and of dominant  
374 overstorey trees such as *Eucalyptus marginata* (Jarrah) due to disease (Mansfield et al., 2024). In  
375 contrast, a cleared site that retains capacity for re-establishment of native trees (from a seed bank  
376 or plantings) would be considered *Highly modified/absent* rather than *Collapsed*.

377 We used the term ‘*Transformer*’ to reflect *invasion by non-locally indigenous taxa with the*  
378 *potential to substantially alter the structure, function and composition of an ecological*

379 *community over substantial areas (Richardson et al. 2000)*. In this sense, ‘Transformer’ is a  
380 subset of *Collapsed*. Examples include altered grass-fire cycles (D’Antonio & Vitousek 1992)  
381 triggered by exotic grasses such as *Cenchrus ciliaris* (buffel grass), that promote frequent high-  
382 severity fires and limit the persistence of ground layer species and overstorey trees (e.g. *Acacia*  
383 *aneura* sens. lat.; Miller et al., 2010).

#### 384 **Modified and Highly modified categories**

385 *Modified* and *Highly modified* categories involve moderate and high levels of change in  
386 ecosystem structure, function or composition relative to *Close to reference* categories (Table 1).  
387 Importantly, ecological layers in these categories retain capacity to respond positively to  
388 common ecological restoration efforts. Accordingly, removed woody layers are classed as *Highly*  
389 *modified/absent* if ecological processes are sufficiently intact to support recovery after  
390 management of pressures (e.g. reduced intensity of livestock grazing) and/or propagule addition.  
391 Sites where local native species have increased substantially in abundance compared with the  
392 relevant reference expression (e.g. woody thickening in grasslands with cessation of burning;  
393 Lunt, 1988) may also be allocated to *Modified* or *Highly modified* categories, depending on the  
394 degree of departure from *Close to reference* characteristics.

#### 395 **A two-dimensional matrix of states**

396 Our second major change to the VAST framework enables distinctions among ecosystem states  
397 of similar ecosystem condition, that differ substantially in structure and composition. For  
398 example, a forest of intermediate condition may comprise a high or moderate condition native  
399 understorey that persists following tree clearing or selective logging, as found in infrequently  
400 used cemeteries, native pastures, and state forests (e.g. Burke et al., 2008; Good et al., 2024).  
401 Conversely, such forests may retain a near-intact **tree layer** with an understorey modified by

402 livestock grazing, as can occur in *Acacia* rangelands (e.g. O’Donnell et al., 2025) and in remnant  
403 woodlands of intensive agricultural landscapes (e.g. Good et al., 2024). These different types of  
404 modification not only have different drivers, but also have significantly different implications for  
405 ecological restoration, emphasising the benefits of their independent characterisation.

406 To reflect this in the forests and woodlands template we recognised the gradient of four  
407 categories separately for the tree layer (overstorey) versus the **shrub layer** plus (herbaceous)  
408 **ground layer** (understorey). This combination of four categories across two layers yields a core  
409 matrix of 16 states, comprising one reference state and 15 **modified states**, Figure 2a,b;  
410 Appendix S4: Section 2).

411 A key conclusion that emerged from the templates workshop was that the forests and woodlands  
412 template could be generalised to other ecosystem types by distinguishing a ‘**defining layer**’ from  
413 ‘**complementary layers**’ (i.e. other layers), and substituting these into the template. The  
414 ‘defining layer’ refers to the ecological layer reflected in the name or characterisation of the  
415 ecosystem type; that is, the tree layer in forests and woodlands, shrub layer in shrublands (even if  
416 emergent trees are present), and the ground layer in grasslands (or other herbaceous terrestrial  
417 ecosystems such as sedgeland, rushland and forbland).

418 As for the forests and woodlands template, the inclusion of complementary layers aims to  
419 accommodate potential independent change in tree or ground layers in shrublands, and sparse  
420 woody layers in grasslands (e.g. Figure 5). For example, excess fire may eliminate shrubs from  
421 chenopod shrublands while the ground layer persists (O’Donnell et al., 2025) or remove  
422 significant habitat trees from sparsely wooded grasslands (Figure 5). Further, invasive species  
423 may drive undesirable increases in transformer species in complementary layers, such as *Acacia*

424 *nilotica* in *Astrebla* grasslands (e.g. Radford et al., 2002), or exotic grasses such as *Ehrharta* spp.  
425 in Californian and south-west Australian shrublands (e.g. Lambert et al., 2010).

426 Thus, in the shrublands and grasslands templates, a gradient in ecosystem condition of the  
427 defining shrub or ground layer, respectively, is represented from left to right, and any  
428 complementary layers from top to bottom (Figure 3a,b; Appendix S4: Section 3). Where  
429 complementary layers are not present, irrelevant states can be deleted during STM development  
430 (e.g. Figure 6; Appendix S4: Section 4).

### 431 **Secondary templates**

432 Our primary ecosystem states templates extend one-dimensional ecosystem condition scales to  
433 distinguish independent changes in defining versus complementary ecological layers. However,  
434 forests, woodlands, and other ecosystems often have three or more observable ecological layers  
435 that can change independently. For example, livestock grazing commonly affects shrub and  
436 ground layers concurrently, consistent with our forests and woodlands template. In contrast,  
437 restoration often improves the shrub layer more than the ground layer (e.g., Parkhurst et al.,  
438 2021), suggesting a three-dimensional matrix could be useful for forest and woodland  
439 ecosystems. However, adding a third dimension would lead to 64 rather than 16 states in our core  
440 matrix for the template; we chose two dimensions to balance complexity and simplicity.

441 To accommodate the potential need for greater complexity in STMs, relevant intermediate states  
442 can readily be added when applying templates to specific contexts. To support systematic  
443 recognition of this complexity, we developed four secondary templates for use alongside primary  
444 templates where appropriate (Appendix S4: Section 3). Three of these secondary templates share  
445 the primary template format, distinguishing additional vegetation components: (1) shrub and  
446 ground layers in forest and woodland understoreys (Fig. 4a), (2) tree and ground layers in

447 shrublands (Fig. 4b), and (3) forbs and grasses in ecosystems with herbaceous ground layers  
448 (Fig. 4c). The secondary template for the rainforest vine layer highlights how exotic vines may  
449 be accommodated (Figure 4d). Note that changes in native (cf. exotic) vine abundance are often  
450 associated with regenerating expressions in rainforests, hence it would be appropriate to  
451 recognise increases in native vines as part of a dynamic reference state rather than as different  
452 ecosystem states. Use of secondary templates can dramatically increase STM complexity, so we  
453 suggest selecting a minimal number of states from secondary templates if simplicity is preferred.

#### 454 **Intensive land-use states**

455 In addition to the sixteen ecosystem states contributing to the core matrix, all three primary  
456 templates recognise a set of potential intensive land-use states (*cultivated woody with modified,*  
457 *highly modified or collapsed/transformer understorey; crops* (herbaceous); *intensively managed*  
458 *exotic pastures; artificial surfaces and infrastructure*). These extend the VAST categories V  
459 (Replaced-Managed) and VI ('Removed'), and aim to facilitate alignment with the intensive  
460 land-use biome used by the IUCN Global Ecosystem Typology (Keith, Ferrer-Paris et al., 2020),  
461 the SEEA EA (UN, 2024) and the Food and Agriculture Organisation land cover classification  
462 (FAO 2000). Where a greater breakdown of intensive land-use states is desirable, we recommend  
463 using existing classifications.

#### 464 **Recovering stages and variants**

465 In addition to states represented on the primary or secondary templates, the templates and guides  
466 enable inclusion of further detail in STMs through use of recovering stages and **variants**  
467 (Appendix S4: Section 5). Recovering stages enable recognition of stages along slow ecosystem  
468 recovery (or modification) pathways. They are not strictly different states (Bestelmeyer et al.,  
469 2003), but can be used to characterise expected changes in ecosystem attributes within

470 timeframes relevant to land management or ecological restoration programs. For example, it can  
471 take 120 years for trees to grow to the hollow-bearing stage (Manning et al., 2013), whereas a  
472 project in Australia’s Nature Repair Market may only have a 25-year permanence period (e.g.  
473 Clean Energy Regulator, 2025).

474 Variants are sub-divisions within states that can be used to highlight variation within that state  
475 (e.g. higher and lower ends of a gradient in exotic abundance, or plantations of different woody  
476 species), without introducing additional states. This option can be important, for example, to  
477 enable recognition of measurable improvements (e.g. lower exotic abundance) that are  
478 insufficient to result in a transition to another ecosystem state. They could similarly be used to  
479 recognise a *High integrity reference* within the broader *Close to Reference* category. Whether  
480 such variation is treated as a variant or a separate state is by discretion, but all variants of a single  
481 state must have the same transitions and drivers to and from other states.

## 482 **LINKING STATES TO ECOSYSTEM CONDITION**

### 483 **Similarity to reference**

484 Applications of STMs in contexts such as natural capital accounting (e.g., Rainsford et al., 2024)  
485 and Australia’s Nature Repair Market (Australian Government, 2025) increasingly require  
486 standardized, comparable ecosystem condition and other scores across ecosystem types and  
487 regions. We adopted the SEEA EA recommendation (UN, 2024) to assess ecosystem condition  
488 (for biodiversity/ecosystem integrity) relative to a nominated reference, aligning with reference  
489 concepts in our templates and with the SER five-star system. Specifically, ecosystem condition is  
490 assessed against an appropriate expression of the *High integrity reference* (Table 1), using  
491 explicit reference concepts as discussed earlier (McNellie et al., 2020; Richards et al., 2020;  
492 Robert, 2024).

## 493 **Ecosystem condition assignment**

494 Building on the concept of similarity to reference, we propose that percent similarity in species  
495 composition to a *High integrity reference* (including animals, plants, lichens, and fungi; Gann et  
496 al., 2024) provides an overarching, conceptual measure of ecosystem condition. Our emphasis on  
497 species composition reflects its role as an emergent property of feedbacks and interactions  
498 among the three key features of ecosystem condition (structure, function, and composition; UN,  
499 2024) within environmental constraints (Tilman, 2001). As such, we argue that under a dynamic  
500 reference framework, an ecosystem supporting reference species composition will typically  
501 correspond to reference structure and function. Further, species themselves are of prime interest  
502 for biodiversity conservation.

503 Applying this concept, we drew on compositional similarity ranges in the SER five-star system  
504 (Table 1; Appendix S4: Section 6) to propose quantitative ranges in ecosystem condition for the  
505 categories *Close to Reference*, *Modified*, *Highly Modified*, and *Collapsed*, for defining and  
506 complementary layers in each state (Table 2). While we propose assigning composition-based  
507 ecosystem condition scores to states in the template, this does not imply that all species must be  
508 measured to assess condition at a site. User-defined methods, including surrogates for species  
509 composition and related structural or functional attributes, can still be applied.

510 Importantly, assigning quantitative ecosystem condition ranges to ecosystem states in the  
511 templates does not imply a judgment about states familiar to users in the field. Rather, it provides  
512 clarity for interpreting terms such as *Close to Reference*, *Modified* and *Highly Modified*, helping  
513 users align their field-observed states with template states. In this way, the ecosystem condition  
514 ranges facilitate comparability among models developed by different users while allowing  
515 flexibility in specifying ecological details of each state.

## 516 **Contribution of defining and complementary layers to ecosystem condition scores**

517 Using the concepts outlined above, ecosystem condition scores can be assigned separately to  
518 defining and complementary layers within each ecosystem state. Where a single score is required  
519 for an ecosystem state, these can be combined using weightings that reflect the perceived relative  
520 significance of each layer for biodiversity persistence in the relevant ecosystem type (Appendix  
521 S4: Section 7).

522 As with any ecosystem condition assessment protocol, weightings involve uncertainty and value  
523 judgments due to incomplete knowledge of the relative contributions of different layers to  
524 biodiversity, as well as differing perceptions of the value of these contributions. The process of  
525 designating weightings would benefit from a systematic framework that encourages explicit  
526 articulation of the values underlying choices (e.g. Raymond et al., 2023), outlines potential  
527 sources of evidence, and indicates how weightings contribute to uncertainty (e.g., a range of  
528 weightings could be applied; Rowland et al., 2021). Within the context of stated values,  
529 weightings can be informed by evidence-based approaches or expert elicitation for specific  
530 ecosystem types. These approaches could focus on the perceived importance of each layer (in its  
531 reference condition) for supporting biodiversity directly (e.g. based on proportional contribution  
532 of each layer to total compositional diversity) and via functional interactions with other layers.

533 At four workshops (1, 2, 4, 5 in Appendix S2: Table S1), expert-preferred weightings for forest  
534 and woodland defining:complementary layers consistently fell within a narrow range (60:40 to  
535 40:60). Variation primarily reflected differing views on fauna versus flora importance, as well as  
536 the ecological complexity of complementary layers. We thus suggest a default 50:50 weighting  
537 for forests and woodlands, with justified departures. For example, greater weight could be

538 assigned to the tree layer in tropical rainforests that have exceptional tree diversity and where  
539 canopy-driven microclimates regulate complementary layer environments (e.g. Bohlman, 2015).  
540 For shrublands and grasslands, weightings depend on the cover and diversity of complementary  
541 layers. Preliminary workshop discussions suggested a default 90:10 ratio for grasslands with  
542 sparse tree or shrub cover, and variations from 100:0 to 70:30 as woody cover increases from  
543 zero to 10% (a common upper limit for grasslands; Reynolds, 2005) (Appendix S2: Table S1,  
544 workshops 7, 11). Similarly, expert elicitation at two workshops (Appendix S2: Table S1,  
545 workshops 3, 10) suggested a default weighting of 70:30 for sclerophyllous shrublands with  
546 graminoid-dominated ground layers and few trees, and 60:40 for chenopod shrublands with rich  
547 herbaceous layers. These ratios are intended as initial guidance only; further research is needed  
548 to refine weighting guidelines, quantify uncertainty, and clarify underlying values frameworks.  
549 To facilitate STM interpretation, we have also assigned colour blind friendly colours to represent  
550 states of different condition ranges in the templates (Appendix S4: Section 7).

### 551 **Ecosystem condition scores in intensive land-use states**

552 Default ecosystem condition scores for biodiversity in intensive land-use states emerged through  
553 comparison with states in the core matrix (Table 2). Woody layers in *Crops* and *Intensively*  
554 *managed exotic pastures* are typically removed (but could regrow if replanted), and ground  
555 layers are typically transformed by intensive fertilization and cultivation (Standish et al., 2008).  
556 Consequently, these states were considered analogous to a *Highly modified defining layer with*  
557 *collapsed/transformer complementary layer* in forests, woodlands and shrublands, and a  
558 *Collapsed defining layer with highly modified complementary layer* in grasslands.

559 Cultivated woody states were recognized as highly variable, with overstoreys ranging from  
560 plantations of regionally native species (analogous to *Modified*) to non-local species such as  
561 orchards (*Highly Modified*), and transformer exotics (e.g., *Pinus radiata* in Australia, analogous  
562 to transformer due to soil impacts; Turner & Lambert, 1988). Understoreys of woody plantings  
563 may similarly range from *Modified* to *Collapsed/Transformer*, resulting in nine potential  
564 combinations (Table 2). These analogies apply similarly to shrubland and grassland templates.

### 565 **Comparison of systematic condition assignment to elicited ecosystem condition ranks**

566 We compared preliminary ecosystem condition rankings elicited for eucalypt and *Callitris* forests  
567 and woodlands at the STM templates workshop with rankings derived using the systematic  
568 condition assignment described above, using a 50:50 weighting for tree:shrub/ground layers  
569 (Appendix S4: Section 7). Rankings were broadly comparable, though not identical (Table 2). In  
570 particular, states combining collapsed and modified or highly modified layers tended to be rated  
571 lower by experts in initial assessments than by the systematic approach. Rankings for other  
572 ecosystem types could not be compared due to missing elicited values.

### 573 **APPLICATION OF THE TEMPLATES AND GUIDES**

574 Figure 6(a-f) provides a hypothetical example of how primary templates can be applied (see also  
575 Appendix S4: Section 4). This section follows the methodology of Good et al. (2024) for  
576 developing STMs, aiming to highlight how the templates and rules can be applied at each of  
577 three steps: selection of ecosystem states, description of ecosystem states, and assignment of  
578 plausible transitions. We then briefly address to final steps: characterisation of transition drivers,  
579 and estimating rates and probabilities of transition; highlighting potential further developments  
580 to facilitate consistency in these phases.

581 The method for developing STMs is user-driven. A common approach is to integrate expert  
582 elicitation with published information and data (Bestelmeyer et al., 2017; Blankenship et al.,  
583 2021), but other approaches (e.g. data-driven identification of ecosystem states, Duniway et al.,  
584 2025) are feasible. Our templates and tools can be applied in all these approaches, although we  
585 focus here on application in expert elicitation contexts.

### 586 **Selection of ecosystem states**

587 Identifying ecosystem states relevant to the STM under development typically involves matching  
588 states known on the ground to those in the template (guided by the given condition ranges for  
589 each layer), excluding states from the template that are not considered relevant, subdividing  
590 states where appropriate, and considering variants or recovering stages (Figure 6; Appendix S4:  
591 Section 4). Additional states can also be drawn from secondary templates at early or later stages  
592 (Appendix S4: Section 8).

### 593 **Describing ecosystem states**

594 Once ecosystem states are identified, their attributes can be described at this or later stages. To  
595 maximise consistency with international standards, our list of attributes was drawn primarily  
596 from the SER five-star system (Gann et al., 2024) and complementary frameworks (Eyre et al.,  
597 2017; Parkes et al., 2003). The biotic and abiotic attributes considered relevant for describing  
598 states in regional-scale STMs, applicable to individual ecological layers where appropriate  
599 (Appendix S3), include: (1) *Physical conditions* (substrate physical and chemical conditions;  
600 water chemo-physical conditions); (2) *Species composition* (desirable plants, fungi and lichens;  
601 desirable animals; undesirable species); (3) *Structural diversity* (ecological layers within  
602 complementary layers); trophic levels; spatial mosaic); and (4) *Ecosystem function* (productivity  
603 and cycling; habitat and interactions; resilience and recruitment).

604 The SER five-star system also includes optional sub-attributes for composition, such as rare and  
605 threatened species, provenance, genetic diversity, and genetic resilience. These, along with other  
606 project-specific attributes (e.g., production-focused metrics in agricultural contexts or ecosystem  
607 service indicators), can be added to the description of states where relevant.

608 Some attributes of the SER five-star system are reflected in drivers of transitions between states,  
609 including threats such as over-utilization, invasive species, and soil contamination, as well as  
610 external exchanges like gene flow, nutrient run-on and habitat connectivity. While these  
611 attributes are not used to describe ecosystem states *per se*, they remain critical for project-level  
612 risk assessment, counterfactual scenario development, and management planning.

613 Similar to the SER five-star system, our attribute list provides a generic structure that users can  
614 adapt. As for ecosystem condition, individual attributes in modified states can be scored relative  
615 to a *High integrity reference*, using similarity or departure measures. For attributes such as  
616 structural diversity or soil chemical concentrations, departure from the reference may indicate  
617 decline in ecosystem condition when values are higher or lower than the reference.

618 Importantly, ecosystem states are characterized by combinations of attributes that commonly co-  
619 occur (potentially represented in radar charts as in the SER five-star system). While these  
620 collectively reflect overall ecosystem condition, not all attributes within an ecosystem state are  
621 expected to achieve the same star rating as the overall ecosystem condition score. Rather, the  
622 attribute scores form a pattern characterising that state. This distinction is particularly relevant  
623 for collapsed states, where not all ecosystem processes need to fail for collapse to occur.

624 **Assigning transitions**

625 After ecosystem states have been selected, the next step is to identify transitions among them  
626 (Good et al., 2024; Figure 6d; Appendix S4: Section 4). Our transition assignment guide  
627 indicates recommended sets of plausible transitions (Appendix S4: Section 9), including  
628 conventions introduced to address inconsistencies observed during expert workshops. For  
629 example, some groups represented transitions to intensive land-use states as direct (‘leapfrog’)  
630 transitions that bypass other states, while others depicted them as stepwise transitions through  
631 other states. To facilitate consistency and simplicity, we recommend transitions not in the  
632 transition guide be applied to STMs only after additional scrutiny—recognising that justifiable  
633 exceptions may occur. Key elements of the transition assignment guide include:

634 (1) Only show transitions that do not need to pass through any other state first. For example, if  
635 separate actions are needed to modify tree versus other layers, or if tree regrowth occurs more  
636 slowly than other layers, these should be treated as separate transitions, even when activities are  
637 implemented simultaneously. As such, most transitions involve vertical or horizontal transition  
638 arrows. Diagonal transitions, which represent a *coincident* change in condition of both the  
639 defining and complementary layers, are generally uncommon, with two exceptions:

640 (i) collapse of one or more layers may occur from any state (or may involve multiple steps);  
641 (ii) land clearing may lead to highly modified defining and complementary layers in one step;  
642 (iii) in shrublands with a ground layer, or grasslands with a shrub layer, rates of change may be  
643 similar across layers, allowing diagonal transitions if relevant.

644 (2) For simplicity, direct transitions to intensive land-use states are allowed from any starting  
645 state, even though in reality these may pass temporarily through highly modified states as a result  
646 of land clearing. Transitions away from intensive land-use states on the other hand, should pass

647 through states that are highly modified or collapsed in both defining and complementary layers  
648 (if present), recognising effects of intensive uses, even if only short-lived.

#### 649 **Characterising transition drivers**

650 Once transitions have been identified, the next step is to assign drivers to these transitions using  
651 expert elicitation and/or documented evidence (Good et al., 2024; Fig. 6f). The stages of  
652 assigning transitions and drivers may involve iteration back to the ecosystem state identification  
653 step, as ecosystem states that had been missed earlier are commonly picked up at these stages.

654 Ideally, assignment of drivers would draw on a standardized list, including Indigenous  
655 management that may be required to maintain or restore ecosystem states. Considerable effort  
656 has been undertaken globally to develop standardized classifications of land uses, drivers,  
657 threats, and actions relevant to ecosystems and biodiversity. For example, the IUCN Restoration  
658 Intervention Typology for Terrestrial Ecosystems forms a core component of the IUCN  
659 Restoration Barometer (IUCN, 2022). Similarly, threat classification schemes underpin IUCN  
660 Red List assessments (e.g. IUCN, 2026), while other frameworks are guided by the Conservation  
661 Standards (Salafsky et al., 2008) or employ general land-use classifications (e.g., ABARES,  
662 2024). However, none of these existing resources were found to be uniquely suitable for our  
663 purpose. A priority for future work is thus the development of a typology of drivers specifically  
664 tailored for state-and-transition modelling, building on and informed by earlier efforts.

#### 665 **Eliciting rates and probabilities of transitions**

666 Once drivers and transitions are allocated, rates and probabilities of transitions may need to be  
667 quantified. This step is undertaken using a user-determined approach (e.g., involving  
668 combinations of expert knowledge and data) at regional scales, as quantitative parameters are

669 likely to vary with environmental context. The state-and-transition simulation model approach  
670 described by Daniel et al. (2016) allows quantitative parameters for transitions to be varied with  
671 finer-grained spatial variation in soils or land types within the broader landscape represented by a  
672 given STM. A similar approach might be taken for other program-scale applications.

## 673 **DISCUSSION AND FUTURE DIRECTIONS**

### 674 **Novel developments**

675 Our primary and secondary templates and associated guides incorporate three novel  
676 developments that collectively improve comparability among STMs. First, they systematically  
677 recognise ecosystem states involving potentially independent ecological change in different  
678 ecological layers or components, leading to templates comprising simple matrices of common  
679 ecosystem states. These provide a systematic starting point for selecting and ordering states in an  
680 STM, enable analogous states to be compared across ecosystem types, and provide a foundation  
681 for moving beyond one-dimensional ecosystem condition scores.

682 Second, our templates explicitly link ecosystem states to pre-assigned ranges for ecosystem  
683 condition scores. Given that experts involved in elicitation of STMs often hold an intuitive  
684 understanding of the condition of ecosystem states they are familiar with, the condition score  
685 ranges for each layer provide guidance on placing these states into the template. For example, an  
686 expert may be aware that the overstorey still has high condition, but the understorey is largely  
687 removed, or that both layers are moderately altered. Providing relatable ‘bins’ of ecosystem  
688 condition ranges in the templates thus facilitates recognition of aligned states across STMs, and  
689 ensures ecological information captured in STMs remains coupled with information about  
690 ecosystem condition for biodiversity. Further, consistent colours and ordering of states establish a  
691 convention that signals the position of a state along modification or recovery gradients.

692 Third, our templates offer a flexible, multi-resolution approach, with primary templates for  
693 broad-scale, lower-resolution STMs; secondary templates, variants and recovering stages to  
694 systematically introduce finer detail; and flexibility to tailor STMs further. Guidance in  
695 application, including attribute lists for describing states and conventions for assigning  
696 transitions, aim to facilitate consistency, but we avoid advocating rigid rules. Rather, STMs  
697 should remain fit for purpose (Westoby et al., 1989).

### 698 **Broad applicability**

699 Although developed in an Australian context, the matrix approach based on ecological layers  
700 used in our templates is relevant to ecosystems globally. For example, in Canadian Maple  
701 forests, partial harvesting can modify the tree layer with minor effects on the understorey, or  
702 understoreys may be considerably influenced by grazing with lesser effect on trees (Burke et al.,  
703 2008). In Oak woodlands of Spain and California, reduced grazing can shift understoreys from  
704 grassy to shrubby without substantially affecting the tree layer, and conversely, grassy or shrubby  
705 understoreys can persist when harvest removes the tree layer (Huntsinger & Bartolome, 1992).  
706 North American Sagebrush (*Artemisia*) shrublands provide a well-established shrubland  
707 example, where the shrub layer can be removed by excess wildfire while maintaining a native  
708 perennial grass layer, or the shrub layer may remain over an exotic ground layer (e.g. Orning et  
709 al., 2023). Californian grasslands similarly include exotic and native ground-layer states, with or  
710 without a tree layer (George et al., 1992), and differing responses of forbs *versus* grass richness  
711 and biomass have been observed in temperate grasslands of inner Mongolia impacted by nutrient  
712 enrichment (e.g. Song et al., 2011).

