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OPINION ARTICLE

Application of a Gondwanan perspective to restore ecological integrity in the south-western Australian global biodiversity hotspot

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Bounded by ocean and desert, the isolated, predominately Mediterranean-climate region of south-western Australia (SWA) includes nine bioregions (circa 44 million hectares). The ecological integrity of the landscapes in this global biodiversity hotspot has been compromised by deforestation, fragmentation, exploitation, and introduced biota. Nature and degree of transformation varies between four interconnected landscapes (Swan Coastal Plain; South-west Forests; Wandoo Woodlands; and Great Western Woodlands). A Gondwanan perspective emphasizes a venerable biota and a cultural component to deep time. The particular importance of remnants and protected areas is recognized in restoring ecological integrity to Gondwanan landscapes. The nature and magnitude of the restoration task in these ancient, and neighboring, landscapes require higher levels of investment and more time than do recent landscapes. The protection, conservation, restoration, and rehabilitation of ecological integrity require multiple approaches in each landscape as well as consideration of the whole. Active conservation of biota and minimizing the impact of industrial- and agricultural-use are priorities. Integrating a climate focus and rethinking fire are critical restoration considerations to future trajectories under anthropogenic climate change. A legislative mandate to coordinate industrial-scale restoration and active conservation to build from protected areas must become a societal priority to restore ecological integrity.

Key words: active conservation, ancient landscapes, anthropogenic climate change, Mediterranean-climate region, protected areas, remnant vegetation

Implications for Practice

- A Gondwanan perspective to conservation emphasizes a venerable biota, and requires long-term investment and incorporation of the cultural components of deep time.
- Application of a Gondwanan perspective prioritizes protection of remnants and conservation landscapes.
- A mainstreamed conservation ethic that accounts for environmental costs must be applied in the use of resources in Gondwanan landscapes.
- Legislating conservation action as mainstream will minimize social costs incurred through degraded landscapes.
- Active environmental governance must support societal engagement in landscape restoration to build on established pathways of pioneering conservation activities.

Introduction

Global changes have initiated the sixth great mass-extinction event in Earth's history (Pimm et al. 1995) leading to prioritization of global biodiversity hotspots (Myers et al. 2000). The south-western part of the Mediterranean Forests, Woodlands, and Scrub Ecoregion (Olson et al. 2001; Fig. 1) of south-western Australia (SWA) encompasses an Australian global biodiversity hotspot representing five of Australia's 15 national hotspots. The biota of SWA is globally significant (Hopper & Gioia 2004; Rix et al. 2014), but also threatened (Klausmeyer & Shaw 2009). Large areas have been exploited, compromising ecological integrity (Wardell-Johnson et al. 2011), and challenging society to choose investment in the future (United Nations 2015).

Evolutionary studies and recognition of the movement of continental land masses have resulted in appreciation of the

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Gondwanan origins of major components of the SWA biota (Hopper et al. 1996). The confluence of an extraordinary endemic Gondwanan biota and large-scale landscape transformation makes restoration of SWA profoundly significant. Ecosystems are complex "arrangements" that challenge synthesis and simple restoration solutions (Catterall et al. 2004). Hence guidelines for national standards for the practice of ecological restoration in Australia have recently been developed (SERA 2016). However, landscape history (Hopper 2009) also plays a key role concerning trajectory and level of input requirements across particular regions. In particular, biological diversity, ecology, and evolution in Gondwanan landscapes are