713 Beyond this relevance to ecosystems globally, our methods are integrated with globally  
714 established frameworks, including utilizing concepts of similarity to reference embedded in the

715 SEEA EA (UN, 2024) and the SER five-star system (Gann et al., 2024), drawing on attribute sets  
716 and indicative ecosystem condition ranges established by SER, and aligning intensive land-use  
717 states with global classifications ; FAO, 2000; Keith, Ferrer-Paris et al., 2020). We also  
718 incorporate dynamic concepts of reference as advocated by Robert (2024).

## 719 **Benefits and impacts**

720 Application of our templates and guides offers benefits to nature conservation and sustainability  
721 initiatives at property, regional, ecosystem type, and program scales. Clear links between  
722 ecosystem states and ecosystem condition allow initiatives that rely on one-dimensional  
723 condition scoring systems to retain critical ecological information, increasing the ability of such  
724 initiatives to directly inform management. At local or farm scales, for example, data on  
725 ecosystem condition expressed consistently through ecosystem states can enable managers to  
726 tailor actions (e.g. plant trees or restore understorey) to specific locations. Consistent structures  
727 for defining ecosystem states also readily facilitate synthesis of such information into natural  
728 capital accounts that can bring financial advantages, for example through favourable bank loans  
729 or reporting via TNFD frameworks (Luxton et al., 2024; Rainsford et al., 2024; TNFD, 2023). At  
730 regional, ecosystem-type and program scales respectively, the templates or their precursors have  
731 already contributed to exploring ecosystem states important for birds in mallee ecosystems, to  
732 rangeland management in Western Australian Mulga (O'Donnell et al., 2025), and to  
733 development of 28 regional STMs (Appendix S2: Table S1; e.g. Prober et al. 2025) and three  
734 Methods (legislative instruments defining how biodiversity certificates are generated) that  
735 underpin operation of Australia's Nature Repair Market (DCCEEW, 2026).

736 The emphasis on ecological layers (defining and complementary) in our templates also points to  
737 significant value that could be gained through improved remote sensing methods to identify sub-

738 canopy characteristics (e.g. Yun et al., 2023). Remotely-sensed mapping of ecosystem states over  
739 large areas would provide a powerful tool to facilitate detection, characterisation and enhanced  
740 understanding of ecological change, informing policy decisions and ecosystem accounting (e.g.  
741 Richards et al., 2023), State of Environment reporting, and assessments for the IUCN Green  
742 Status of Ecosystems (IUCN Green Status of Ecosystems Taskforce, 2026b).

### 743 **Limitations and risks**

744 We emphasise that STMs and our associated STM templates and guides aim to synthesise  
745 existing information, rather than generate new information (Bestelmeyer et al., 2017). Thus, they  
746 are constrained by the quality of existing knowledge and data, and associated uncertainties. In  
747 this context, they can be used to highlight data gaps and help prioritise on-ground data collection.  
748 Indeed, when applied to programs that collect data, we encourage development of mechanisms  
749 that enable data to feed into ongoing improvement of STMs.

750 A key strength of STMs is their flexibility to be applied to specific ecosystems and problem-  
751 types (Westoby et al., 1989). Although we built flexibility into our templates and guides, there  
752 remains a risk that their application may unintentionally constrain outcomes. At one extreme, the  
753 templates could encourage inclusion of rarely observed or contextually irrelevant states, simply  
754 because they exist in the templates. At the other extreme, we recognise that the templates do not  
755 capture all potentially important differences that may occur within or among ecosystem states of  
756 similar condition. For example, modified ground layers may be enriched in soil nutrients and  
757 invaded by exotic plants, or depleted in moisture and ground-cover due to soil compaction (e.g.  
758 Prober et al., 2014), with differing implications for ecological restoration. Ultimately, we  
759 emphasise that models should be tailored to context.

760 Defining a reference can also introduce risks, including misinterpretation that it must also serve  
761 as the target (even when this is impractical or incompatible with other objectives), and potential  
762 manipulation, such as using unduly low standards in establishing alternative references.

763 These challenges aside, STMs will not be the appropriate solution for all problems in ecosystem  
764 dynamics and assessment. For example, ecosystem states largely apply to site-level  
765 characteristics, and other metrics are needed to account for landscape and regional dynamics,  
766 either linked to STMs or through other approaches (Furlaud et al., 2025). STMs are also limited  
767 by their discrete states, that can obscure variability within states. Continuous metrics used in  
768 combination with STMs (or independently) can help overcome this issue.

#### 769 **Potential extension and improvement**

770 While our templates and guides progress methods for STM development, our synthesis  
771 highlights key areas for improvement and extension. We have already discussed the need to  
772 establish frameworks for characterizing reference states (Robert, 2024) and for weighting the  
773 importance of different ecological layers for biodiversity, both requiring clear articulation of  
774 values, choices, and uncertainties (e.g. Raymond et al., 2023; Rowland et al., 2021). Consistency  
775 could also be enhanced by developing a common typology of transition drivers (e.g., disturbance  
776 types, restoration actions) and improving methods to estimate transition rates and probabilities  
777 and their uncertainties.

778 Other key areas for further extension include the following.

779 **1. Expansion of the templates to other ecosystem types and contexts.** These include  
780 herbaceous wetland, riverine, coastal-intertidal and potentially some marine benthic and pelagic

781 ecosystems, and trialling the templates in continents and regions with differing histories of land  
782 use intensification.

783 **2. Stronger representation of fauna and other biodiversity.** The utility of STMs could be  
784 enhanced through improved characterisation of links between ecosystem states and animals,  
785 fungi and other biodiversity. For example, work is underway to map the suitability of ecosystem  
786 states for each of 20 bird species within Australia's Threatened Mallee Bird community, with the  
787 intention to combine expert knowledge with validation through acoustic recordings (A. Maisey,  
788 J. Radford, unpub. data). Other studies have similarly used STM approaches to inform  
789 management of threatened fauna (e.g. Orning et al., 2023) or characterise below-ground diversity  
790 (Albornoz et al., 2023). Further, linking STMs with landscape metrics that reflect the relative  
791 extent and/or configuration of expressions and states in a landscape compared with the archetype  
792 or reference landscape (e.g. Furlaud et al., 2025; Tulloch et al., 2018) will be important to reflect  
793 habitat diversity and accessibility for fauna, as well as other ecosystem processes such as plant  
794 recruitment or impacts of changing fire regimes.

795 **3. Improved links with Indigenous knowledge- and rights-holders.** Meaningful Indigenous  
796 participation in STM development has the potential to improve cultural and biodiversity  
797 outcomes in associated nature conservation programs, through respectful inclusion of Indigenous  
798 perspectives, improving understanding of the dynamics and characteristics of reference sites, and  
799 recognition of cultural values. Development of our STM templates and regional STMs  
800 (Appendix S2: Table 1) included Indigenous knowledge and input where feasible, but  
801 representation was substantially unequal compared with western scientists and non-Indigenous  
802 land managers. Further, our methods may not reflect how Indigenous people would prefer their  
803 knowledge to be collected and represented.

804 We recommend several pathways for facilitating greater inclusion, potentially including: (a)  
805 alternative approaches and timeframes for knowledge elicitation that are more amenable and  
806 respectful of the cultural obligations of Indigenous people, especially Indigenous-led approaches,  
807 (b) exploration of alternative means for expressing and illustrating in a culturally safe manner the  
808 content of STMs where Traditional Knowledge has informed development (e.g. as artworks,  
809 illustrations or stories), (c) promoting greater opportunities for respectful inclusion and  
810 acknowledgement of the values held by Indigenous people (e.g. emphasis on culturally  
811 significant species, obligation to Country, cultural governance), (d) appropriate recompense for  
812 time, and (e) attention to management of Indigenous cultural and intellectual property.

813 Indeed, Indigenous groups have already played leading roles in related initiatives such as the  
814 development of the ‘Desert Habitat Method’ for Accounting for Nature (Indigenous Desert  
815 Alliance, 2023), exploration of STMs for regional ecosystem accounting (Woodward et al.,  
816 2023) and championing the inclusion of Indigenous rights and interests in legislative reform  
817 enacted to enable the Nature Repair Market (Australian Government, 2025).

818 **4. Standardised approaches to inclusion of climate change in STMs.** As climate change  
819 continues to accelerate, it is imperative to integrate climate change into future-oriented STMs.  
820 This requires methods for eliciting plausible future dynamics, informed where possible by  
821 modelled projections, underlying eco-physiological processes, frameworks for characterising  
822 alternative reference states (Robert, 2024), and approaches for combining or defining boundaries  
823 between models where trajectories toward alternative ecosystem types occur.

824 In summary, our templates and guides progress state-and-transition modelling by promoting  
825 consistency and comparability among STMs for broad-scale applications, while maintaining  
826 flexibility across varied ecological contexts. By explicitly linking ecosystem states to measures

827 of ecosystem condition and supporting use at multiple resolutions, they establish a robust  
828 platform to underpin application of STMs in sustainability and conservation programs, natural  
829 capital and environmental accounting, and adaptive management. Future priorities include  
830 enhancing inclusion of climate change considerations, representation of fauna, engagement with  
831 Indigenous knowledge, and linking with landscape metrics.

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## 844 **AUTHOR CONTRIBUTIONS**

845 SMP, AER, MKG, HM, AJO, MCP, KJW led the development and synthesis of concepts,  
846 workshops and outputs, FEA, STB, JRE, KMG, DNG, SJL, ACM, BM, SEMM, ECR, JQR, IRW  
847 and PAW contributed to refinement and/or workshop facilitation, and DB, FD, DNG, BM, JHP,

848 JQR, LR, JCW, MW and SvL contributed to project oversight. SMP led the writing and all  
849 authors contributed to workshops and/or other content and contributed to the manuscript.

## 850 **CONFLICT OF INTEREST STATEMENT**

851 The authors have no conflicts of interest to declare.

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1099 **TABLE 1.** Compositional similarity thresholds and Society for Ecological Restoration (SER)  
 1100 star ratings used to guide assignment of ecosystem condition ranges to template ecosystem states.

Template category (for defining or complementary layers)	Aligned VAST* category	% compositional similarity to high integrity reference <sup>†</sup>	SER star rating
High integrity reference (high extreme of Close to reference category)	I (Residual)	100%	Not applicable
Close to reference	I (Residual)	>75-100%	4, 5
Modified	II (Modified)	>25-75%	2, 3
Highly modified/ absent	III (Transformed)	>5-25% <sup>‡</sup>	1
Collapsed/ transformer	IV (Replaced-adventive)	0-5%	0

1101 \*VAST: Vegetation Assets, States and Transitions framework (Thackway & Lesslie, 2006).

1102 <sup>†</sup>Compositional similarity is used in a conceptual context and accounts for plants, animals, fungi  
 1103 and lichens (easily observed biological entities as described by Gann et al., 2024). See Appendix  
 1104 S2 for alignment with star ratings. <sup>‡</sup>Occasionally, layers may have no remaining ‘reference’  
 1105 species (e.g. an entirely cleared overstorey with no trees to support fauna), but still retain  
 1106 ecological processes that could support reference species. Such layers are allocated a minimum  
 1107 score of 5%, to differentiate them from collapsed layers that can no longer support the layer.

1108

1109 **TABLE 2.** Example assignment and ranking of ecosystem condition ranges to ecosystem states  
 1110 for forests and woodlands.

Ecosystem state	Ecosystem condition		Systematic rank <sup>†</sup>	Elicited rank <sup>†</sup>
	range*	Midpoint		
Reference o/s with Reference u/s	0.75-1.0	0.875	1	1
Reference o/s with Modified u/s	0.5-0.875	0.6875	2	2
Modified o/s with Reference u/s	0.5-0.875	0.6875	2	2
Reference o/s with Highly modified u/s	0.4-0.625	0.5125	3	3
Highly modified/absent o/s with Reference u/s	0.4-0.625	0.5125	3	3
Modified o/s with Modified u/s <sup>‡</sup>	0.25-0.75	0.5	3 <sup>§</sup>	3
Reference o/s with Collapsed/transformer u/s	0.375-0.525	0.45	4	5
Collapsed/transformer o/s with Reference u/s	0.375-0.525	0.45	4	5
Modified o/s with Highly modified u/s <sup>‡</sup>	0.15-0.5	0.325	5	4
Highly modified/absent o/s with Modified u/s <sup>‡</sup>	0.15-0.5	0.325	5	4
Modified o/s with Collapsed/transformer u/s <sup>‡</sup>	0.125-0.4	0.2625	6	6
Collapsed/transformer o/s with Modified u/s <sup>‡</sup>	0.125-0.4	0.2625	6	6
Highly modified/absent o/s with Highly modified u/s <sup>‡</sup>	0.05-0.25	0.15	7	5
Highly modified/absent o/s with Collapsed/transformer u/s <sup>‡</sup>	0.025-0.15	0.0875	8	7
Collapsed/transformer o/s with Highly modified u/s <sup>‡</sup>	0.025-0.15	0.0875	8	7
Crops (herbaceous)	0.025-0.15	0.0875	8	7-9
Intensively managed exotic pastures	0.025-0.15	0.0875	8	7-9
Collapsed/transformer o/s with Collapsed/transformer u/s <sup>‡</sup>	0-0.05	0.025	9	8
Artificial surfaces and infrastructure	0	0	10	10

1111 O/s=overstorey, referring to the defining layer, and u/s=understorey, referring to the  
 1112 complementary shrub/ground layers. \*Ecosystem condition range reflects compositional  
 1113 similarity to high integrity reference from Table 1 using 50:50 default weightings for the relative  
 1114 importance of the tree versus shrub/grass layers for biodiversity. <sup>†</sup>Rankings (1=highest ecosystem  
 1115 condition) obtained using this systematic approach are compared with those elicited for eucalypt  
 1116 and Callitris forests and woodlands at the workshop. <sup>‡</sup>Aligned with relevant cultivated woody  
 1117 states, dependent on type of plantation and plantation understorey. <sup>§</sup>Ranked with other ecosystem  
 1118 states scoring 0.5125.

1119 **FIGURE CAPTIONS**

1120 Figure 1. Workflow for developing state-and-transition model templates and guidelines. VAST is  
1121 the Vegetation Assets, States and Transitions (VAST) framework (Thackway & Lesslie, 2006),  
1122 and the SER five-star system refers to the Society for Ecological Restoration (SER) ‘Five-star  
1123 system sub-attributes table’ described in Gann et al. (2024).

1124 Figure 2. (a) Primary ecosystem states template to guide development of state-and-transition  
1125 models in forests and woodlands (see also Appendix S4: Section 2). The colour scheme  
1126 highlights states with similar condition ranges, here displayed using weightings of 50:50 for  
1127 forests and woodlands (see Appendix S4: Section 7 for explanation of colour scales). (b)  
1128 Illustration of different states in order of the defining  $\times$  complementary layer matrix using  
1129 eucalypt woodlands as an example (not showing fourth row with collapsed/transformer  
1130 complementary layer). Images: S. M. Prober and J. Stol.

1131 Figure 3. Primary ecosystem states templates to guide development of state-and-transition  
1132 models in (a) shrublands and (b) grasslands (see also Appendix S4: Section 2). The colour  
1133 scheme highlights states with similar condition ranges (see Appendix S4: Section 7 for  
1134 explanation of colour scales). Here we display colours reflecting weightings of 60:40 for  
1135 shrublands and 90:10 for grasslands, noting these ratios are adjustable based on local context.

1136 Figure 4. Secondary ecosystem states templates for (a) complementary layers in forests and  
1137 woodlands (shrub  $\times$  ground layer), (b) complementary layers in shrublands (tree  $\times$  ground layer),  
1138 (c) ground layers in grasslands and grassy forests and woodlands (grass  $\times$  forb components), and  
1139 (d) invasive vine layers in rainforests (explicit exotic vine component) (see also Appendix S4:  
1140 Section 2). The colour schemes demonstrated highlight states with similar condition ranges, here

1141 displayed using weightings of 50:50 for each layer, noting these may be adjusted to suit (see  
1142 Appendix S4: Section 7 for explanation of colour scales).

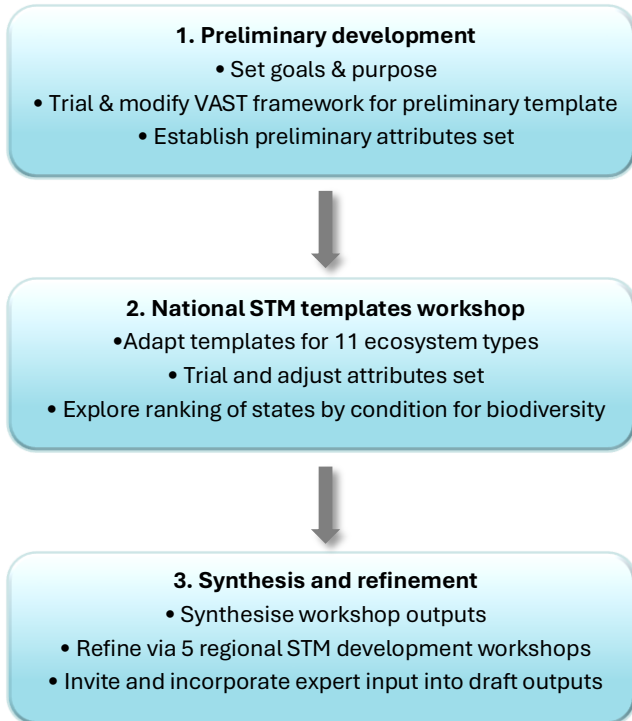
1143 Figure 5. Examples indicating variation in relative importance for biodiversity of defining versus  
1144 complementary ecological layers in shrublands and grasslands. a) Sandplain shrubland with  
1145 limited tree or ground layers, Forrestania, Western Australia; b) *Themeda triandra* grassland with  
1146 no woody layers, Pilbara, Western Australia; c) Chenopod shrubland with substantive ground  
1147 layer, Menindee, New South Wales; d) Hummock (*Triodia*) grassland with scattered shrub  
1148 (*Acacia inaequilatera*) layer, Pilbara, Western Australia; e) Chenopod shrubland with herbaceous  
1149 and patchy tree (*Alectryon oleifolius*) layers, Ivanhoe, NSW; f) Hummock (*Triodia*) grassland  
1150 with scattered shrub and tree (*Eucalyptus gongylocarpa*) layers, Great Victoria Desert, Western  
1151 Australia. Images S. M. Prober.

1152 Figure 6. Conceptual example indicating application of templates to create a state-and-transition  
1153 model including (in sequence from top to bottom): (a) primary template, (b) removal of  
1154 irrelevant states, (c) dividing states, (d) adding transitions, (e) revising to add missed state (green  
1155 border), and (f) adding drivers (Appendix S4: Section 4). The colour scheme highlights states  
1156 with potentially similar condition ranges (see Appendix S4: Section 7 for explanation of colour  
1157 scales) using default weightings of 50:50 (see text).

1158

1159 FIGURE 1

1160



1161

1162 FIGURE 2

1163 (a)



1164

1165 (b)

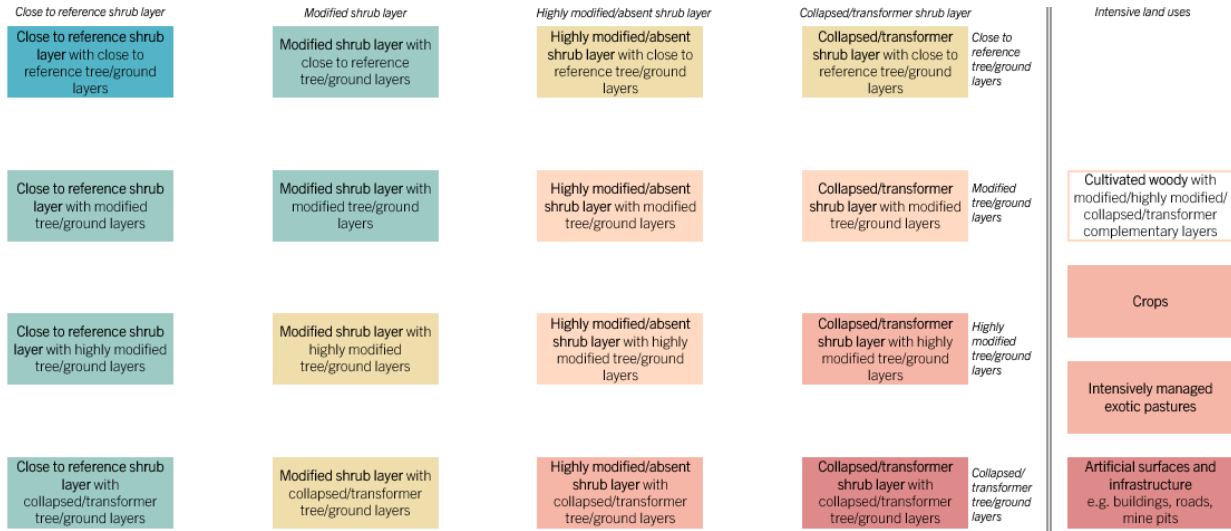


1166

1167

1168 FIGURE 3

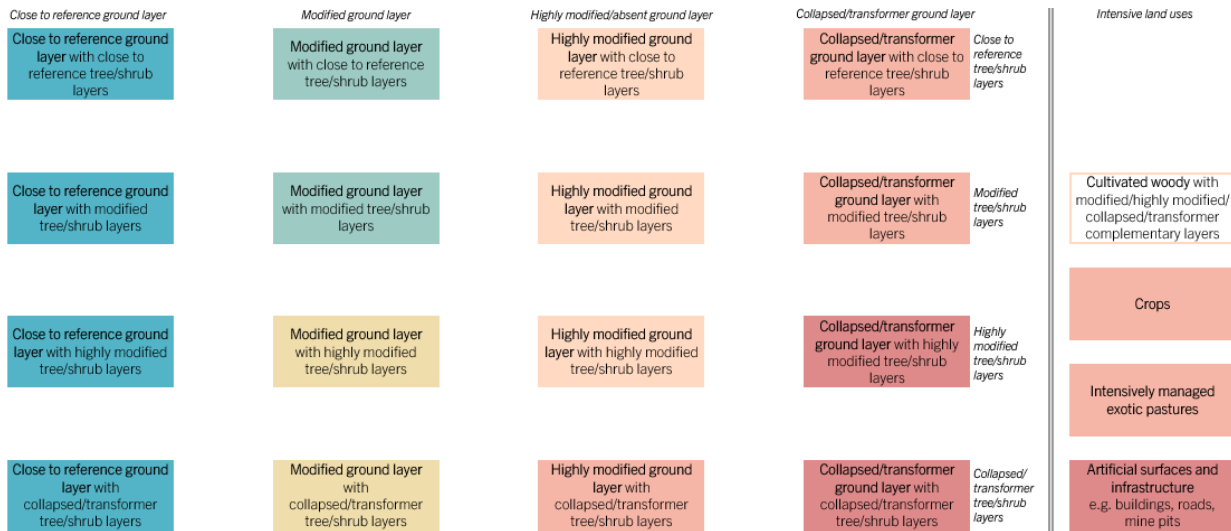
1169 (a)



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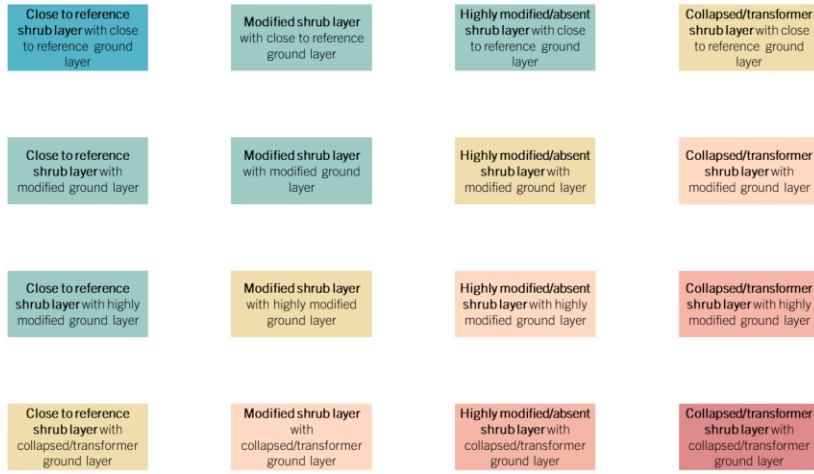
1172 (b)



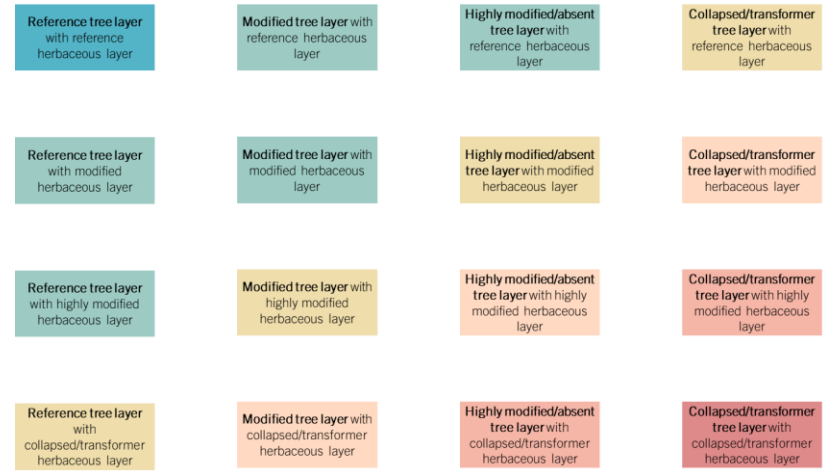
1173

FIGURE 4

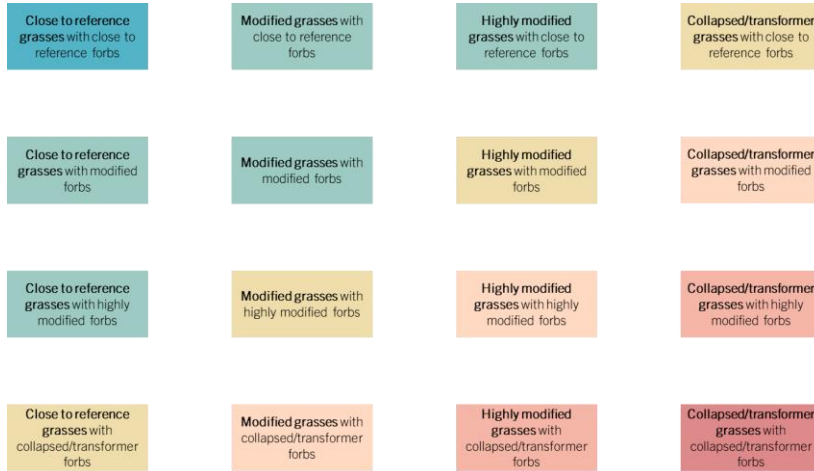
(a) Complementary layers in forests and woodlands



(b) Complementary layers in shrublands



(c) Ground layers



(d) Invasive vine layers in rainforests

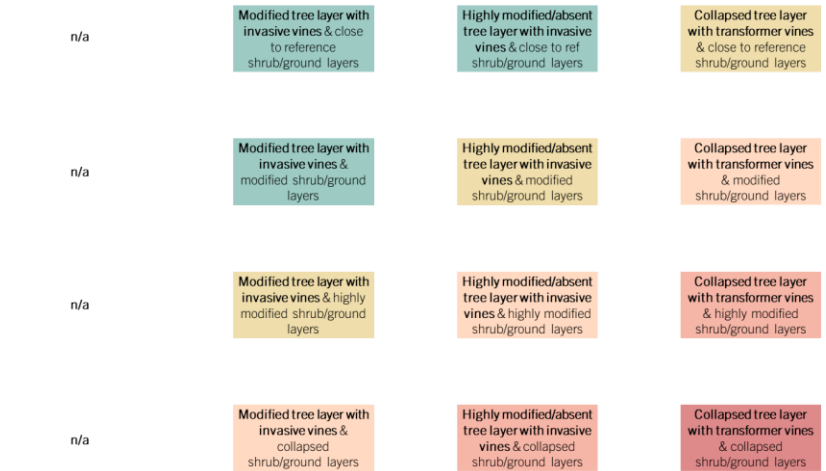


FIGURE 5

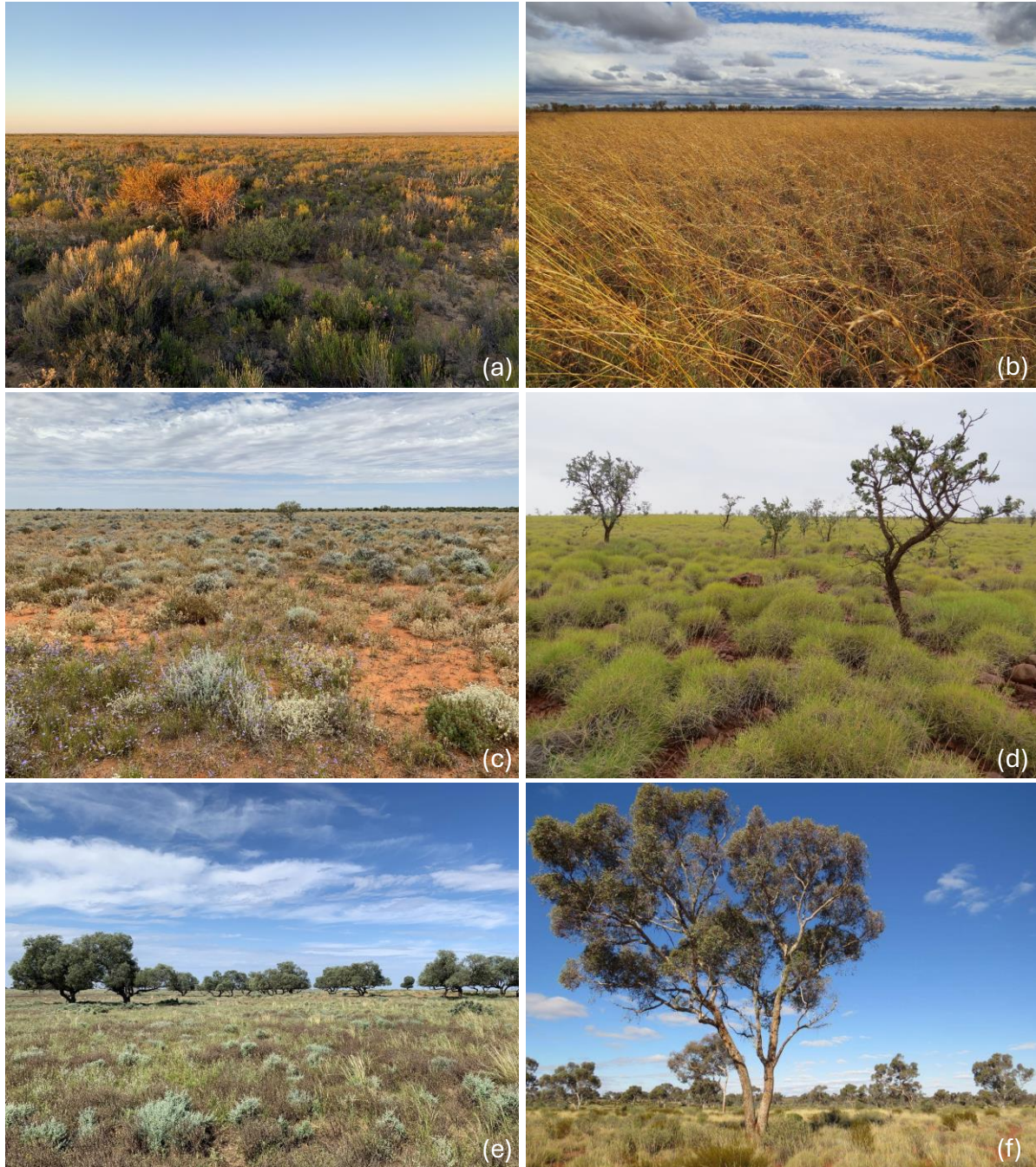
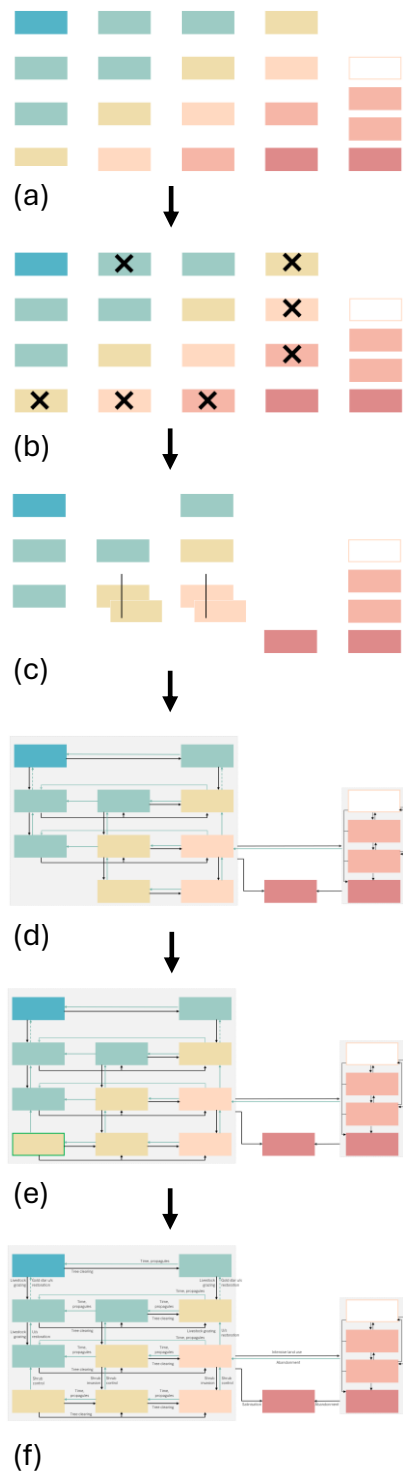


FIGURE 6



Prober, S. M., M. K. Good, H. Murphy, A. J. O’Donnell, M. C. Piper, K. J. Williams, F. E. Albornoz, S. T. Brooks, J. R. England, K. M. Giljohann, D. N. Gunawardana, S. J. Luxton, B. Morris, S. E. M. Munroe, E. C. Rochelmeyer, I. R. Warren, D. Butler, N. Cuff, F. Dickson, J. W. Dorrough, D. J. Eldridge, T. J. Eyre, J. M. Facelli, B. Howland, R. Jordan, A. Leedman, D. L. Lewis, A. C. Maisey, S. McIntyre, T. Parkhurst, J. H. Pascoe, E. C. Pryde, J. Q. Radford, L. Rumpff, K. X. Ruthrof, R. J. Standish, A. Tulloch, P. A. M. Turner, S. van Leeuwen, P. A. Waddell, J. C. Walsh, M. Ward, G. M. Wardle, I. W. Watson, M. Westoby, M. D. White, L. J. Williams, S. Roxburgh, R. Young, and A. E. Richards. “Towards Comparability among State-and-Transition Models: A Set of Generalised Templates Linked to Ecosystem Condition.”

## APPENDICES

### Appendix S1. Glossary

Modified from Murphy et al. (2025), O’Donnell et al. (2025).

Term	Definition
<b>Archetype</b>	Archetypes in the <b>Australian Ecosystem Models Framework</b> (Richards et al., 2020) represent the endogenous disturbance (reference) dynamics and <b>ecosystem expressions</b> that characterise ecosystems with high integrity, using box and arrow diagrams. These dynamics include those driven by Indigenous land management to which the biota have adapted over millennia. The models provide a conceptual guide for description of a <b>High integrity reference</b> and <b>modified states</b> in state-and-transition models. Although described using box and arrow diagrams, archetype models are not considered to be state-and-transition models, as they include transient dynamics and successional stages, and do not involve post-industrialisation disturbances. Rather, the archetype model can be nested inside a reference state in a state-and-transition model, to highlight that the reference state is dynamic.
<b>Australian Ecosystem Models Framework</b>	The Australian Ecosystem Models (AusEcoModels) Framework systematically captures ecological knowledge about the dynamics of Australian ecosystems in pre- and post-industrialisation contexts (Richards et al., 2020). The framework recognises 14 aggregate ecosystem groups that reflect the Major Vegetation Groups of Australia’s <a href="#">National Vegetation Information System</a> (DCCEEW 2026). Within each of these aggregate ecosystem groups, two types of conceptual models can be accommodated: (1) <b>archetype</b> models and (2) state-and-transition models.
<b>Collapse</b>	Collapse of an ecosystem across one or more <b>ecological layers</b> ( <i>for our purposes, at a location or site</i> ) involves a transformation of identity with loss of defining features, potentially including complete loss of layers or their replacement by novel elements, such that characteristic native biota are no longer sustained. Further, this ‘collapse’ is associated with failure or transformation of one or more ecosystem processes such that recovery is unlikely without extreme intervention to restore those processes (adapted from Keith et al., 2013 for applicability to the STM templates).
<b>Complementary layer</b>	Complementary layers are the <b>ecological layers</b> other than the <b>defining layer</b> of an ecosystem type, i.e. the shrub and ground layers in forests and woodlands, tree and ground layers in shrublands (if present) and the tree and shrub layers in grasslands (if present). This aligns with ‘secondary’ layers in other vegetation classification systems, but the term complementary was selected to provide a neutral descriptor that does not imply differences in ecological value or importance among layers for biodiversity.
<b>Defining layer</b>	The defining layer is the <b>ecological layer</b> reflected in the name or characterisation of the ecosystem type, i.e. the tree layer in forests and woodlands, shrub layer in

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	shrublands (even if emergent trees are present) and the ground layer in grasslands or related herbaceous communities (which are defined to have <10% tree cover). This aligns with the ‘dominant’ or ‘primary’ layer in some vegetation classification systems, but the term ‘defining’ was selected to avoid implying greater importance for biodiversity.
<b>Ecological layer</b>	The biotic assemblage and ecological processes associated with a defined stratum of an ecosystem.
<b>Ecosystem condition</b>	<p>As defined by UN (2024), ‘ecosystem condition is the quality of an ecosystem measured in terms of its abiotic and biotic characteristics. Condition is assessed with respect to an ecosystem’s composition, structure and function, which, in turn, underpin the integrity of the ecosystem, and support its capacity to supply ecosystem services on an ongoing basis. Measures of ecosystem condition may reflect multiple values and may be undertaken across a range of temporal and spatial scales.’</p> <p>For brevity in this paper we use the term ecosystem condition from a biodiversity perspective, i.e. relating to the integrity of the ecosystem with regards to its capacity to maintain the structure, function, and composition necessary for the persistence of native species that would be expected in a reference (intact) state.</p> <p>Ecosystem condition scores typically range from 0.0 (<b>ecosystem integrity</b> extinguished) to a maximum of 1.0 (<b>High integrity reference</b>).</p>
<b>Ecosystem expression</b>	Ecosystem expressions refer to the range of observable <del>conditions</del> or attributes that an ecosystem can exhibit while remaining within a single defined state. These expressions arise in response to internal ecological processes such as seasonal variability, recruitment pulses, resource availability, or regeneration and successional phases. Although these variations may affect vegetation cover, species dominance, or productivity, they do not constitute a fundamental change in ecosystem state. Instead, expressions represent the natural ecological variability and dynamics inherent to a state and reflect the system’s resilience and internal feedback mechanisms.
<b>Ecosystem integrity</b>	Ecosystem integrity is “the ecosystem’s capacity to maintain its characteristic composition, structure, functioning and self-organization over time within a natural range of variability” (Müller et al., 2000; Parrish et al., 2023; United Nations, 2024). ‘Natural’ is commonly defined in relation to a pre-colonization, pre-intensification or pre-industrial state (McNellie et al. 2020).
<b>Ecosystem state</b>	A distinct, persistent configuration of an ecosystem at a particular point in space and time, characterised by its structure, function and composition. Ecosystem states represent commonly observed forms that an ecosystem takes across a landscape, are typically maintained by characteristic ecological processes, and may be classified as reference states or <b>modified</b> states.
<b>Ecosystem type</b>	A distinct ecological system or community that is functionally coherent and has characteristic attributes and ecological drivers.
<b>Ground layer</b>	The assemblage of herbaceous plants, often including grasses and forbs, that grow close to the ground. It excludes cryptogamic soil crusts and woody seedlings but can include low sub-shrubs (suffrutescent plants) and herbaceous creepers and twiners.
<b>Modified state</b>	An <b>ecosystem state</b> that has become modified in terms of its composition, structure and/or function compared with a <b>reference state</b> (according to its <b>archetype</b> dynamics), typically by changes in disturbance regimes or climate. A modified state can be assigned an <b>ecosystem condition</b> score representing its integrity relative to the <b>reference state</b> . The templates include <i>Modified</i> , <i>Highly modified</i> and <i>Collapsed/transformer</i> categories, all of which would come under the general umbrella of modified.

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<b>Reference state</b>	<p>A reference state refers to a state against which past, present and/or future ecosystems are compared in order to evaluate relative change over time (UN, 2024). In the context of the state-and-transition model templates, a reference state has the characteristics reflecting highest <b>ecosystem condition</b> of the ecological community of interest. A reference state is not necessarily static but reflects a dynamic ecosystem operating within a natural range of variability, e.g. cycles of fire and regeneration (see <b>archetype</b>).</p> <p>A reference can be selected from a number of framings (e.g. McNellie et al., 2020), which should be explicitly stated. One common choice is an Indigenous cultural reference, reflecting characteristics and dynamics prior to colonization of Indigenous cultures by Colombian, Roman, European or other colonizers, and including Indigenous-driven ecosystem management regimes. This is the typical application of reference in Australia for example, where the Indigenous cultural reference reflects ecosystems prior to European colonization (commonly defined as pre-1750), and also aligns with concepts such as pre-industrial, pre-intensification (i.e. prior to amplified rates of ecological change attributed to human disturbance (McNellie et al. 2020), and pre-Homogenocene (Curnutt, 2000).</p> <p>On continents or in regions where characterization of a historical reference is too difficult, e.g. where there is little information or where climate change is expected to prevent persistence of past ecosystems, improved frameworks are needed to provide standardised guidance on selecting alternatives.</p> <p>In the state-and-transition model templates, we recognise two levels of a reference state to reflect different degrees of ecosystem condition:</p> <ol style="list-style-type: none"> <li>1. <b>High integrity reference:</b> This represents an ecosystem in its highest condition for biodiversity, where ecological structure, composition, and function are intact and reflect the archetype relevant to the selected reference (see above). The High integrity reference serves as an ideal reference for ecosystem condition and is used to define its upper limit.</li> <li>2. <b>Close to reference:</b> This includes a broader range of ecosystem condition, encompassing the High integrity reference, but may exhibit some departure or degradation of ecosystem attributes. These departures may result from exogenous disturbances that have, for example, caused minor changes in native species composition, or invasion by low biomass, non-transformer exotic plant species. This Reference level is useful for pragmatic reduction of complexity in state-and-transition models (with fewer, more broadly-defined states), and practical assessments where a High integrity reference state is no longer present or well understood.</li> </ol>
<b>Shrub layer</b>	The assemblage of shrubs and vines at a site, excluding plants that form part of the tree or <b>ground layers</b> . Vines are considered part of the <b>tree layer</b> where they are found in the crowns of established trees.
<b>Transformer species</b>	Transformer species are invasive, non-locally indigenous taxa (including weeds and feral animals) with the potential to substantially alter the structure, function and composition of an ecological community over substantial areas (Richardson et al. 2000).
<b>Transition</b>	A transition is the pathway by which an ecosystem changes from one <b>ecosystem state</b> to another in response to a driver of substantial change (e.g. flooding or livestock grazing). In state-and-transition models, transitions are typically difficult to reverse without active change in management, an extreme event, or a long timeframe. They are distinguished from pathways between different <b>ecosystem expressions</b> within a state, which often result from slow acting but incremental successional processes.

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<b>Tree layer</b>	The highest ecological stratum in a forest or woodland, composed of the crowns of trees and any vines that occur within them. Attributes of tree saplings and seedlings are also included in descriptions of this layer although they physically occur in lower layers.
<b>Variant</b>	A sub-division within an <b>ecosystem state</b> that is used to highlight variation within that state (e.g. higher and lower ends of a gradient in exotic abundance, or plantations of different woody species) without introducing new states into the state-and-transition model. Whether such variation is treated as a variant or a separate state is by discretion, but variants must have the same transitions and drivers to and from other states.

## Appendix S1: REFERENCES

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## Appendix S2. Extended methods for the ecosystem states templates workshop, and post-workshop alignment decisions

### Participant selection

Members of the core team used their networks and knowledge of the literature to identify potential workshop participants. Expertise sought was demonstrated scientific or practical experience and understanding of the dynamics of Australian rainforests, forests, woodlands, shrublands and/or grasslands, or knowledge about state-and-transition modelling and ecosystem assessment. This included land managers, scientists and government decision makers, resulting in 54 workshop participants, including 13 team members from CSIRO and TERN, and 40 external experts. The workshop and wider project adhered to human ethics procedures (CSIRO Human Research Ethics approval numbers 248/23 and 046/24).

### Workshop exercises

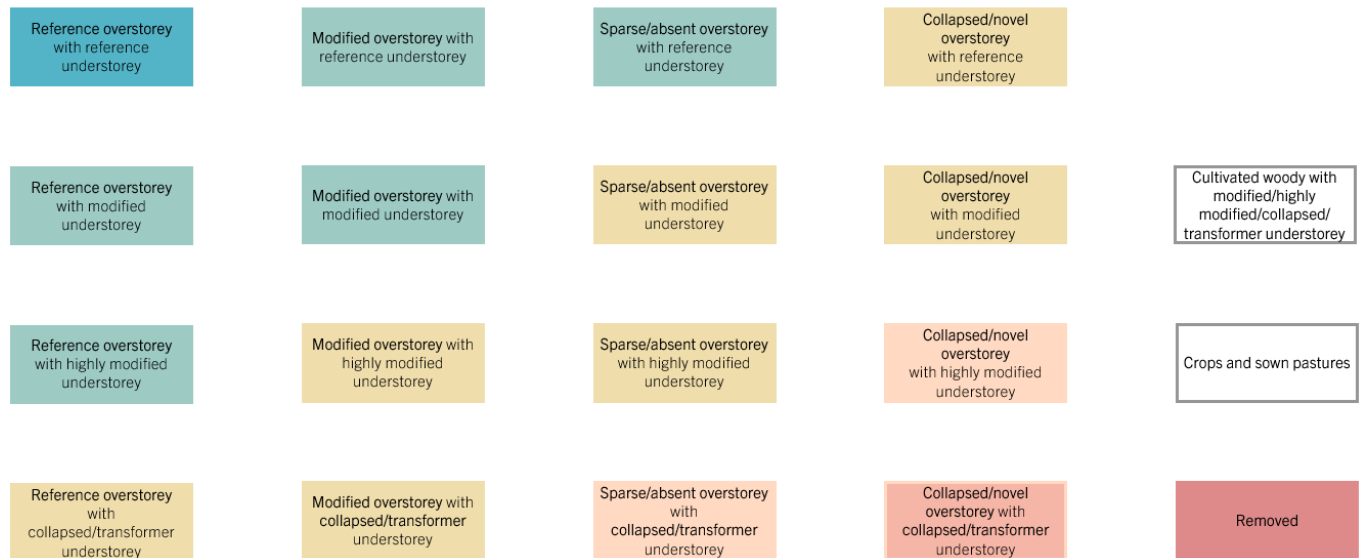
Participants were broken into groups focusing on one or two of 11 different terrestrial ecosystem types that reflect aggregations of the major vegetation groups (excluding wetlands, mangroves and saltmarsh) of Australia's National Vegetation Information system (DCEEW, 2025; Appendix S4: Section 1). The aggregated ecosystem groups were:

- (1) rainforests (including temperate to tropical rainforests and vine thickets),
- (2) eucalypt forests and woodlands (dominated by *Eucalyptus*, *Corymbia*, *Eudesmia*, or *Blakella* spp., with shrubby or grassy understoreys),
- (3) casuarina woodlands (dominated by *Casuarina* and *Allocasuarina* spp.),
- (4) forests and woodlands dominated by *Melaleuca* spp.,
- (5) forests and woodlands dominated by *Callitris* spp.,
- (6) forests and woodlands dominated by *Acacia* spp.,
- (7) mallee woodlands (dominated by low, multi-stemmed *Eucalyptus* species that resprout from a large lignotuber after fire),
- (8) chenopod shrublands (dominated by succulent shrubs of the Chenopodioideae subfamily of the family Amaranthaceae),
- (9) heathlands (including sclerophyllous coastal and inland shrublands dominated by species from the families Proteaceae, Myrtaceae, Ericaceae and/or Casuarinaceae),
- (10) tussock grasslands (including temperate to tropical grasslands dominated by tussock grasses such as *Themeda triandra*, *Poa* spp., *Austrostipa* spp., *Rytidosperma* spp., *Dichanthium* spp., *Astrebla* spp.), and
- (11) hummock grasslands (grasslands dominated by hummock forming grasses, typically *Triodia* spp.).

Each group undertook the following exercises over two days, guided by facilitators, instructions on workshop slides (reproduced below) and plenary discussions:

**1) Modify the following draft template (developed for forests and woodlands, Figure 1) based on instructions for Outputs 1 and 2:**

## Template for forests and woodlands



Appendix S2: Figure S1. Preliminary template for forests and woodlands.

### 1. Review the templates

#### Output 1: Equal resolution (primary) templates

- Review the forests and woodlands template and its applicability to one or more of the aggregated ecosystem groups
- Simplify the template for non-forest/woodland ecosystems by removing states that aren't relevant (e.g. cleared overstorey in grasslands), assuming overstorey=tree layer, understorey=shrub and ground-layer
- If essential, add or adjust states but aim to match the resolution of the initial template
- Check the template against each aggregated ecosystem grouping to consider whether it would apply (list which do apply)
- Adjust template for each ecosystem grouping if generic version not suitable (and label it with the relevant archetype)

#### Output 2: Higher resolution (secondary) templates

- Start with your Output 1 template
- Consider whether to add a new dimension, row or column to increase resolution, e.g. of shrub/ground layer (in simpler ecosystems). *Treat this as a separate model without overstorey*; avoid >16 states, describe why you made these decisions
- For example, you may wish to divide understorey into a shrub layer and ground layer to produce a new matrix of shrub vs ground layer ecosystem states, or the ground layer into finer layers
- Check the template against each ecosystem grouping to consider whether it would apply (list which do apply)
- Adjust template for ecosystem grouping if generic version not suitable (and label it with the relevant archetype)

#### Guidelines for modifying the template

- What constitutes ‘requiring its own state’? Distinct groupings of ecosystem structure, function and/or composition with similar condition ranges
- Keep it simple. Aim for no more than 16 natural states
- Aim for consistency in degree of resolution across aggregate ecosystem groupings and archetypes
- Minimise the number of different templates. One template to fit them all would be ideal!
- Natural ecosystem expressions (that appear in the archetype model) don’t need to be represented as new states unless something has changed (e.g. needs a management intervention to return to the dominant expression)
- Remember there is flexibility when downscaling (i.e. applying the template to develop regional STMs) to add new states, divide states into more-finely distinguished variants or states, and build in recovering stages

## 2. Describe the attributes of ecosystem states for each template

- First, provide a general description of each ecosystem state or class
- Describe attributes of structure, function and composition for ecosystem states or classes
- Describe attributes as a function of a High integrity reference (i.e. as departure from reference)
- Decide if your reference state is a ‘Close to reference’ state or High integrity reference
- Start with the equal resolution template (i.e. avoiding subdivisions of states)
- Complete attribute table with descriptions and/or values, using the SER recovery wheel as a guide (Appendix S3)
- Some attributes are pre-filled based on SER recovery wheel: composition of plants, animals, exotic species abundance
- Some attributes need threshold values (where possible): Canopy and ground cover, large tree number, stem density
- Some attributes are descriptive (e.g. habitat provision, recruitment, soil properties)
- Give examples of each ecosystem state and any maintenance disturbances required to keep the ecosystem in that state
- Some ecosystem states are broad – can describe separate ‘variants’

## 3. Rank ecosystem states

- Rank according to degree of departure from reference (not how easy or hard it is to restore)
- Assume equal weight to overstorey and understorey [or equivalent] for this exercise
- Different states can have the same rank
- Aim for comparability across models built from the same template
- Should be logically aligned to templates with reduced or expanded states (e.g. using the same understorey [complementary layer] ranks where applicable)
- *Question: Where do cultivated states fit? E.g. woody and herbaceous crops, sown pastures, plantations*

**Appendix S2: Table S1.** State-and-transition model elicitation workshops at which various iterations of the STM templates and guides were reviewed or implemented, and their timing in relation to the National STM templates workshop. Support for each workshop shown in brackets, DCCEEW, Department of Climate Change, Energy and Environment; TERN, Terrestrial Ecosystems Research Network; DPIRD WA, Department of Primary Industries and Regional Development, Western Australia (O'Donnell et al. 2025); LTU, A. Maisey, J. Radford and others, La Trobe University). Methods for regional elicitation workshops involved two-to-three day workshops with experts familiar with ecosystem types of interest in the relevant regions, including scientists, land managers (farmers, natural resource managers, natural area managers etc.) and Indigenous knowledge holders; and a staged process to elicit and describe ecosystem states, transitions and drivers using various iterations of the templates and tools. Where available, expert knowledge was augmented with published information and data before and after workshops. Models published as part of the Ecological Knowledge System of Australia's Nature Repair Market are available at Richards et al. (2025).

**Appendix S2: Table S1.**

<b>Workshop coverage</b>	<b>Ecosystem type</b>	<b># expert contributors</b>
<b>Preliminary template development phase</b>		
1. North central Victoria, May 2024 (DCCEEW, TERN)		
	Resprouter eucalypt forests	14
	Lowland resprouter temperate and subtropical eucalypt woodlands	15
	Rainfall-driven arid and semi-arid tussock grasslands	9
	Chenopod/ tussock grass mallee	8
2. Burnett-Mary region, Queensland, May 2024 (DCCEEW, TERN)		
	Lowland resprouter temperate and subtropical eucalypt woodlands	13
	Tropical/subtropical rainforests	9
	Mangroves and saltmarsh	6
3. Mulga rangelands, Western Australia, August 2024 (DPIRD, WA)		
	Mulga woodlands and shrublands	23
	Chenopod shrublands	8
4. Brigalow belt, Queensland, October 2024 (DCCEEW, TERN)		
	Brigalow forests and woodlands	17
	Lowland resprouter temperate and subtropical eucalypt woodlands	12
	Semi-evergreen rainforests and vine thickets	5
<b>5. National STM templates workshop, February 2025 (TERN, DCCEEW)</b>		
	11 generic ecosystem types	54
<b>Synthesis and refinement phase</b>		
6. Threatened mallee bird community of eastern Australia, March 2025 (LTU, DCCEEW)		
	Mesic heathy mallee	28
	Shrubby/ Triodia mallee	
	Shrubby/ Triodia mallee	
	Chenopod/ tussock grass mallee	
7. North-east Tasmania, April 2025 (DCCEEW, TERN)		
	Cool temperate rainforests	7
	Resprouter eucalypt forests	6
	Lowland resprouter temperate and subtropical eucalypt woodlands	8
	Temperate mesic grasslands	10
	Dry heathlands and shrublands	8
8. Western New South Wales, July 2025 (DCCEEW, TERN)		
	Fire-intolerant Callitris woodlands	11
	Rainfall pulse-disturbed Casuarina woodlands	9
9. Shrubland archetype model and template review workshop, Sept 2025 (TERN, DCCEEW)		
	Alpine shrublands	6
	Coastal shrublands	7
	Dry heathlands and shrublands	10
	Wet heathlands	9
10. Cape York Peninsula, Queensland, October 2025 (DCCEEW, TERN)		
	Wet-dry tropical eucalypt forests and woodlands	12
	Wet-dry Melaleuca forests and woodlands	7
	Dry heathlands and shrublands	6
11. Central deserts, Northern Territory/Western Australia, November 2025 (DCCEEW, TERN)		
	Inland floodplain eucalypt forests and woodlands	5
	Mulga woodlands and shrublands	6
	Hummock grasslands	8

## Post-workshop alignment decisions

Heterogeneity in outcomes among workshop groups for selecting and defining states and applying the SER five-star system (Gann, 2024) was addressed through post-workshop discussion amongst the core project team to ensure consistency among templates, as follows:

*Treatment of crops and pastures.* Some groups treated crops and pastures as a single group, and others separated them or merged pastures with *highly modified* states. The project core team agreed to treat crops separately from intensively managed exotic pastures, recognising these can be merged if the distinction is not required in downscaled models. To distinguish them from *highly modified* states, the pasture state was more explicitly defined as intensively-managed exotic pastures.

*Treatment of cultivated woody plantations.* It was recognised that plantations represent a heterogeneous group applicable to planted woody crops (native or exotic). For simplicity, the core project team decided to represent this as a single box on the template that represents three potential ecosystem states, i.e. cultivated woody plantations with modified, highly modified or transformer/collapsed complementary layers. Additionally, the characteristics of the woody planting can vary substantially, for example, some plantations may resemble native overstoreys (e.g. plantations of regionally-native tree species), whereas others may involve monocultures of exotic species, impinging on their assessment in terms of departure from a High integrity reference. Where multiple types of plantation are relevant in regional applications, these can be recognised as separate states or variants, and ecosystem condition assigned according to Table 2 (main text).

*Sparse/absent overstorey (or defining layer).* The terminology for this defining layer category was changed to *Highly modified/absent* to reflect potential not only for it to represent largely cleared states, but also other types of modification, such as substantial increases in native woody layers in grasslands.

*Novel overstorey (or defining layer).* ‘Novel’ was renamed to ‘transformer’, to distinguish this category from states involving locally native species that have substantially increased in cover compared with the High integrity reference expressions. The latter may be considered Modified or Highly modified where appropriate. ‘Transformer’ was defined as invasion by exotic species leading to alteration of ecosystem processes to the extent that few other characteristic plant species of the ecological layer can be supported. ‘Exotic’ includes species from other continents or regions unlikely to arrive without human intervention.

*Collapsed and transformer categories.* Collapsed and transformer categories were combined in the template as they were expected to have similar ecosystem condition scores and, where both occur in a specific ecosystem type, they can be recognised as separate states. Note there can be high variability in the drivers and abiotic characteristics of collapsed layers that would be defined when the templates are downscaled in developing a regional-specific STM.

*Uncommon or implausible states.* Working groups for different ecosystem types identified that some states were uncommon or not known to occur. This was particularly the case for *Collapsed defining layer with reference complementary layer*, and *Reference defining layer with collapsed/transformer complementary layers*. For consistency these states have been included in the generalised templates and should be excluded where appropriate at the downscaling stage when applying the templates to develop an STM.

*Recovering or successional stages.* Points along long-term recovery trajectories from modified states can be allocated “recovering stages” where this is useful for practical applications (e.g., to describe expected

ecosystem characteristics at a specific timeframe within a program such as a 25-year permanence period in Australia's Nature Repair Market). Recovery stages will be particularly relevant to recovery of long-lived woody layers, and should not be confused with *Modified* woody layers that are in a more stable state (e.g. due to tree thinning and lack of subsequent regeneration, or stable changes in species composition).

Distinctive successional stages in rainforests, including those with high native vine components, were a significant discussion point. These should not be confused with *Modified* states, rather, where they are part of a natural disturbance cycle, can be captured as expressions reflecting the pre-colonization dynamics of such ecosystems within the archetype reference models (or similar dynamics within modified states). Where they involve active or passive recovery from modified or highly modified states, their unique attributes can be captured in descriptions of 'recovering stages'. This contrasts with the presence of exotic vines and lianas, that are recognised through the secondary template for the rainforest vine layer.

*Aligning SER star ratings with ecosystem states and ecosystem condition.* There was initially variation among working groups in their assignment of SER star ratings 0–5 and associated attribute descriptions to the four categories in the STM templates (Supporting Information S3). These were resolved as follows:

*Close to reference.* The *Close to reference* category was assigned from a species composition perspective to the combined four and five star ratings for eight ecosystem types and to the five star rating only for two ecosystem types. These differences reflected subjective choices among independent working groups rather than expected differences among ecosystem types, reflecting the trade-off between down-grading the highest quality reference sites, and down-grading high quality close to reference sites. A compromise was to include both the four and five star ratings in the *Close to reference* category, with recognition of a High integrity reference and potential to create further divisions within this category when models are downscaled. Given challenges in exact definition and measurement of reference conditions, the broader category was considered more pragmatic, with greater potential for detection using remote sensing.

*Modified categories.* Similarly, for *Modified* and *Highly Modified* categories, the majority of workshop groups (seven ecosystem types) accepted the proposed default SER star ratings (2–3 stars for *Modified*, 1 star for *Highly Modified*), while the minority (three ecosystem types) assigned different thresholds to these categories. Again, these differences among groups were considered to be reflective of subjective choices rather than expected differences among ecosystem types. In the absence of a strong ecological rationale to deviate from the proposed default SER star ratings, the decision was made to align with the majority consensus and retain the default ratings.

Using this approach, we note that the range in indicative ecosystem condition for the *Modified* category is higher than other categories (range of 0.5; values of 0.25 to 0.75). This reflects a preference of most workshop participants to remain consistent with the SER five-star system, requiring merging of six star ratings (0–5) into four. Partitioning of modified categories to smaller ecosystem condition ranges, or accounting for this range in other ways, could be a high priority in some contexts (e.g. see O'Donnell et al., (2025), where our *Modified* category would relate to their good and fair categories).

## Appendix S2: REFERENCES

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### Appendix S3. Guide to ecosystem attributes for describing ecosystem states.

NA = not applicable. SER = Society for Ecological Restoration five-star system sub-attributes table (Gann et al., 2024). Habitat Hectares is described in Parkes et al. (2003) and BioCondition is described in Eyre et al. (2017). For simplicity, minor changes and corrections from the original workshop version that was trialled are not shown here.

Derivation of attribute	Attribute	Sub-attribute	Describe for ecosystem layers or state?	Description of attribute
NA	General information	Description (defining features of class or state)	layers	Text summary of the ecosystem state
NA	General information	Maintenance disturbances	state	List of disturbances that maintain a state e.g. grazing, harvesting, fire, inundation, erosion or deposition rates (proportion of area), crop management, weed management.
NA	General information	Examples	state	Descriptive examples of the ecosystem state observed in a region
SER	Physical conditions	Substrate physical conditions (both abiotic and biotic components, including topography)	state	Description focused on information about: Similarity to the landforms in the surrounding landscape; Macro and micro variability measures; Soil profile; Water erosion (e.g., erosion rills, gullies, piping); Wind erosion (e.g., sediment movement or loss); Compaction; % bare ground; Soil roughness; Surface resistance to disturbance; Soil development and characteristics (rock/sand/silt/clay percents); Soil coarse fraction content; Soil fraction particle size analysis (texture); Bulk density; Hydraulic conductivity; Soil strength; Particle size and erodibility; Biocrusts; Soil biota
SER	Physical conditions	Substrate chemical conditions	state	Description focused on information about: pH; Salinity; Macronutrients and micronutrients; Heavy metals; Rates of litter mass change; Soil nutrient availability
SER	Physical conditions	Water chemo-physical conditions	state	Description focused on information about: Depth to water table; Water infiltration of soil/substrate; Water holding capacity
SER	Species composition	Desirable plants, fungi and lichens	layers	Diversity (richness and evenness) of characteristic native plant, fungi, and lichen species and genes present relative to a high integrity reference state
SER	Species composition	Desirable animals	layers	Diversity (richness and evenness) of characteristic native animal species and genes

Derivation of attribute	Attribute	Sub-attribute	Describe for ecosystem layers or state?	Description of attribute
				present relative to a high integrity reference state
SER	Species composition	Undesirable species cover	layers	Relative cover (mean of cover of exotic, invasive or other undesirable plant and animal species (including overabundant native species) / total cover of all species in that layer for all values > zero)
SER	Structural diversity	Trophic complexity	state	Description focused on information about: Food webs; Complexity and interactions of primary producers, primary consumers, secondary consumers, tertiary consumers, apex predators, and decomposers; Soil microbiome; Appropriate balance of trophic levels and populations within them
SER	Structural diversity	Spatial mosaic	state	Description focused on information about: Spatial distribution of features (e.g., vegetation, animal populations, habitats, gap fractions); Arrangement and distribution of species, habitats and habitat features; Patch history and size
Habitat hectares	Structural diversity	<vegetation layers> cover % of reference	layers	Cover of different vegetation layers compared to a high integrity reference. Cover is defined as foliage projective cover for layers dominated by woody species, and is the percentage of ground area occupied by the vertical projection of the foliage of native woody vegetation. For the ground layer, vegetation cover is the amount of native plant material (dead or alive) that covers the soil surface, expressed as a percentage
BioCondition	Structural diversity	Large tree density (number/ha) % of reference (forests and woodlands only)	layers (overstorey only)	Number of large trees as a proportion of the number in a high integrity reference state. Large tree size is defined in the high integrity reference vegetation description and can vary from 20cm to 80 cm DBH. If a large DBH threshold is not provided in benchmark information, then generic thresholds of >20 cm DBH for non-eucalypts and >30 cm DBH for eucalypts can be used.
NA	Structural diversity	Stem size class distribution compared to reference (forests)	layers (overstorey only)	Density of stems in different diameter size classes compared to a high integrity reference

<b>Derivation of attribute</b>	<b>Attribute</b>	<b>Sub-attribute</b>	<b>Describe for ecosystem layers or state?</b>	<b>Description of attribute</b>
		and woodlands only)		
SER	Ecosystem function	Productivity/cycling	state	Description focused on information about: Productivity (e.g., photosynthesis and growth); Water cycling; Nutrient cycling; Carbon cycling; Demographics
SER	Ecosystem function	Habitat provision and quality (per ecosystem layer)	layers	Description focused on information about: Habitat provision; Host/nectar plants for pollinators; Host/fruited plants for frugivores; Occurrence of ecosystem engineers (e.g., ants, digging vertebrates; large herbivores); Specialized nesting habitats (e.g., old growth trees); Occurrence of specialized nests; Coarse woody debris and leaf litter; Habitat quality indices; Occurrence of epiphytes and other specialized habitat providers; Constructed habitat features (breeding and refuge); Vegetation and litter habitat (foraging, breeding and refuge).
SER	Ecosystem function	Recruitment (per ecosystem layer)	layers	Description focused on information about: whether gap phase or post-disturbance plant recruitment is occurring; Capability for self-replacement (growth rates, seedbanks, seedling recruitment over multiple generations); Species reproduction and recruitment (flowering, seed production, provision of seedbanks); Presence of different successional groups. Note that species are described for the layer to which their mature phase belongs, e.g. tree seedlings and saplings as part of the tree layer.

### Appendix S3: REFERENCES

Eyre, T. J., A. L. Kelly, and V. J. Neldner. 2017. *Method for the establishment and survey of reference sites for BioCondition*, version 3. Brisbane: Queensland Herbarium, Department of Science, Information Technology and Innovation.

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Appendix S4

# State-and-transition model templates, guides and demonstrations

# Citation and copyright

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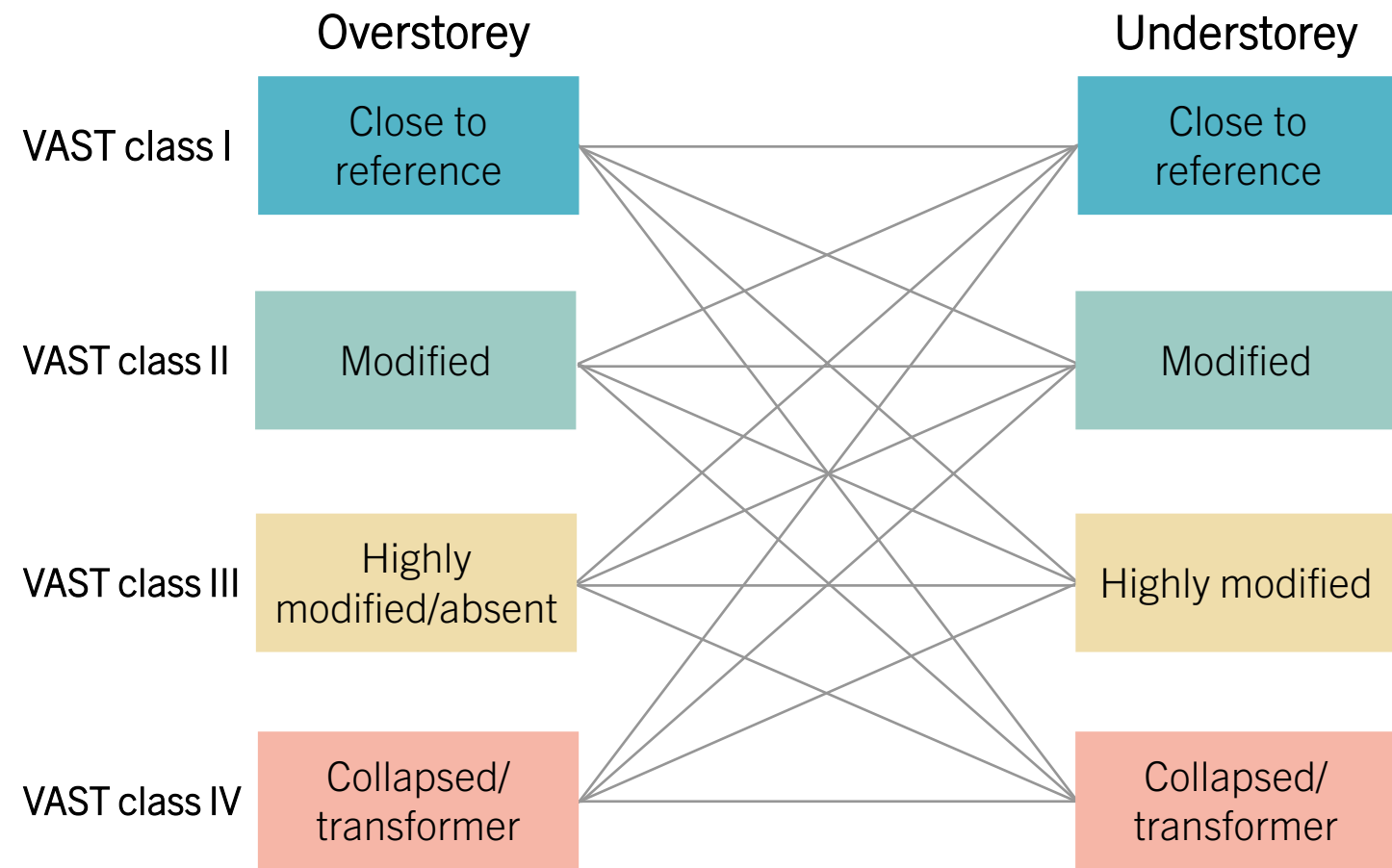


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# 1. Derivation of templates



**Extended VAST classes I-IV: combinations of overstorey and understorey modification in forests and woodlands**  
VAST classes described in Thackway, R., Lesslie, R. (2006). Reporting vegetation condition using the Vegetation Assets, States and Transitions (VAST) framework. Ecological Management & Restoration, 7(s1), S53-S62.





**Sparsely vegetated ecosystems**

Not developed

**Terrestrial ecosystems**

**Forests and woodlands**

- 1. Rainforest
- 2. Eucalypt
- 3. Casuarina
- 4. Melaleuca
- 5. Callitris
- 6. Acacia
- 7. Mallee

Tree layer  
x  
Shrub/ground layer

**Shrublands**

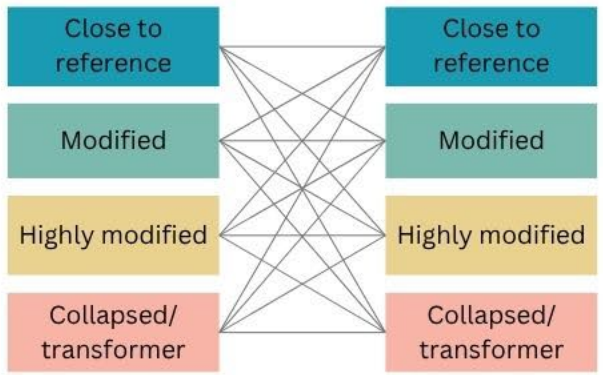
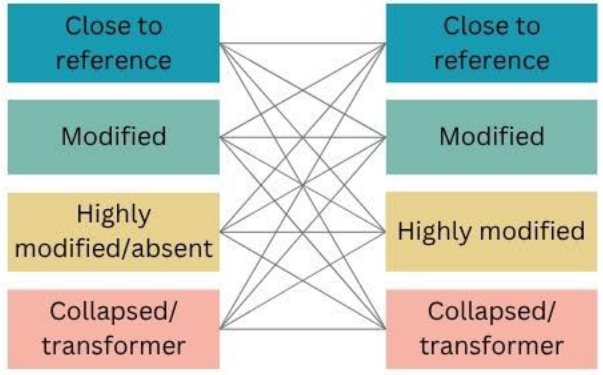
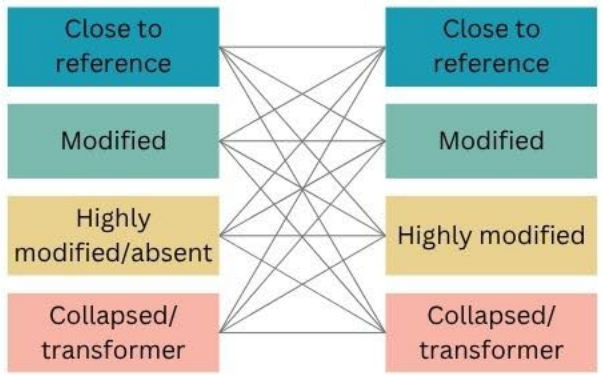
- 8. Chenopod
- 9. Heathland

Shrub layer  
x  
Tree/ground layer

**Grasslands**

- 10. Tussock
- 11. Hummock

Ground layer  
x  
Tree/shrub layer





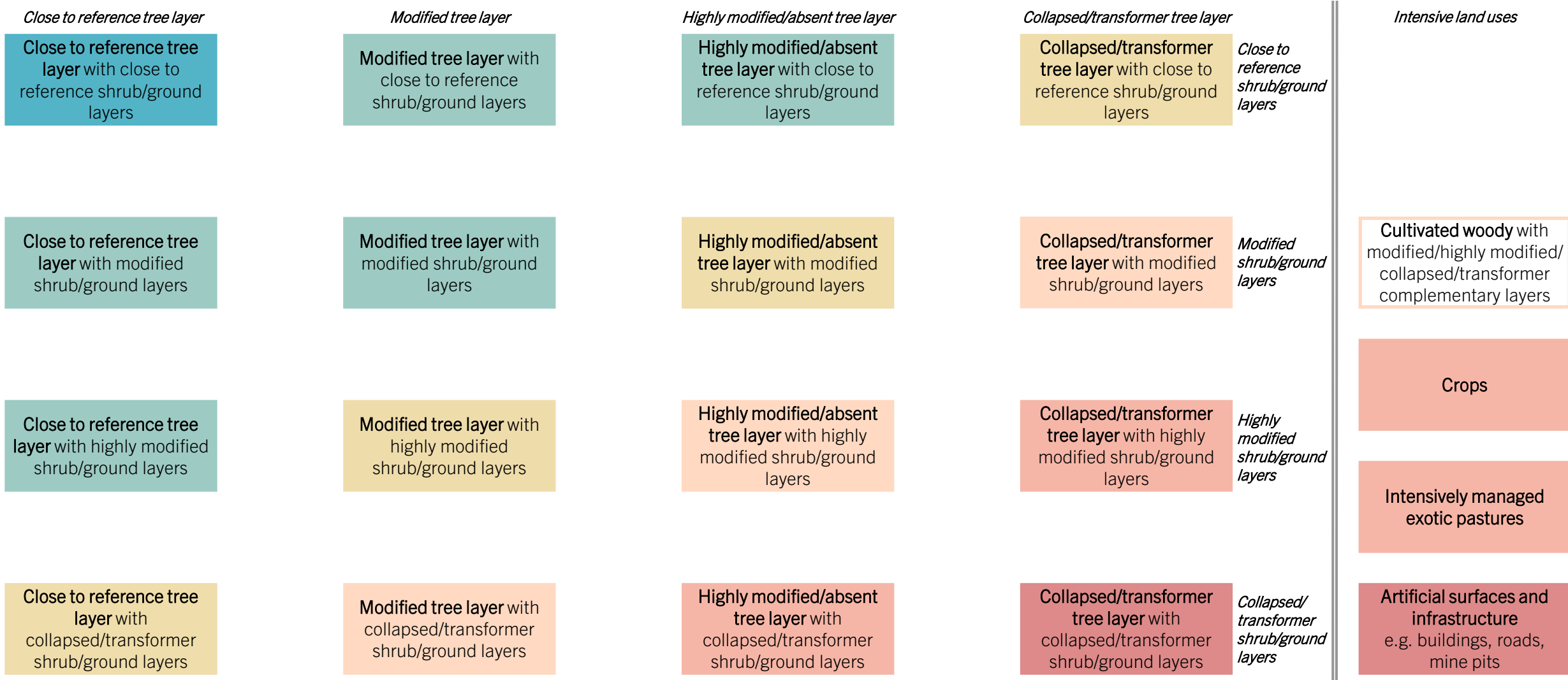
# 2. Primary templates





# Forests and woodlands template





**Primary template for forests and woodlands**



*Close to reference o/s and close to reference u/s*



*Modified o/s (thinned), close to reference u/s*



*Highly modified/absent o/s, close to reference u/s*



*Collapsed o/s, close to reference u/s*



*Close to reference o/s, modified u/s*



*Modified o/s (Acacia predominance), modified u/s*



*Highly modified/absent o/s, modified u/s*



*Collapsed o/s, modified u/s*



*Close to reference o/s, highly modified u/s*



*Modified o/s (thinned), highly modified u/s*



*Highly modified/absent o/s, highly modified u/s*



*Collapsed o/s, highly modified u/s*

Example Reference and modified states for eucalypt woodlands, reflecting 12 of 16 states in the core template for forests and woodlands



# Shrublands template





*Close to reference shrub layer*

Close to reference shrub layer with close to reference tree/ground layers

Close to reference shrub layer with modified tree/ground layers

Close to reference shrub layer with highly modified tree/ground layers

Close to reference shrub layer with collapsed/transformer tree/ground layers

*Modified shrub layer*

Modified shrub layer with close to reference tree/ground layers

Modified shrub layer with modified tree/ground layers

Modified shrub layer with highly modified tree/ground layers

Modified shrub layer with collapsed/transformer tree/ground layers

*Highly modified/absent shrub layer*

Highly modified/absent shrub layer with close to reference tree/ground layers

Highly modified/absent shrub layer with modified tree/ground layers

Highly modified/absent shrub layer with highly modified tree/ground layers

Highly modified/absent shrub layer with collapsed/transformer tree/ground layers

*Collapsed/transformer shrub layer*

Collapsed/transformer shrub layer with close to reference tree/ground layers

Collapsed/transformer shrub layer with modified tree/ground layers

Collapsed/transformer shrub layer with highly modified tree/ground layers

Collapsed/transformer shrub layer with collapsed/transformer tree/ground layers

*Close to reference tree/ground layers*

*Modified tree/ground layers*

*Highly modified tree/ground layers*

*Collapsed/transformer tree/ground layers*

*Intensive land uses*

Cultivated woody with modified/highly modified/collapsed/transformer complementary layers

Crops

Intensively managed exotic pastures

Artificial surfaces and infrastructure  
e.g. buildings, roads, mine pits

**Primary template for shrublands**



Example shrubland that is predominantly made up of the shrub layer, Forrestania, WA, SMProber CSIRO



Example of a (chenopod) shrubland that has a significant ground layer, , Menindee NSW, SMProber CSIRO



Example of a (chenopod) shrubland that has a significant sparse woody layer, Kitchener, WA, SMProber CSIRO



# Grasslands template





*Close to reference ground layer*

Close to reference ground layer with close to reference tree/shrub layers

*Modified ground layer*

Modified ground layer with close to reference tree/shrub layers

*Highly modified/absent ground layer*

Highly modified ground layer with close to reference tree/shrub layers

*Collapsed/transformer ground layer*

Collapsed/transformer ground layer with close to reference tree/shrub layers

*Close to reference tree/shrub layers*

*Intensive land uses*

Close to reference ground layer with modified tree/shrub layers

Modified ground layer with modified tree/shrub layers

Highly modified ground layer with modified tree/shrub layers

Collapsed/transformer ground layer with modified tree/shrub layers

*Modified tree/shrub layers*

Cultivated woody with modified/highly modified/collapsed/transformer complementary layers

Close to reference ground layer with highly modified tree/shrub layers

Modified ground layer with highly modified tree/shrub layers

Highly modified ground layer with highly modified tree/shrub layers

Collapsed/transformer ground layer with highly modified tree/shrub layers

*Highly modified tree/shrub layers*

Crops

Close to reference ground layer with collapsed/transformer tree/shrub layers

Modified ground layer with collapsed/transformer tree/shrub layers

Highly modified ground layer with collapsed/transformer tree/shrub layers

Collapsed/transformer ground layer with collapsed/transformer tree/shrub layers

*Collapsed/transformer tree/shrub layers*

Intensively managed exotic pastures

Artificial surfaces and infrastructure  
e.g. buildings, roads, mine pits

**Primary template for grasslands**



*Themeda* sp. tussock grassland (minimal woody layers); Hamersley, WA, SMProber CSIRO



*Austrostipa* sp. tussock grassland with scattered shrub layer, Vic., SMProber CSIRO



Hummock grassland with scattered shrub layer, Gibson Desert, WA, SMProber CSIRO

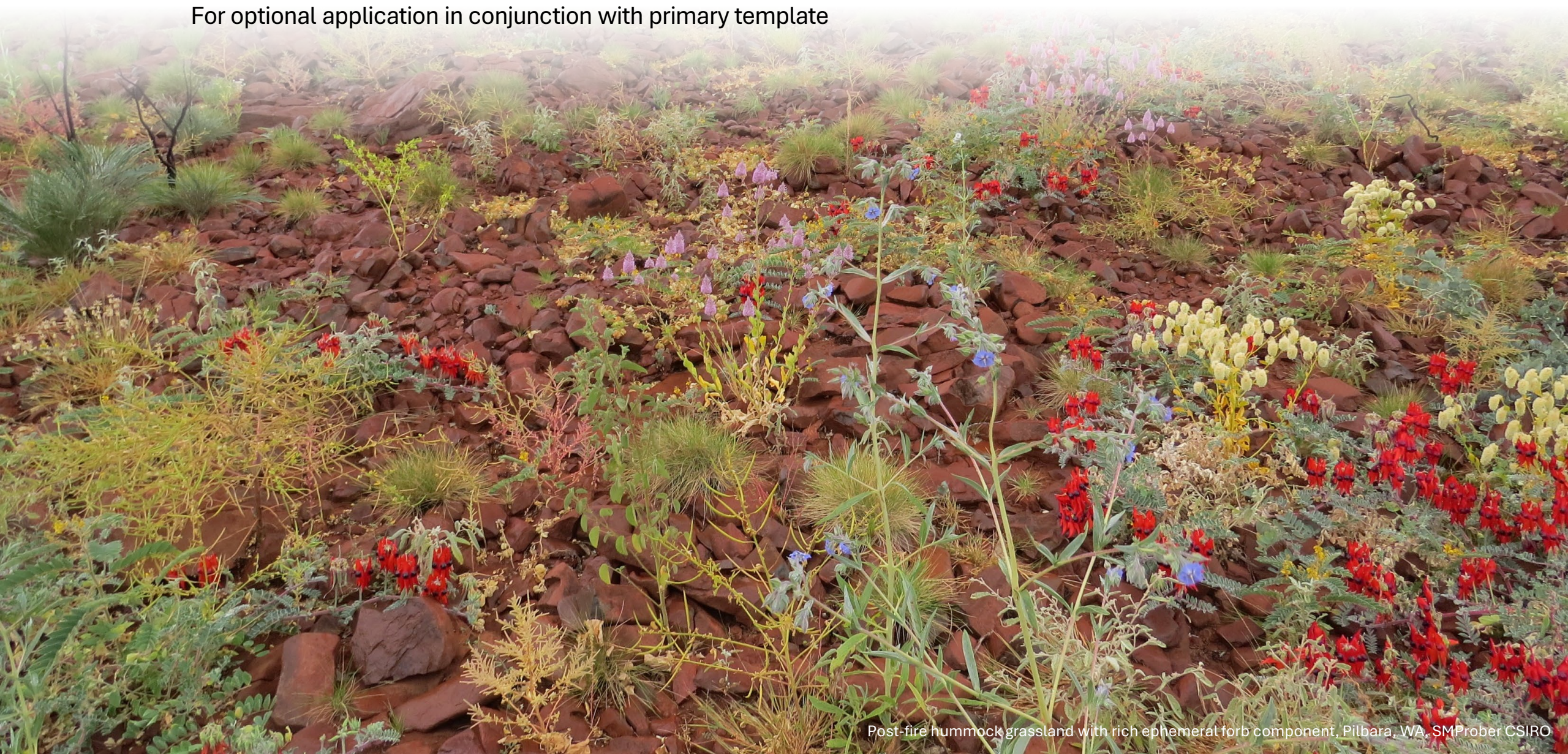


Hummock grassland with tree (*Eucalyptus gongylocarpa*) and shrub layers, Great Victoria Desert, WA, SMProber CSIRO



# 3. Secondary templates

For optional application in conjunction with primary template





*Close to reference shrub layer*

Close to reference shrub layer with close to reference ground layer

*Modified shrub layer*

Modified shrub layer with close to reference ground layer

*Highly modified/absent shrub layer*

Highly modified/absent shrub layer with close to reference ground layer

*Collapsed/transformer shrub layer*

Collapsed/transformer shrub layer with close to reference ground layer

*Close to reference ground layer*

Close to reference shrub layer with modified ground layer

Modified shrub layer with modified ground layer

Highly modified/absent shrub layer with modified ground layer

Collapsed/transformer shrub layer with modified ground layer

*Modified ground layer*

Close to reference shrub layer with highly modified ground layer

Modified shrub layer with highly modified ground layer

Highly modified/absent shrub layer with highly modified ground layer

Collapsed/transformer shrub layer with highly modified ground layer

*Highly modified ground layer*

Close to reference shrub layer with collapsed/transformer ground layer

Modified shrub layer with collapsed/transformer ground layer

Highly modified/absent shrub layer with collapsed/transformer ground layer

Collapsed/transformer shrub layer with collapsed/transformer ground layer

*Collapsed/transformer ground layer*

## Secondary template for forest and woodland shrub/ground layers



*Reference tree layer*

**Reference tree layer**  
with reference ground  
layer

*Modified tree layer*

**Modified tree layer** with  
reference ground layer

*Highly modified/absent tree layer*

**Highly modified/absent  
tree layer** with reference  
ground layer

*Collapsed/transformer tree layer*

**Collapsed/transformer  
tree layer** with reference  
ground layer

*Reference  
herbaceous  
layer*

**Reference tree layer**  
with modified ground  
layer

**Modified tree layer** with  
modified ground layer

**Highly modified/absent  
tree layer** with modified  
ground layer

**Collapsed/transformer  
tree layer** with modified  
ground layer

*Modified  
herbaceous  
layer*

**Reference tree layer**  
with highly modified  
ground layer

**Modified tree layer** with  
highly modified ground  
layer

**Highly modified/absent  
tree layer** with highly  
modified ground layer

**Collapsed/transformer  
tree layer** with highly  
modified ground layer

*Highly  
modified  
herbaceous  
layer*

**Reference tree layer**  
with  
collapsed/transformer  
ground layer

**Modified tree layer** with  
collapsed/transformer  
ground layer

**Highly modified/absent  
tree layer** with  
collapsed/transformer  
ground layer

**Collapsed/transformer  
tree layer** with  
collapsed/transformer  
ground layer

*Collapsed/  
transformer  
herbaceous  
layer*

**Secondary template for shrublands with tree and ground layers**



*Close to reference grasses*

*Modified grasses*

*Highly modified/absent grasses*

*Collapsed/transformer grasses*

Close to reference grasses with close to reference forbs

Modified grasses with close to reference forbs

Highly modified grasses with close to reference forbs

Collapsed/transformer grasses with close to reference forbs

*Close to reference forbs*

Close to reference grasses with modified forbs

Modified grasses with modified forbs

Highly modified grasses with modified forbs

Collapsed/transformer grasses with modified forbs

*Modified forbs*

Close to reference grasses with highly modified forbs

Modified grasses with highly modified forbs

Highly modified grasses with highly modified forbs

Collapsed/transformer grasses with highly modified forbs

*Highly modified forbs*

Close to reference grasses with collapsed/transformer forbs

Modified grasses with collapsed/transformer forbs

Highly modified grasses with collapsed/transformer forbs

Collapsed/transformer grasses with collapsed/transformer forbs

*Collapsed/transformer forbs*

**Secondary template for grasses and forbs in the ground layer**



*Close to reference tree layer*

*Modified tree layer  
with invasive vines*

*Highly modified/absent tree layer with  
invasive vines*

*Collapsed tree layer  
with transformer vines*

n/a

Modified tree layer with  
invasive vines & close to  
reference shrub/ground  
layers

Highly modified/absent  
tree layer with invasive  
vines & close to reference  
shrub/ground layers

Collapsed tree layer with  
transformer vines  
& close to reference  
shrub/ground layers

*Close to  
reference  
shrub/ground  
layers*

n/a

Modified tree layer with  
invasive vines & modified  
shrub/ground layers

Highly modified/absent  
tree layer with invasive  
vines & modified  
shrub/ground layers

Collapsed tree layer with  
transformer vines  
& modified shrub/ground  
layers

*Modified  
shrub/ground  
layers*

n/a

Modified tree layer with  
invasive vines & highly  
modified shrub/ground  
layers

Highly modified/absent  
tree layer with invasive  
vines & highly modified  
shrub/ground layers

Collapsed tree layer with  
transformer vines &  
highly modified  
shrub/ground layers

*Highly  
modified  
shrub/ground  
layers*

n/a

Modified tree layer with  
invasive vines &  
collapsed shrub/ground  
layers

Highly modified/absent  
tree layer with invasive  
vines & collapsed  
shrub/ground layers

Collapsed tree layer with  
transformer vines &  
collapsed shrub/ground  
layers

*Collapsed/  
transformer  
shrub/ground  
layers*

## Secondary template for rainforest vine layer



# 4. Primary template demonstration



# Hypothetical model build

Close to reference tree layer with close to reference shrub/ground layers

Modified tree layer with close to reference shrub/ground layers

Highly modified/absent tree layer with close to reference shrub/ground layers

Collapsed/transformer tree layer with close to reference shrub/ground layers

Close to reference tree layer with modified shrub/ground layers

Modified tree layer with modified shrub/ground layers

Highly modified/absent tree layer with modified shrub/ground layers

Collapsed/transformer tree layer with modified shrub/ground layers

Cultivated woody with modified/highly modified/collapsed/transformer complementary layers

Close to reference tree layer with highly modified shrub/ground layers

Modified tree layer with highly modified shrub/ground layers

Highly modified/absent tree layer with highly modified shrub/ground layers

Collapsed/transformer tree layer with highly modified shrub/ground layers

Crops

Close to reference tree layer with collapsed/transformer shrub/ground layers

Modified tree layer with collapsed/transformer shrub/ground layers

Highly modified/absent tree layer with collapsed/transformer shrub/ground layers

Collapsed/transformer tree layer with collapsed/transformer shrub/ground layers

Intensively managed exotic pastures

Artificial surfaces and infrastructure  
e.g. buildings, roads, mine pits

Example using forests and woodlands template with 50:50 weights for defining : complementary layers

# Hypothetical model build

Close to reference tree layer with close to reference shrub/ground layers

~~Modified tree layer with close to reference shrub/ground layers~~

Highly modified/absent tree layer with close to reference shrub/ground layers

~~Collapsed/transformer tree layer with close to reference shrub/ground layers~~

Close to reference tree layer with modified shrub/ground layers

Modified tree layer with modified shrub/ground layers

Highly modified/absent tree layer with modified shrub/ground layers

~~Collapsed/transformer tree layer with modified shrub/ground layers~~

Cultivated woody with modified/highly modified/collapsed/transformer complementary layers

Close to reference tree layer with highly modified shrub/ground layers

Modified tree layer with highly modified shrub/ground layers

Highly modified/absent tree layer with highly modified shrub/ground layers

~~Collapsed/transformer tree layer with highly modified shrub/ground layers~~

Crops

Intensively managed exotic pastures

~~Close to reference tree layer with collapsed/transformer shrub/ground layers~~

~~Modified tree layer with collapsed/transformer shrub/ground layers~~

~~Highly modified/absent tree layer with collapsed/transformer shrub/ground layers~~

~~Collapsed/transformer tree layer with collapsed/transformer shrub/ground layers~~

Artificial surfaces and infrastructure  
e.g. buildings, roads, mine pits

Remove states not relevant to focal ecosystem or management question

# Hypothetical model build

Close to reference tree layer with close to reference shrub/ground layers

Highly modified/absent tree layer with close to reference shrub/ground layers

Close to reference tree layer with modified shrub/ground layers

Modified tree layer with modified shrub/ground layers

Highly modified/absent tree layer with modified shrub/ground layers

Cultivated woody with modified/highly modified/collapsed/transformer complementary layers

Close to reference tree layer with highly modified shrub/ground layers

Modified tree layer with highly modified shrub/ground layers

Highly modified/absent tree layer with highly modified shrub/ground layers

Crops

Intensively managed exotic pastures

Collapsed/transformer tree layer with collapsed/transformer shrub/ground layers

Artificial surfaces and infrastructure  
e.g. buildings, roads, mine pits

Remove states not relevant to focal ecosystem or management question

# Hypothetical model build

Close to reference tree layer with close to reference shrub/ground layers

Highly modified/absent tree layer with close to reference shrub/ground layers

Close to reference tree layer with modified shrub/ground layers

Modified tree layer with modified shrub/ground layers

Highly modified/absent tree layer with modified shrub/ground layers

Cultivated woody with modified/highly modified/collapsed/transformer complementary layers

Close to reference tree layer with highly modified shrub/ground layers

Modified tree layer with highly modified shrub/ground layers

Highly modified/absent tree layer with highly modified shrub/ground layers

Crops

Intensively managed exotic pastures

Collapsed/transformer tree layer with collapsed/transformer shrub/ground layers

Artificial surfaces and infrastructure  
e.g. buildings, roads, mine pits



Divide states where recognition of more than one distinct state is preferred

# Hypothetical model build

Close to reference tree layer with close to reference shrub/ground layers

Highly modified/absent tree layer with close to reference shrub/ground layers

Close to reference tree layer with modified shrub/ground layers

Modified tree layer with modified shrub/ground layers

Highly modified/absent tree layer with modified shrub/ground layers

Cultivated woody with modified/highly modified/collapsed/transformer complementary layers

Close to reference tree layer with highly modified shrub/ground layers

Modified tree layer with highly modified shrub/ground layers 2

Highly modified/absent tree layer with highly modified shrub/ground layers 2

Crops

Intensively managed exotic pastures

Collapsed/transformer tree layer with collapsed/transformer shrub/ground layers

Artificial surfaces and infrastructure e.g. buildings, roads, mine pits

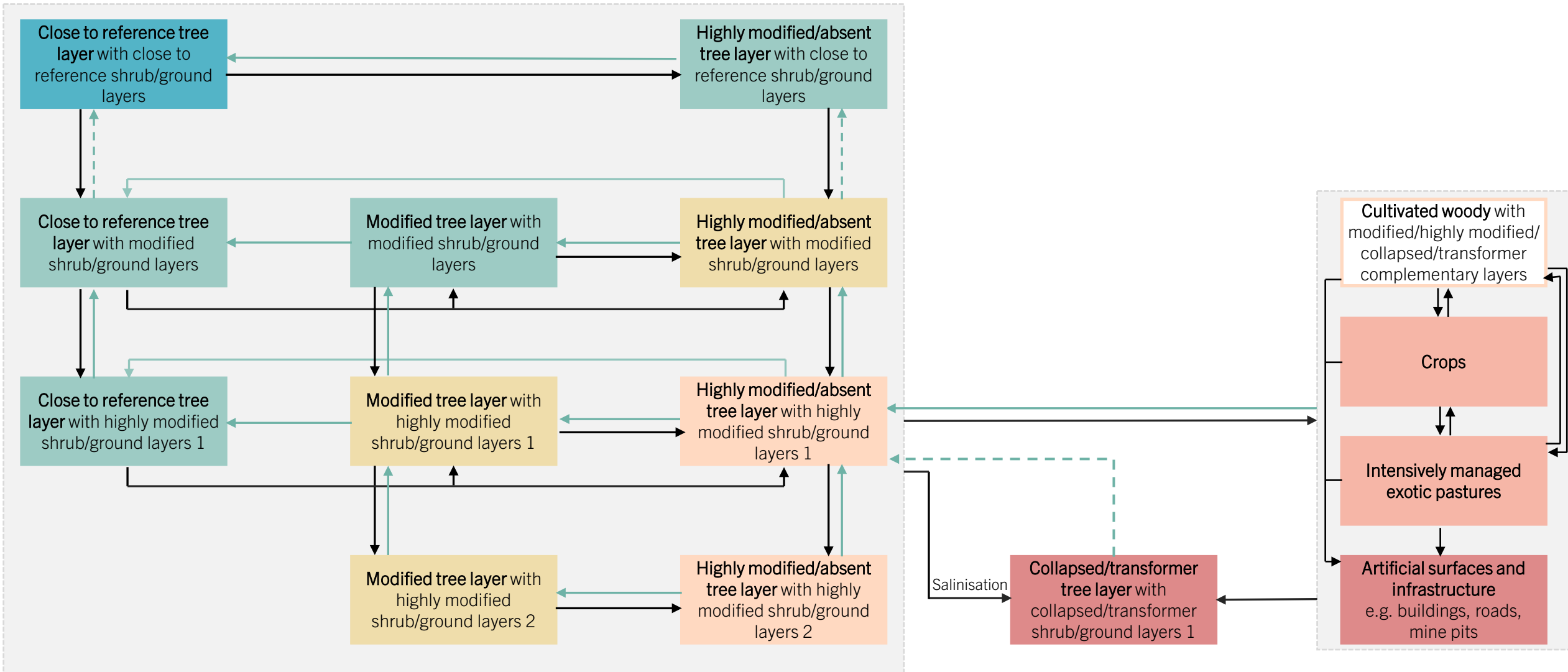
Divide states where recognition of more than one distinct state is preferred

# Hypothetical model build

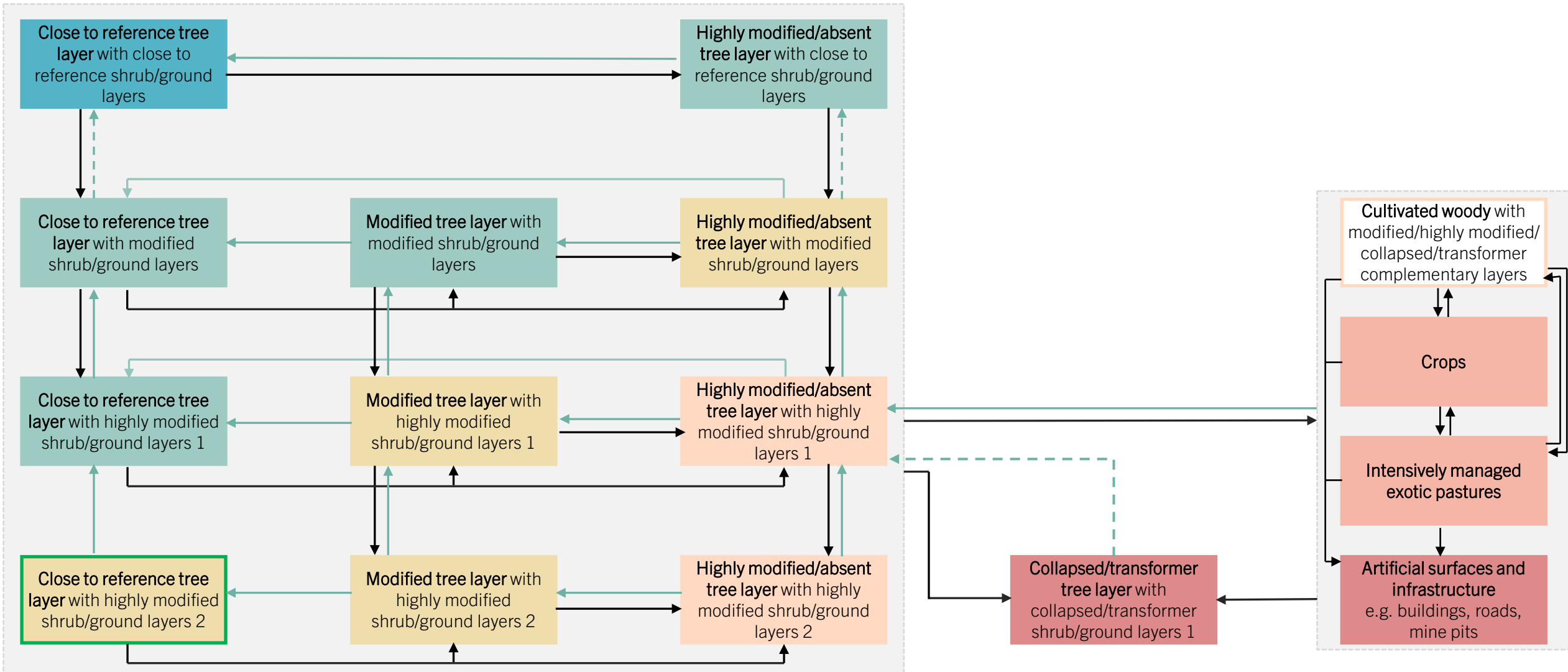
(b)



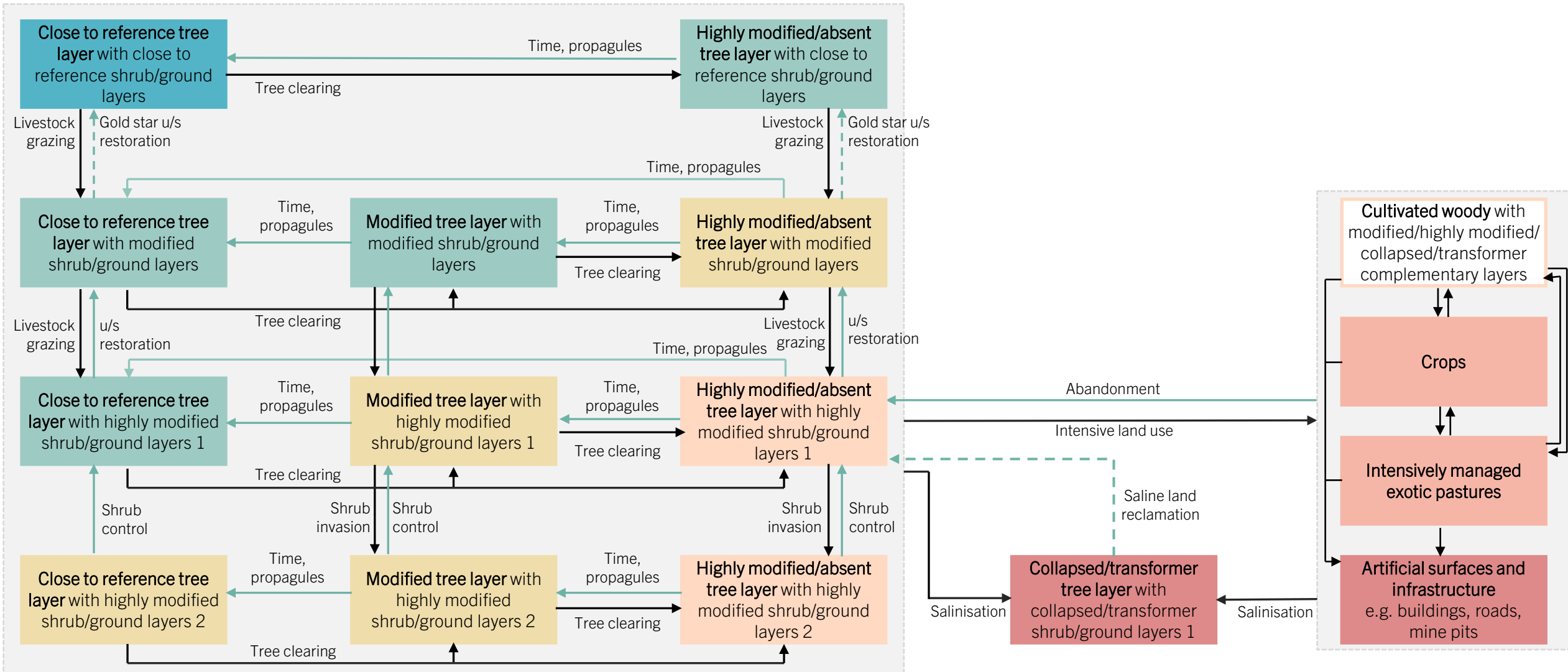
Resulting ordered set of states



Add transitions following the transition guide



Review for missing states after considering transitions

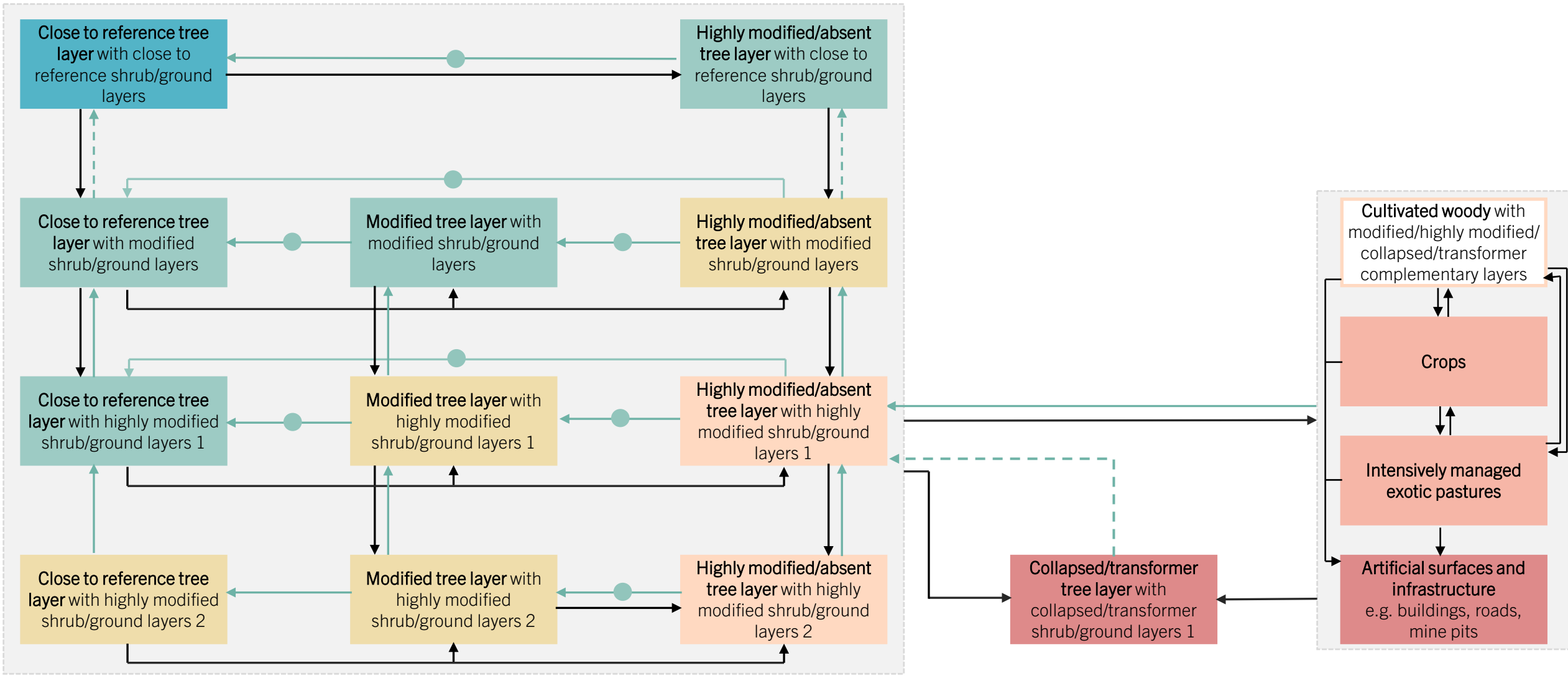


Add drivers to transition arrows



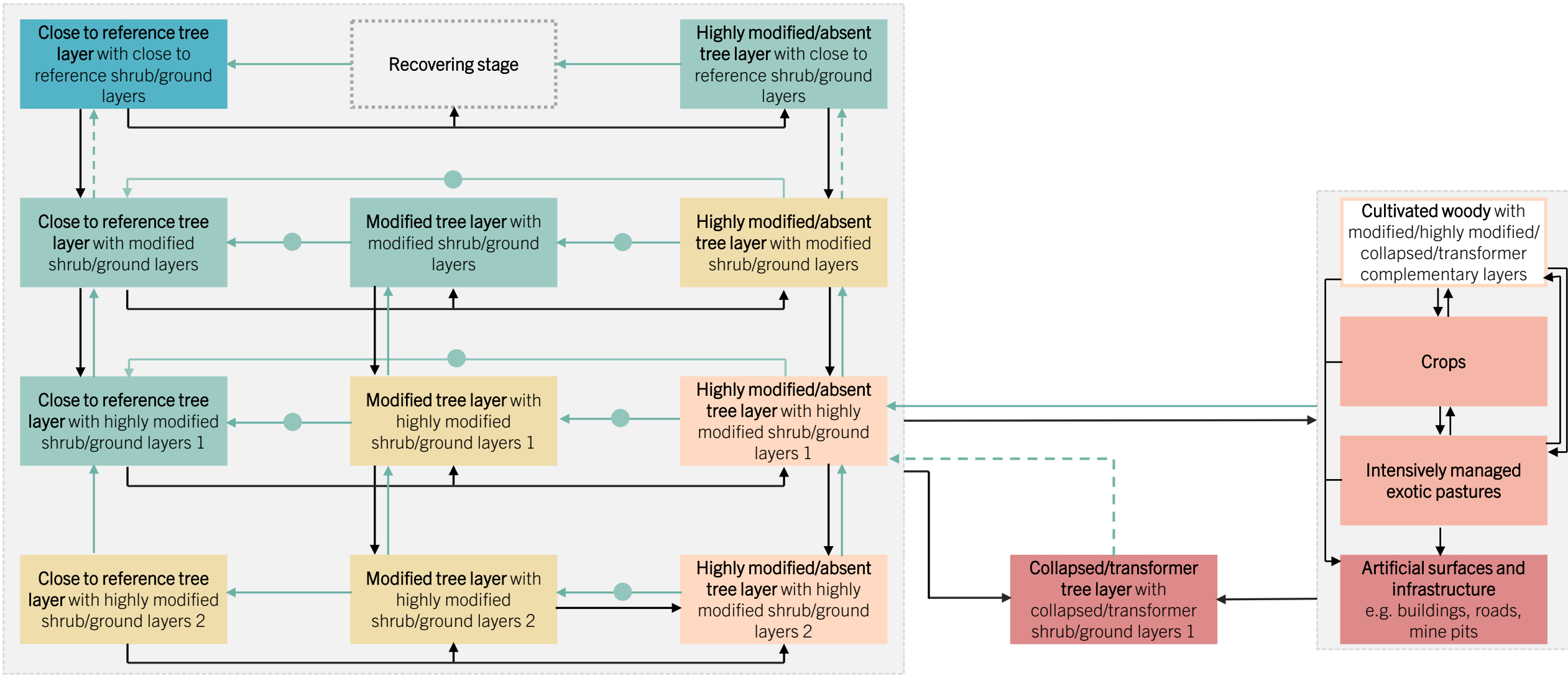
# 5. Recovering stages and variants





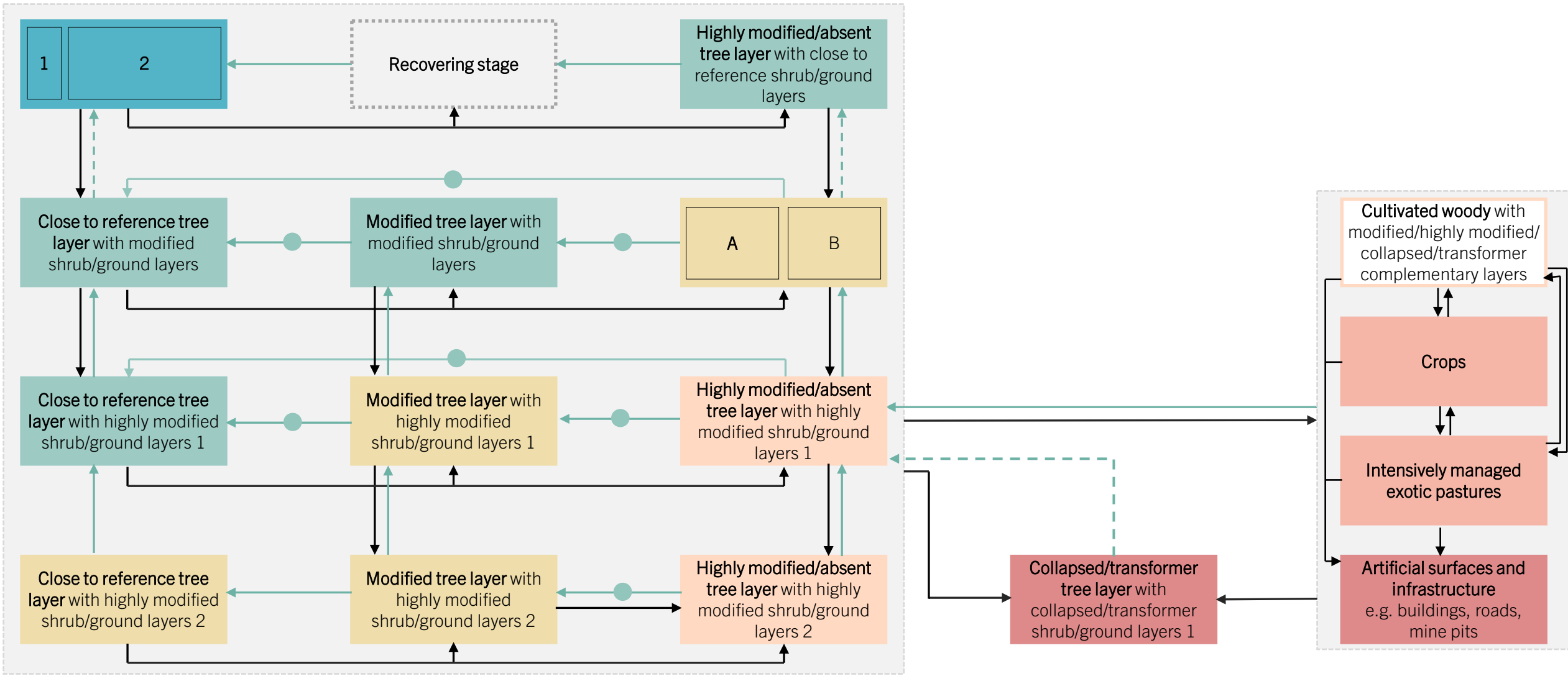
● Recovering stage

Insert recovering stages where shorter timeframes are relevant



● Recovering stage

Alternative representation of recovering stage



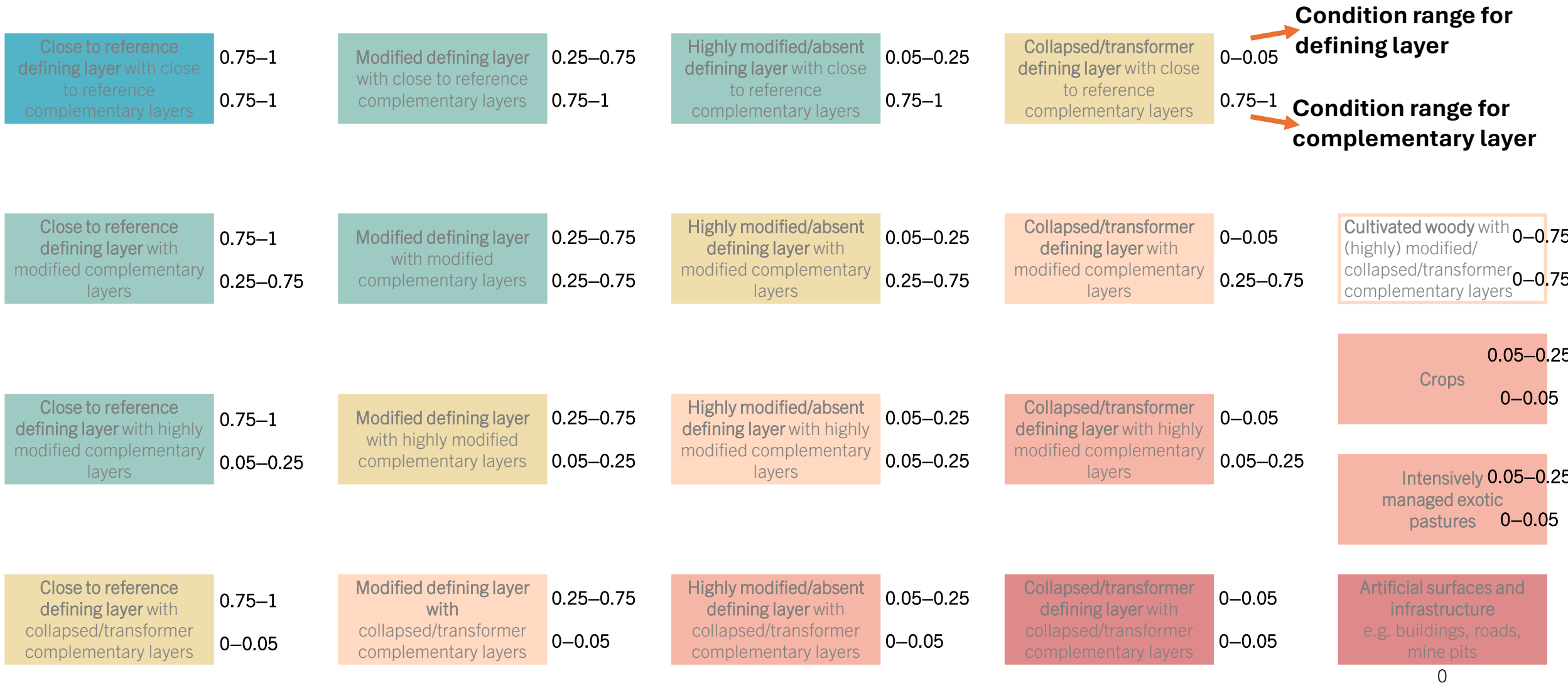
● Recovering stage      1 Variant

Add variants within states where preferred



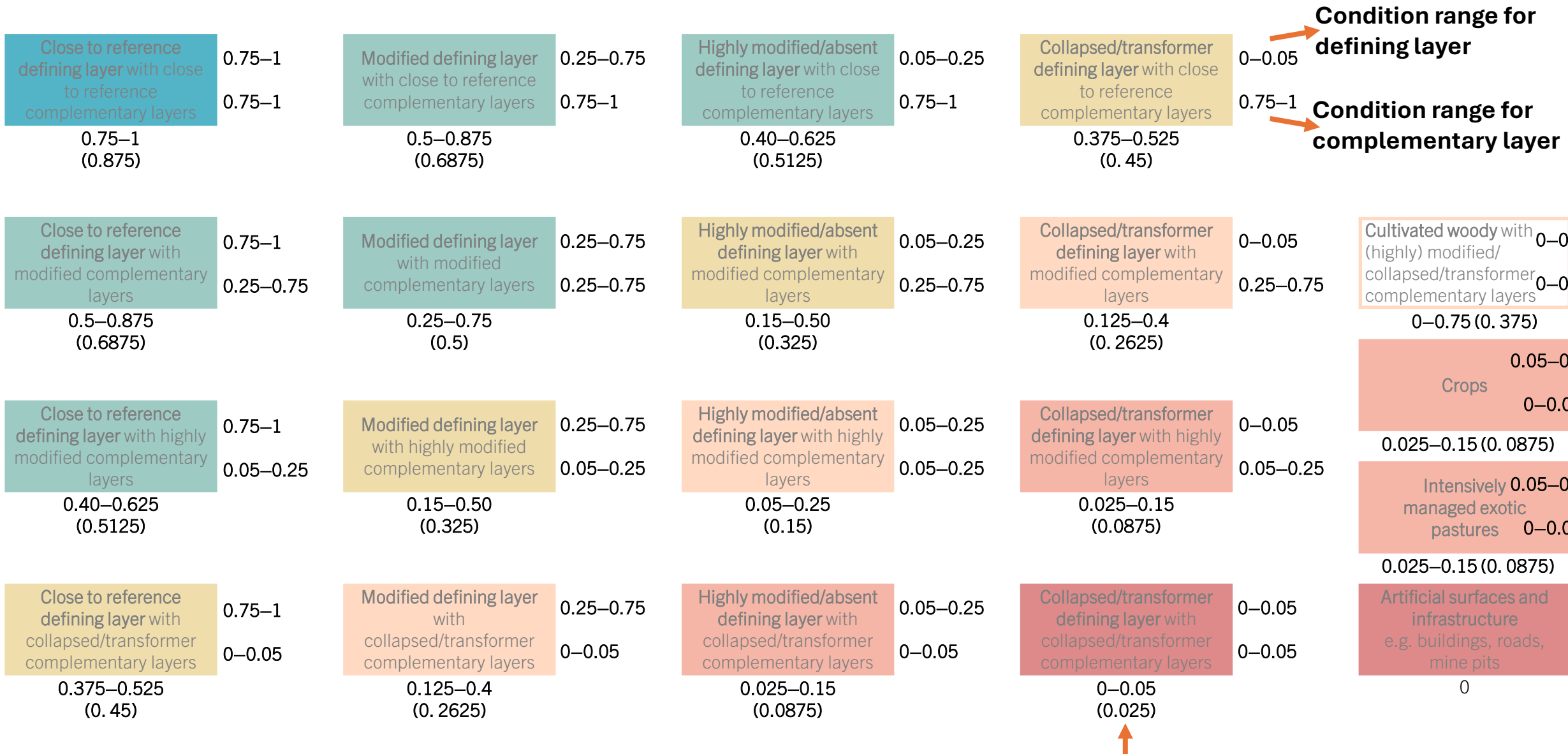
## 6. Ranges in ecosystem condition assigned to template states





## Indicative ranges in ecosystem condition for biodiversity allocated to defining and complementary layers

(aligned with Society for Ecological Restoration (SER) Five-Star system, Gann et al. 2024). The template provides a “shell” framework for ecosystem specific characterisation. The condition ranges for each layer can be used to guide assignment of a state users are familiar with on the ground to a state in the template, facilitating comparability among models.



Ecosystem condition range for a state depends on weighting of layers

Condition range and mid-point for state at 50:50 weighting of layers



Close to reference defining layer with close to reference complementary layers

Modified defining layer with close to reference complementary layers

Highly modified/absent defining layer with close to reference complementary layers

Collapsed/transformer defining layer with close to reference complementary layers

Close to reference defining layer with modified complementary layers

Modified defining layer with modified complementary layers

Highly modified/absent defining layer with modified complementary layers

Collapsed/transformer defining layer with modified complementary layers

Cultivated woody with modified/highly modified/collapsed/transformer complementary layers

Close to reference defining layer with highly modified complementary layers

Modified defining layer with highly modified complementary layers

Highly modified/absent defining layer with highly modified complementary layers

Collapsed/transformer defining layer with highly modified complementary layers

Crops

Intensively managed exotic pastures

Close to reference defining layer with collapsed/transformer complementary layers

Modified defining layer with collapsed/transformer complementary layers

Highly modified/absent defining layer with collapsed/transformer complementary layers

Collapsed/transformer defining layer with collapsed/transformer complementary layers

Artificial surfaces and infrastructure e.g. buildings, roads, mine pits

High integrity reference layer indicated by blue shading:

High integrity defining and complementary layers

High integrity defining layer

High integrity complementary layers



# 7. Colour scales and effect of weightings on ecosystem condition



Mulga woodlands, Gascoyne, WA, SMProber CSIRO

The colour of ecosystem states in subsequent slides highlight states within similar condition ranges (ranges modified from Williams et al., 2023: blue-green-yellow-pinks-red - diagonally from top left: 0.75-1, 0.5-0.75, 0.3-0.5, 0.15-0.3, 0.05-0.15, 0-0.05). Cultivated woody=variable condition. Williams, K.J., et al. (2023). Extended methods used in developing the Habitat Condition Assessment System (HCAS) version 2.3, ecosystem condition account-ready data and experimental accounts for two mixed-use landscapes. EP2023-1426.



Close to reference  
**defining layer** with close  
to reference  
complementary layers

Modified **defining layer**  
with close to reference  
complementary layers

Highly modified **defining  
layer** with close to  
reference  
complementary layers

**Collapsed/transformer  
defining layer** with close  
to reference  
complementary layers

Close to reference  
**defining layer** with  
modified complementary  
layers

Modified **defining layer**  
with modified  
complementary layers

Highly modified **defining  
layer** with modified  
complementary layers

**Collapsed/transformer  
defining layer** with  
modified complementary  
layers

**Cultivated woody** with  
modified/highly modified/  
collapsed/transformer  
complementary layers

Close to reference  
**defining layer** with highly  
modified complementary  
layers

Modified **defining layer**  
with highly modified  
complementary layers

Highly modified **defining  
layer** with highly modified  
complementary layers

**Collapsed/transformer  
defining layer** with highly  
modified complementary  
layers

Crops

Intensively managed  
exotic pastures

Close to reference  
**defining layer** with  
collapsed/transformer  
complementary layers

Modified **defining layer**  
with  
collapsed/transformer  
complementary layers

Highly modified **defining  
layer** with  
collapsed/transformer  
complementary layers

**Collapsed/transformer  
defining layer** with  
collapsed/transformer  
complementary layers

Artificial surfaces and  
infrastructure  
e.g. buildings, roads,  
mine pits



Close to reference defining layer with close to reference complementary layers

Modified defining layer with close to reference complementary layers

Highly modified defining layer with close to reference complementary layers

Collapsed/transformer defining layer with close to reference complementary layers

Close to reference defining layer with modified complementary layers

Modified defining layer with modified complementary layers

Highly modified defining layer with modified complementary layers

Collapsed/transformer defining layer with modified complementary layers

Cultivated woody with modified/highly modified/collapsed/transformer complementary layers

Close to reference defining layer with highly modified complementary layers

Modified defining layer with highly modified complementary layers

Highly modified defining layer with highly modified complementary layers

Collapsed/transformer defining layer with highly modified complementary layers

Crops

Close to reference defining layer with collapsed/transformer complementary layers

Modified defining layer with collapsed/transformer complementary layers

Highly modified defining layer with collapsed/transformer complementary layers

Collapsed/transformer defining layer with collapsed/transformer complementary layers

Intensively managed exotic pastures

Artificial surfaces and infrastructure  
e.g. buildings, roads, mine pits



Close to reference defining layer with close to reference complementary layers

Modified defining layer with close to reference complementary layers

Highly modified defining layer with close to reference complementary layers

Collapsed/transformer defining layer with close to reference complementary layers

Close to reference defining layer with modified complementary layers

Modified defining layer with modified complementary layers

Highly modified defining layer with modified complementary layers

Collapsed/transformer defining layer with modified complementary layers

Cultivated woody with modified/highly modified/collapsed/transformer complementary layers

Close to reference defining layer with highly modified complementary layers

Modified defining layer with highly modified complementary layers

Highly modified defining layer with highly modified complementary layers

Collapsed/transformer defining layer with highly modified complementary layers

Crops

Close to reference defining layer with collapsed/transformer complementary layers

Modified defining layer with collapsed/transformer complementary layers

Highly modified defining layer with collapsed/transformer complementary layers

Collapsed/transformer defining layer with collapsed/transformer complementary layers

Intensively managed exotic pastures

Artificial surfaces and infrastructure  
e.g. buildings, roads, mine pits



Close to reference defining layer with close to reference complementary layers

Modified defining layer with close to reference complementary layers

Highly modified defining layer with close to reference complementary layers

Collapsed/transformer defining layer with close to reference complementary layers

Close to reference defining layer with modified complementary layers

Modified defining layer with modified complementary layers

Highly modified defining layer with modified complementary layers

Collapsed/transformer defining layer with modified complementary layers

Cultivated woody with modified/highly modified/collapsed/transformer complementary layers

Close to reference defining layer with highly modified complementary layers

Modified defining layer with highly modified complementary layers

Highly modified defining layer with highly modified complementary layers

Collapsed/transformer defining layer with highly modified complementary layers

Crops

Close to reference defining layer with collapsed/transformer complementary layers

Modified defining layer with collapsed/transformer complementary layers

Highly modified defining layer with collapsed/transformer complementary layers

Collapsed/transformer defining layer with collapsed/transformer complementary layers

Intensively managed exotic pastures

Artificial surfaces and infrastructure  
e.g. buildings, roads, mine pits



Close to reference defining layer with close to reference complementary layers

Modified defining layer with close to reference complementary layers

Highly modified defining layer with close to reference complementary layers

Collapsed/transformer defining layer with close to reference complementary layers

Close to reference defining layer with modified complementary layers

Modified defining layer with modified complementary layers

Highly modified defining layer with modified complementary layers

Collapsed/transformer defining layer with modified complementary layers

Cultivated woody with modified/highly modified/collapsed/transformer complementary layers

Close to reference defining layer with highly modified complementary layers

Modified defining layer with highly modified complementary layers

Highly modified defining layer with highly modified complementary layers

Collapsed/transformer defining layer with highly modified complementary layers

Crops

Intensively managed exotic pastures

Close to reference defining layer with collapsed/transformer complementary layers

Modified defining layer with collapsed/transformer complementary layers

Highly modified defining layer with collapsed/transformer complementary layers

Collapsed/transformer defining layer with collapsed/transformer complementary layers

Artificial surfaces and infrastructure  
e.g. buildings, roads, mine pits



Close to reference defining layer with close to reference complementary layers

Modified defining layer with close to reference complementary layers

Highly modified defining layer with close to reference complementary layers

Collapsed/transformer defining layer with close to reference complementary layers

Close to reference defining layer with modified complementary layers

Modified defining layer with modified complementary layers

Highly modified defining layer with modified complementary layers

Collapsed/transformer defining layer with modified complementary layers

Cultivated woody with modified/highly modified/collapsed/transformer complementary layers

Close to reference defining layer with highly modified complementary layers

Modified defining layer with highly modified complementary layers

Highly modified defining layer with highly modified complementary layers

Collapsed/transformer defining layer with highly modified complementary layers

Crops

Intensively managed exotic pastures

Close to reference defining layer with collapsed/transformer complementary layers

Modified defining layer with collapsed/transformer complementary layers

Highly modified defining layer with collapsed/transformer complementary layers

Collapsed/transformer defining layer with collapsed/transformer complementary layers

Artificial surfaces and infrastructure  
e.g. buildings, roads, mine pits



Close to reference defining layer with close to reference complementary layers

Modified defining layer with close to reference complementary layers

Highly modified defining layer with close to reference complementary layers

Collapsed/transformer defining layer with close to reference complementary layers

Close to reference defining layer with modified complementary layers

Modified defining layer with modified complementary layers

Highly modified defining layer with modified complementary layers

Collapsed/transformer defining layer with modified complementary layers

Cultivated woody with modified/highly modified/collapsed/transformer complementary layers

Close to reference defining layer with highly modified complementary layers

Modified defining layer with highly modified complementary layers

Highly modified defining layer with highly modified complementary layers

Collapsed/transformer defining layer with highly modified complementary layers

Crops

Intensively managed exotic pastures

Close to reference defining layer with collapsed/transformer complementary layers

Modified defining layer with collapsed/transformer complementary layers

Highly modified defining layer with collapsed/transformer complementary layers

Collapsed/transformer defining layer with collapsed/transformer complementary layers

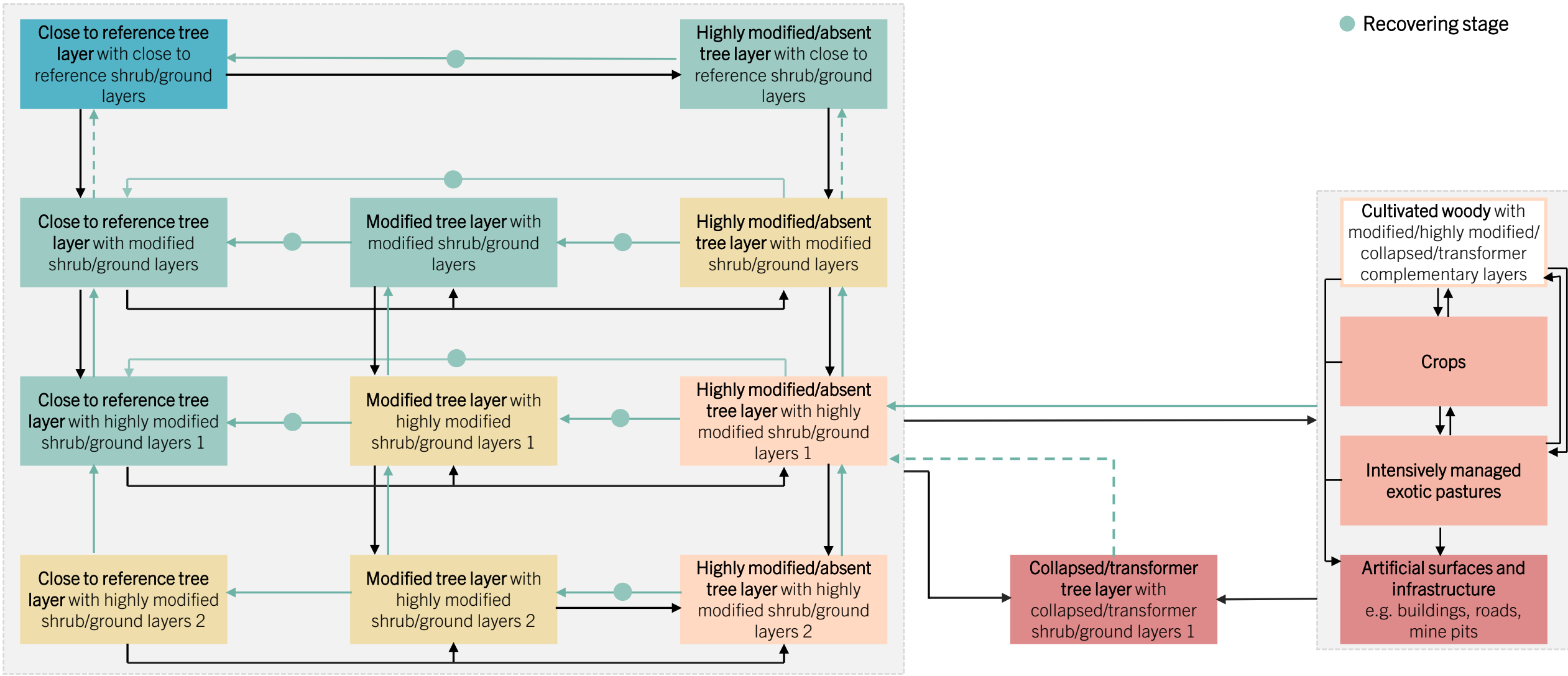
Artificial surfaces and infrastructure  
e.g. buildings, roads, mine pits



# 8. Secondary template demonstration



Post-fire hummock grassland with rich ephemeral forb component, Pilbara, WA, SMProber CSIRO



Example beginning with model previously demonstrated



*Close to reference shrub layer*

Close to reference shrub layer with close to reference ground layer

*Modified shrub layer*

Modified shrub layer with close to reference ground layer

*Highly modified/absent shrub layer*

Highly modified/absent shrub layer with close to reference ground layer

*Collapsed/transformer shrub layer*

Collapsed/transformer shrub layer with close to reference ground layer

*Close to reference ground layer*

Close to reference shrub layer with modified ground layer

Modified shrub layer with modified ground layer

Highly modified/absent shrub layer with modified ground layer

Collapsed/transformer shrub layer with modified ground layer

*Modified ground layer*

Close to reference shrub layer with highly modified ground layer

Modified shrub layer with highly modified ground layer

Highly modified/absent shrub layer with highly modified ground layer

Collapsed/transformer shrub layer with highly modified ground layer

*Highly modified ground layer*

Close to reference shrub layer with collapsed/transformer ground layer

Modified shrub layer with collapsed/transformer ground layer

Highly modified/absent shrub layer with collapsed/transformer ground layer

Collapsed/transformer shrub layer with collapsed/transformer ground layer

*Collapsed/transformer ground layer*

Select desired state(s) from secondary template for forest and woodland shrub/ground layers



*Close to reference shrub layer*

Close to reference shrub layer with close to reference ground layer

*Modified shrub layer*

Modified shrub layer with close to reference ground layer

*Highly modified/absent shrub layer*

Highly modified/absent shrub layer with close to reference ground layer

*Collapsed/transformer shrub layer*

Collapsed/transformer shrub layer with close to reference ground layer

*Close to reference ground layer*

Close to reference shrub layer with modified ground layer

Modified shrub layer with modified ground layer

Highly modified/absent shrub layer with modified ground layer

Collapsed/transformer shrub layer with modified ground layer

*Modified ground layer*

Close to reference shrub layer with highly modified ground layer

Modified shrub layer with highly modified ground layer

0.25–0.75  
0.05–0.25

Highly modified/absent shrub layer with highly modified ground layer

Collapsed/transformer shrub layer with highly modified ground layer

*Highly modified ground layer*

0.15–0.50  
(0.325)

Close to reference shrub layer with collapsed/transformer ground layer

Modified shrub layer with collapsed/transformer ground layer

Highly modified/absent shrub layer with collapsed/transformer ground layer

Collapsed/transformer shrub layer with collapsed/transformer ground layer

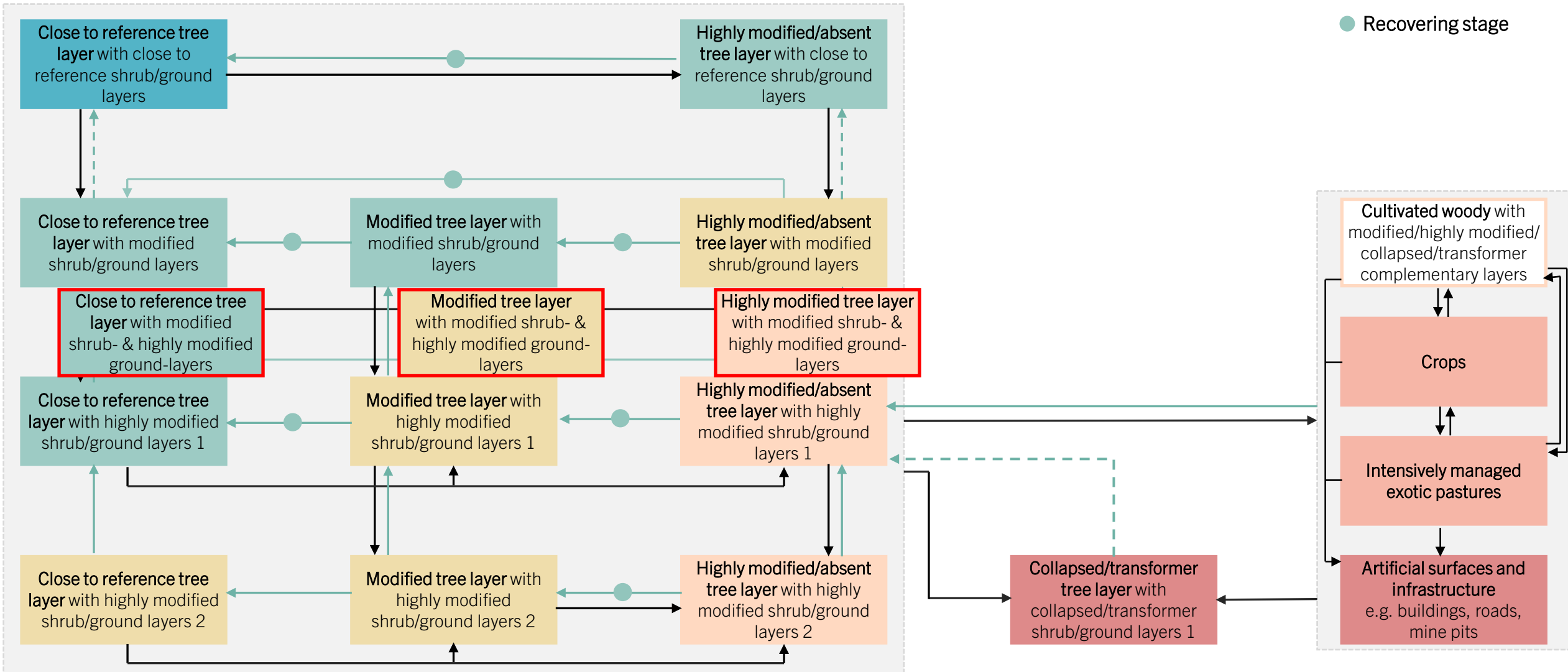
*Collapsed/transformer ground layer*

Example selected to reflect novel shrub/ground layer combination achieved after restoration of shrub but not ground layer

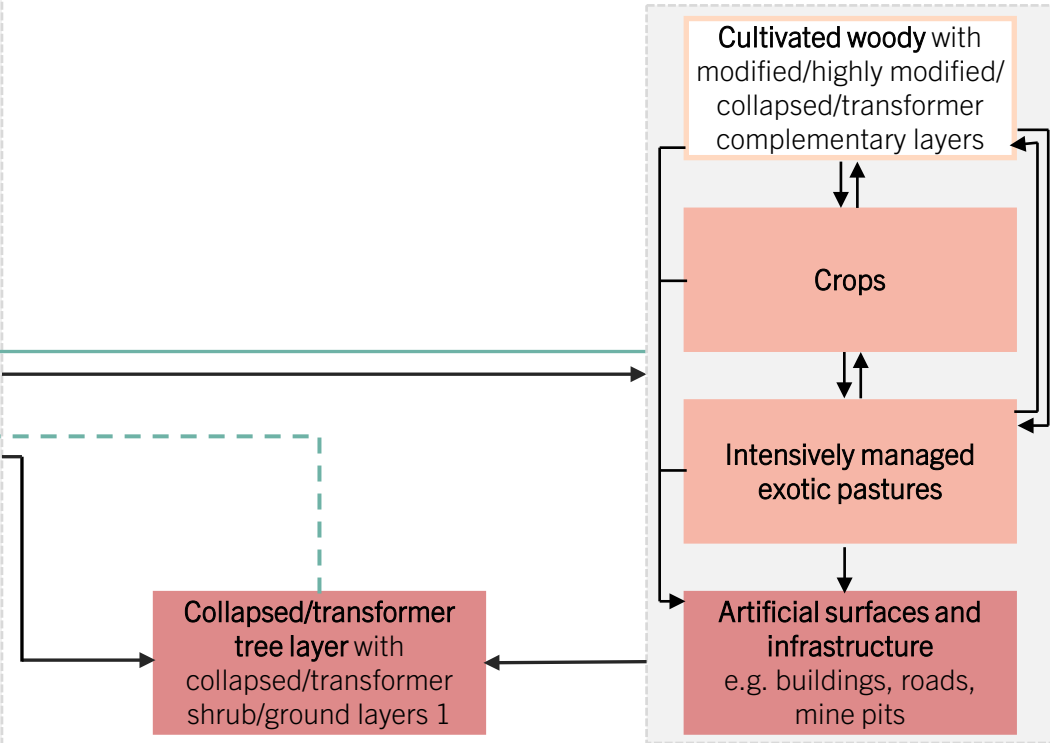
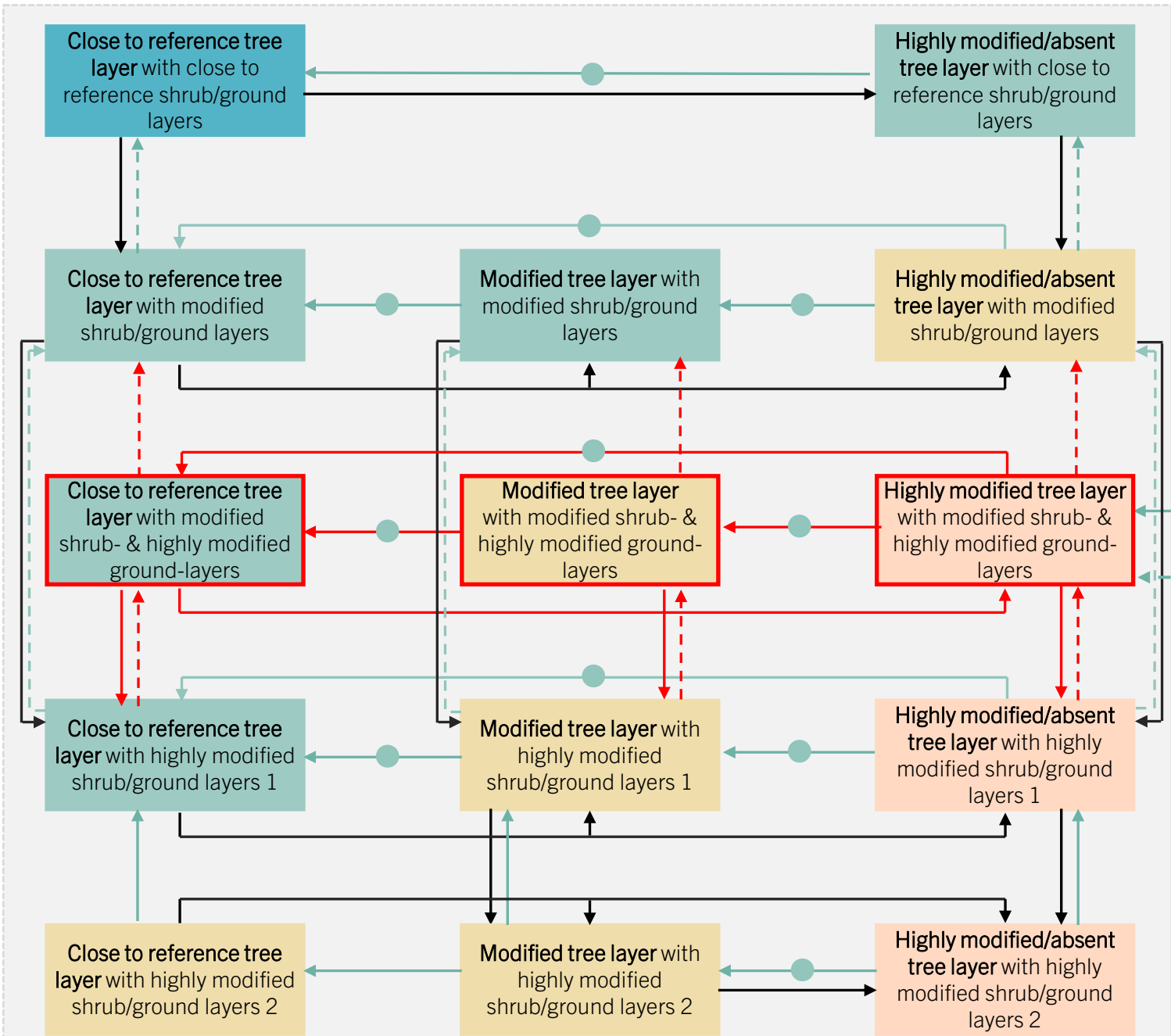


<b>Close to reference shrub layer with close to reference ground layer</b> 0.75–1 0.75–1 0.75–1 (0.875)		<b>Modified shrub layer with close to reference ground layer</b> 0.25–0.75 0.75–1	<b>Highly modified/absent shrub layer with close to reference ground layer</b> 0.05–0.25 0.75–1 0.40–0.625 (0.5125)	<b>Collapsed/transformer shrub layer with close to reference ground layer</b> 0–0.05 0.75–1 0.375–0.525 (0.45)
<b>Close to reference shrub layer with modified ground layer</b> 0.75–1 0.25–0.75 0.5–0.875 (0.6875)		<b>Modified shrub layer with modified ground layer</b> 0.25–0.75 0.25–0.75	<b>Highly modified/absent shrub layer with modified ground layer</b> 0.05–0.25 0.25–0.75 0.15–0.50 (0.325)	<b>Collapsed/transformer shrub layer with modified ground layer</b> 0–0.05 0.25–0.75 0.125–0.4 (0.2625)
<b>Close to reference shrub layer with highly modified ground layer</b> 0.75–1 0.05–0.25 0.40–0.625 (0.5125)		<b>Modified shrub layer with highly modified ground layer</b> 0.25–0.75 0.05–0.25 0.15–0.50 (0.325)	<b>Highly modified/absent shrub layer with highly modified ground layer</b> 0.05–0.25 0.05–0.25 0.05–0.25 (0.15)	<b>Collapsed/transformer shrub layer with highly modified ground layer</b> 0–0.05 0.05–0.25 0.025–0.15 (0.0875)
<b>Close to reference shrub layer with collapsed/transformer ground layer</b> 0.75–1 0–0.05 0.375–0.525 (0.45)		<b>Modified shrub layer with collapsed/transformer ground layer</b> 0.25–0.75 0–0.05 0.125–0.4 (0.2625)	<b>Highly modified/absent shrub layer with collapsed/transformer ground layer</b> 0.05–0.25 0–0.05 0.025–0.15 (0.0875)	<b>Collapsed/transformer shrub layer with collapsed/transformer ground layer</b> 0–0.05 0–0.05 0–0.05 (0.025)

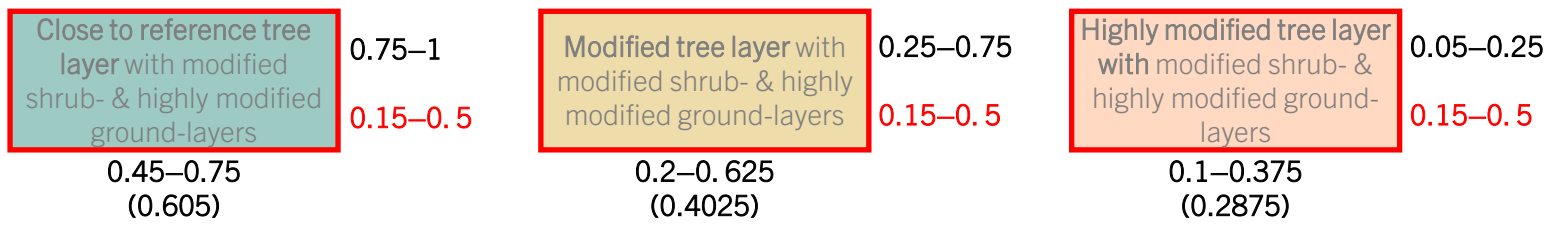
Condition range for secondary template analogous to primary template. 50:50 shrub/ground layer weighting applied.



Add new shrub/ground layer restoration combination to each potential tree layer category, in position of expected condition ranking



Add transitions



Assign default condition of new states by combining tree layer default with new shrub/ground layers at preferred weighting (50:50 used in example)



Close to reference tree layer with modified shrub/ground layers	0.75–1 0.25–0.75	Modified tree layer with modified shrub/ground layers	0.25–0.75 0.25–0.75	Highly modified/absent tree layer with modified shrub/ground layers	0.05–0.25 0.25–0.75
0.5–0.875 (0.6875)		0.25–0.75 (0.5)		0.15–0.50 (0.325)	
Close to reference tree layer with modified shrub- & highly modified ground-layers	0.75–1 0.15–0.5	Modified tree layer with modified shrub- & highly modified ground-layers	0.25–0.75 0.15–0.5	Highly modified tree layer with modified shrub- & highly modified ground-layers	0.05–0.25 0.15–0.5
0.45–0.75 (0.605)		0.2–0.625 (0.4025)		0.1–0.375 (0.2875)	
Close to reference tree layer with highly modified shrub/ground layers 1	0.75–1 0.05–0.25	Modified tree layer with highly modified shrub/ground layers 1	0.25–0.75 0.05–0.25	Highly modified/absent tree layer with highly modified shrub/ground layers 1	0.05–0.25 0.05–0.25
0.40–0.625 (0.5125)		0.15–0.50 (0.325)		0.05–0.25 (0.15)	

Default condition of new states is intermediate between modified and highly modified shrub/ground layers



# 9. Transition assignment guide



*Eucalyptus mannifera* fenced woodland, NSW, SMProber CSIRO



Close to reference defining layer with close to reference complementary layers

Modified defining layer with close to reference complementary layers

Highly modified defining layer with close to reference complementary layers

Collapsed/transformer defining layer with close to reference complementary layers

Close to reference defining layer with modified complementary layers

Modified defining layer with modified complementary layers

Highly modified defining layer with modified complementary layers

Collapsed/transformer defining layer with modified complementary layers

Cultivated woody with modified/highly modified/collapsed/transformer complementary layers

Close to reference defining layer with highly modified complementary layers

Modified defining layer with highly modified complementary layers

Highly modified defining layer with highly modified complementary layers

Collapsed/transformer defining layer with highly modified complementary layers

Crops

Close to reference defining layer with collapsed/transformer complementary layers

Modified defining layer with collapsed/transformer complementary layers

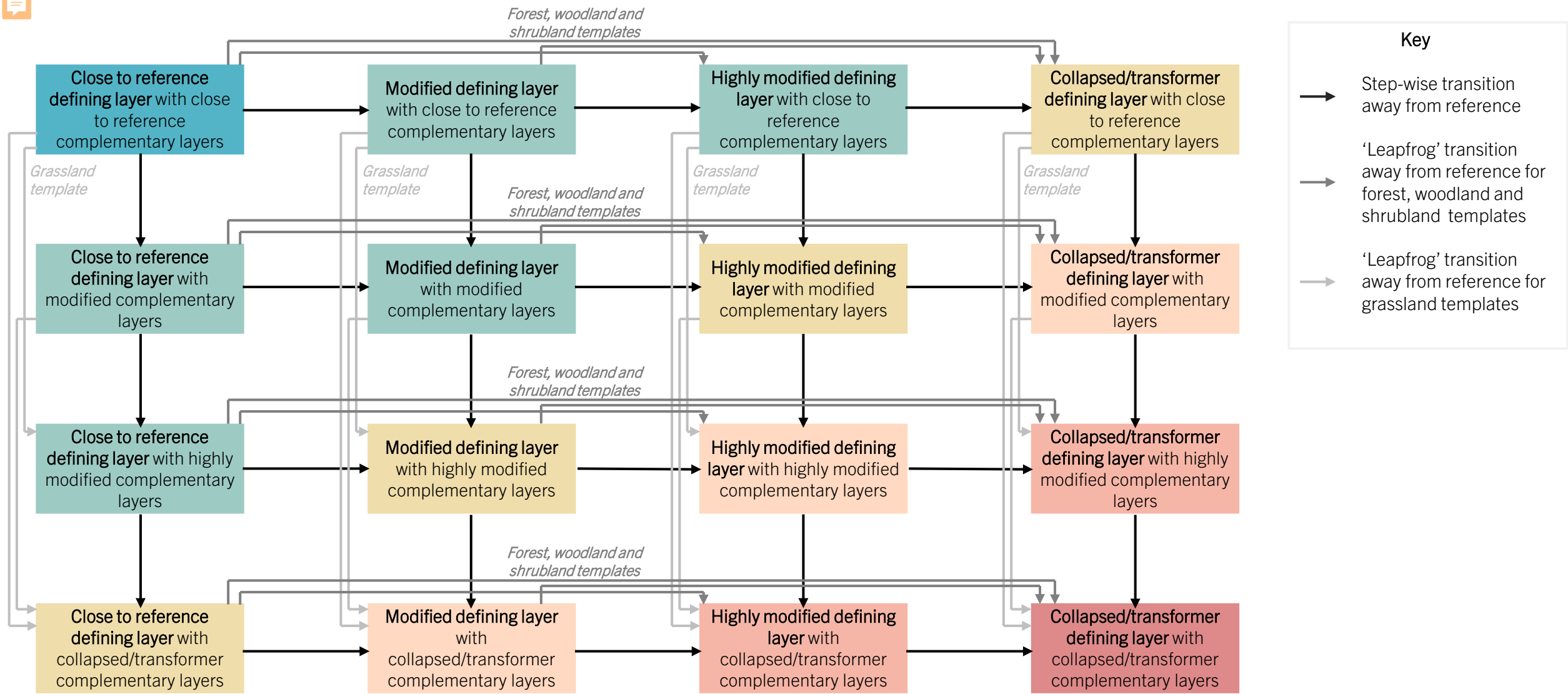
Highly modified defining layer with collapsed/transformer complementary layers

Collapsed/transformer defining layer with collapsed/transformer complementary layers

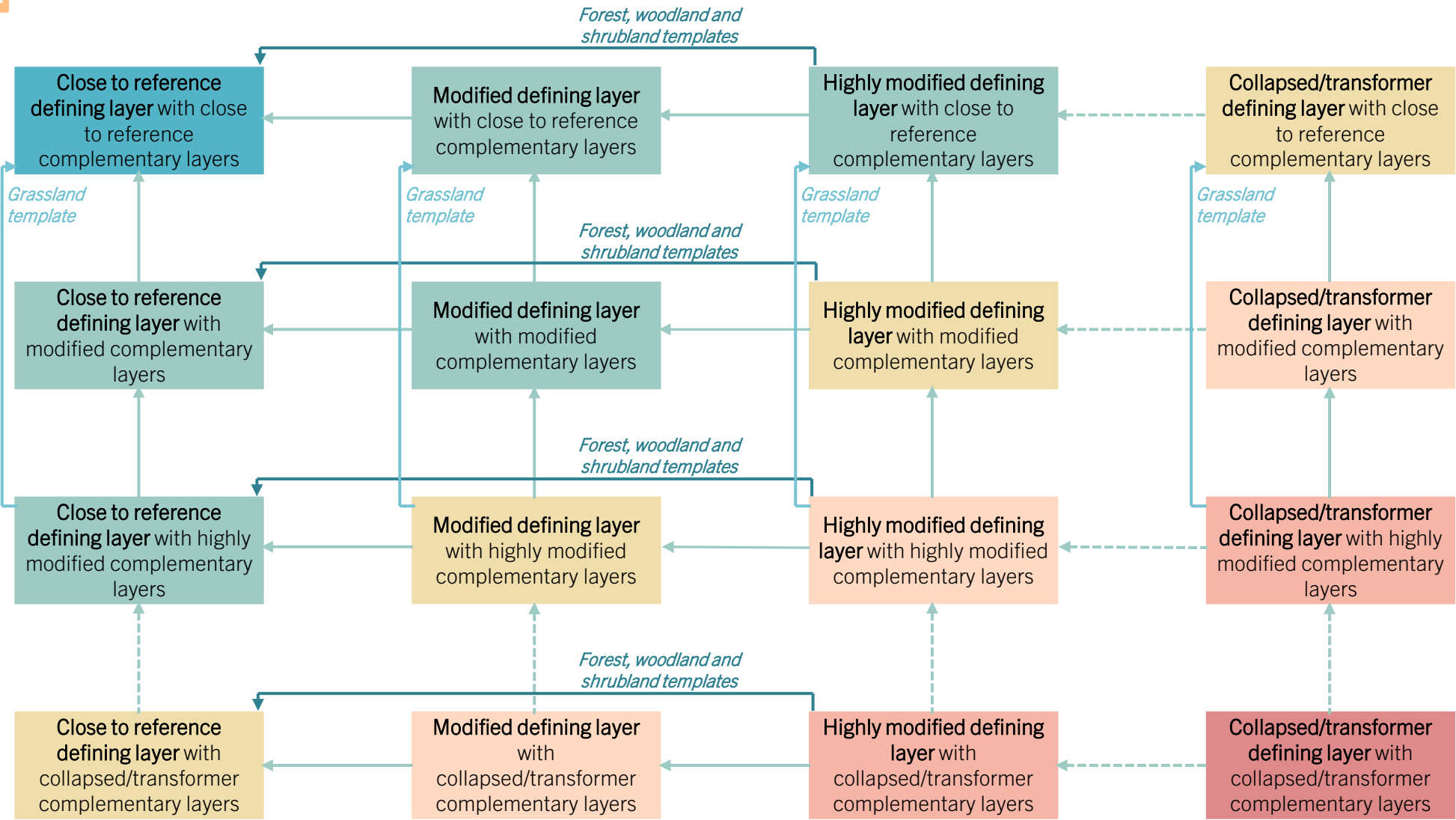
Intensively managed exotic pastures

Artificial surfaces and infrastructure  
e.g. buildings, roads, mine pits

1. Maintenance of self is plausible for all states – but might require active management



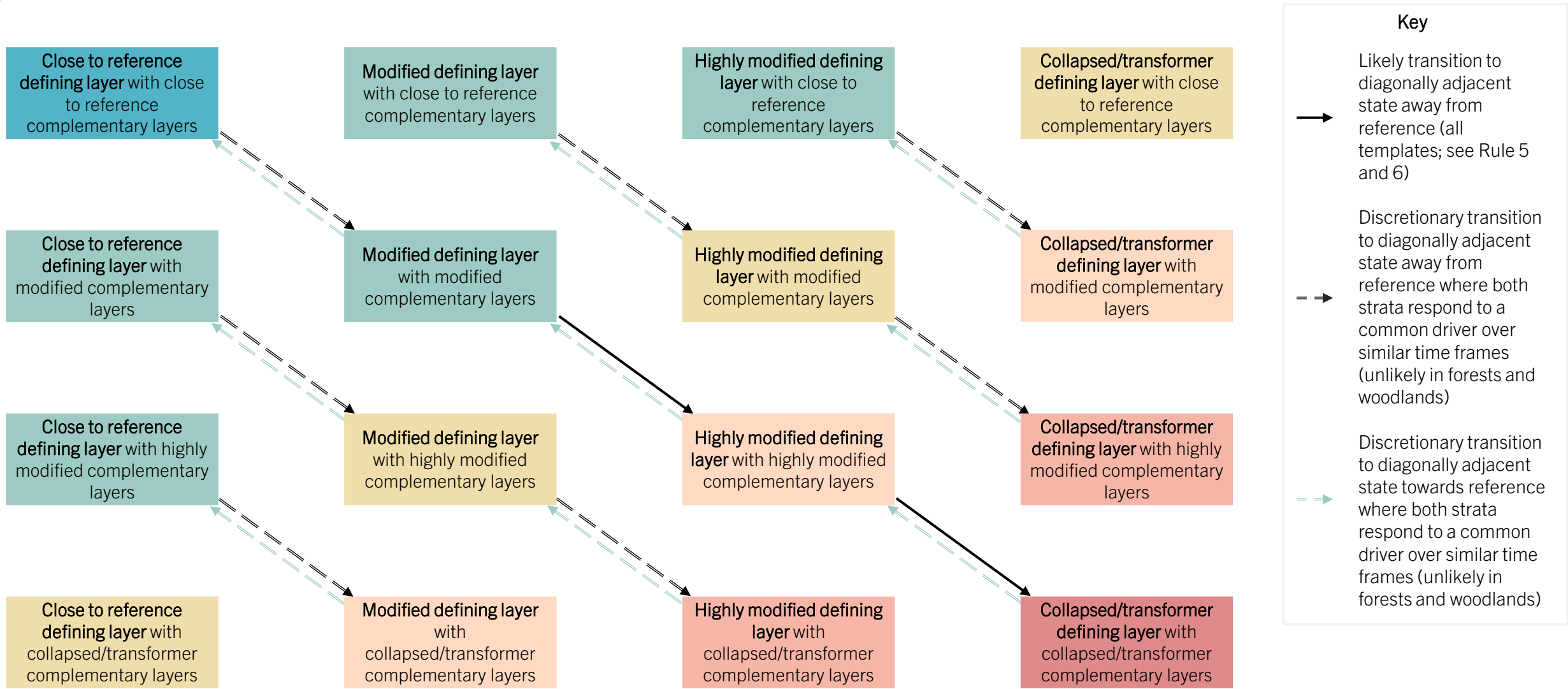
2. Non-diagonal transitions away from reference are plausible to adjacent states, and to non-adjacent states if the change is rapid or difficult to arrest



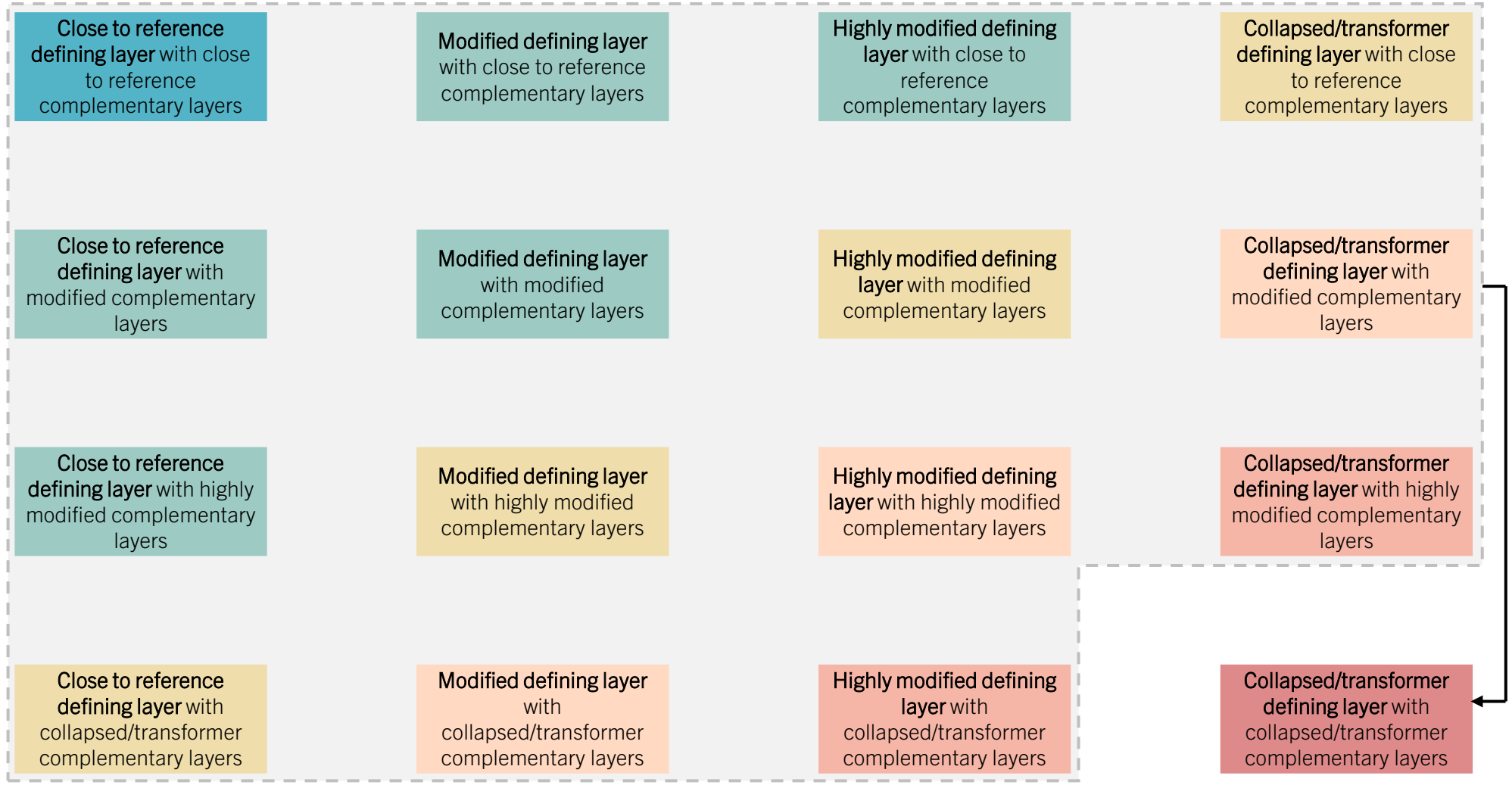
**Key**

- Step-wise transition towards reference
- Unlikely step-wise transition towards reference
- 'leapfrog' transition towards reference for forest, woodland and shrubland templates
- 'leapfrog' transition towards reference for grassland templates

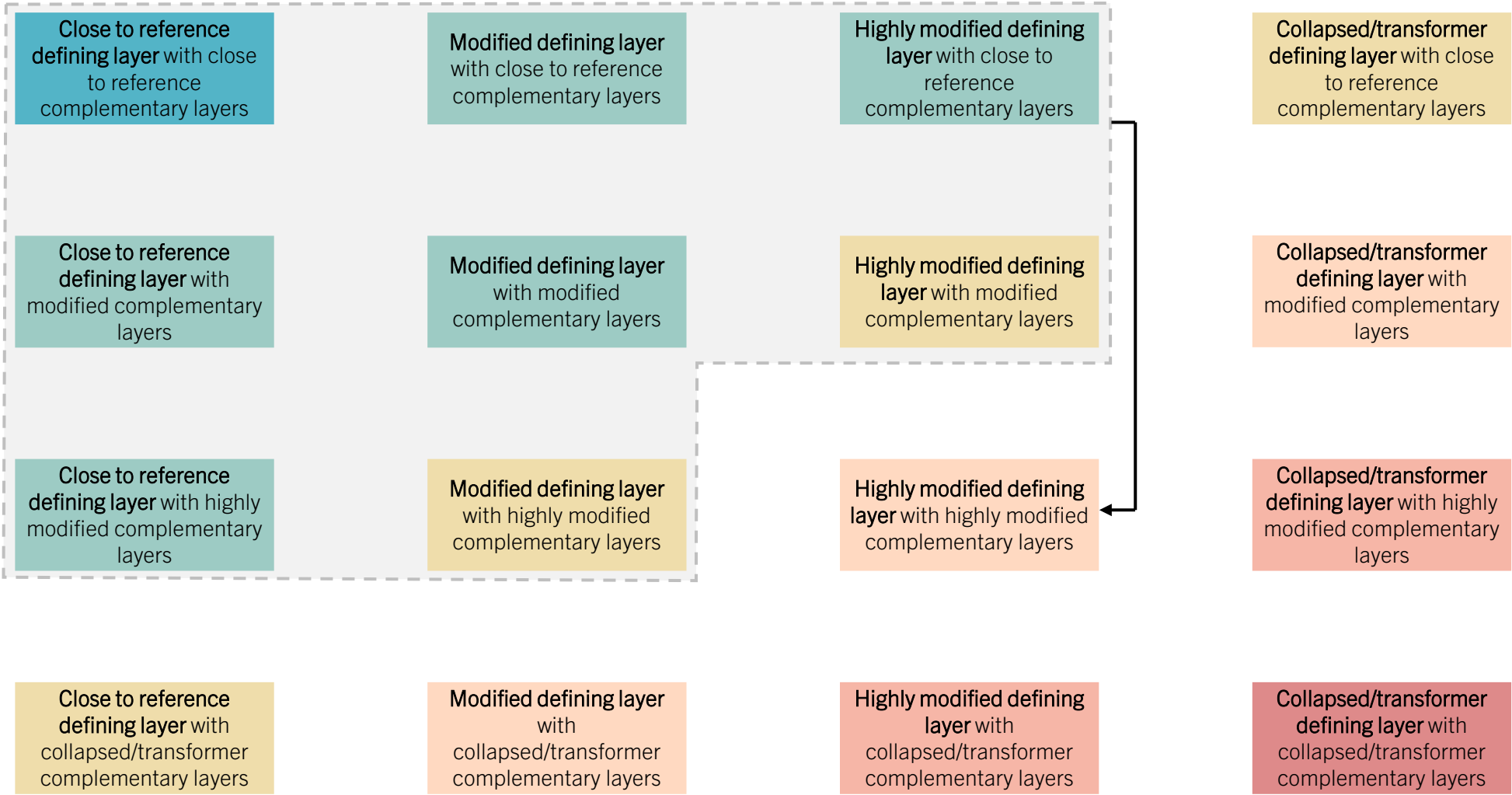
3. Non-diagonal transitions towards reference are plausible to adjacent states and for restoring woody layers from highly modified states, but unlikely from collapsed/transformer states without extreme intervention



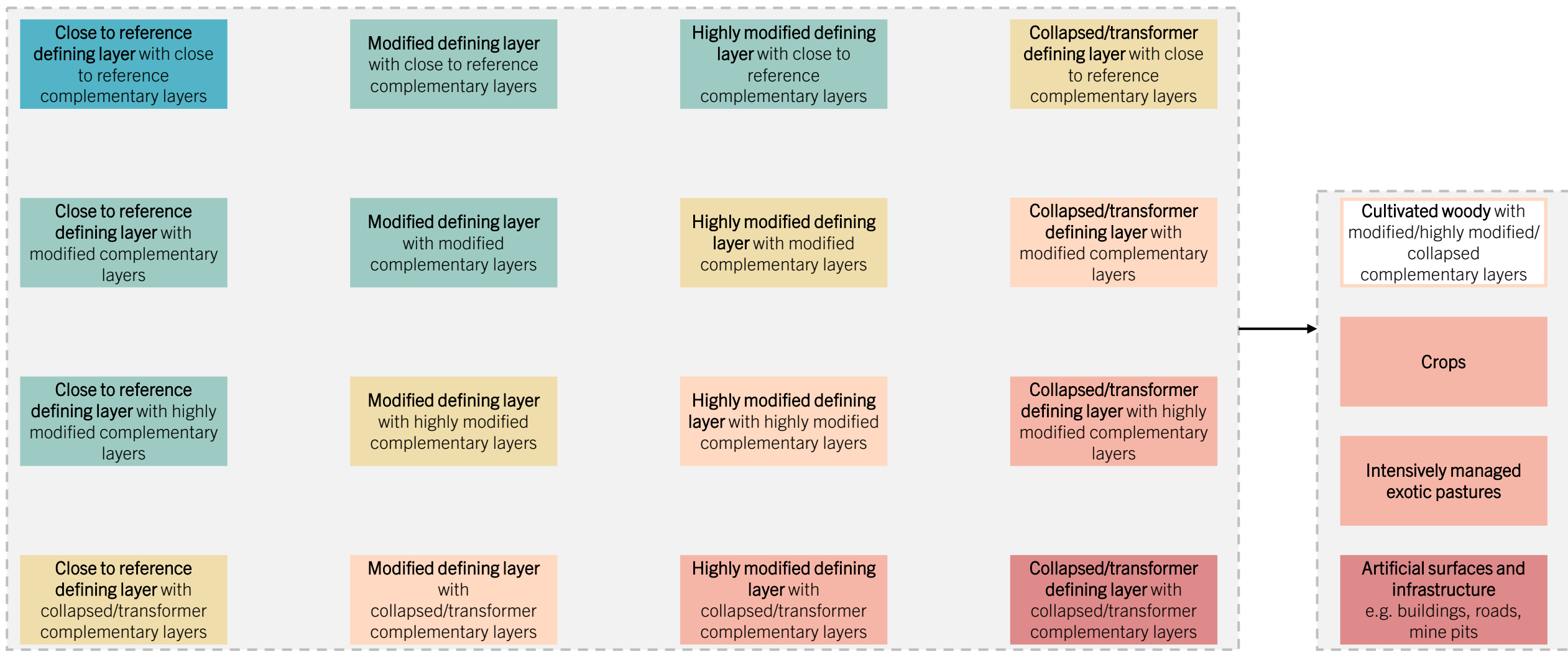
4. Direct transitions to diagonally adjacent states are generally unlikely where a tree layer is involved (but see 5,6), and discretionary in shrubland with ground layer or grassland with shrub layer



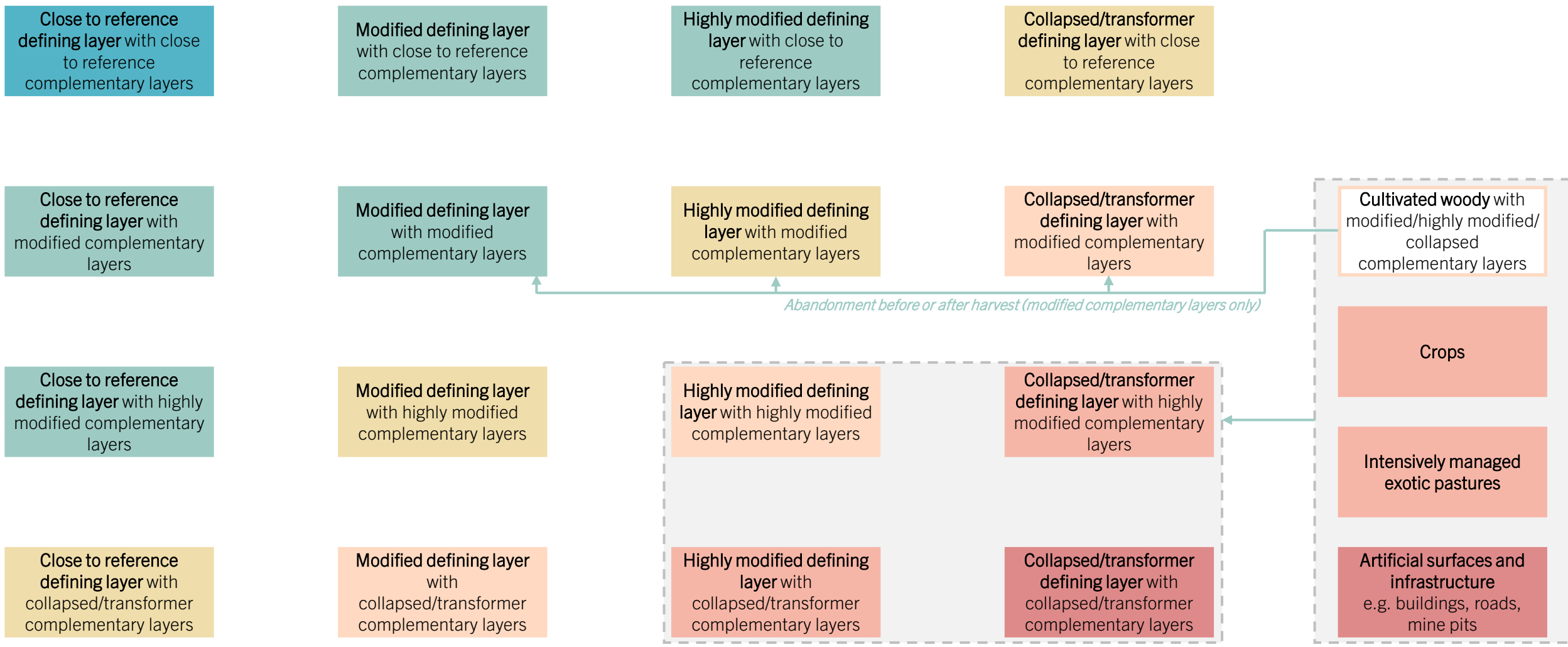
5. Ecosystem collapse plausible from any state



6. Direct transitions to *Highly modified defining layer with highly modified complementary layers* are plausible in one step from all higher condition states with land clearing, but see 7



## 7. Transitions to intensive land-use states plausible from any state



8. Transitions away from intensive land-use states typically pass through highly modified/collapsed combinations

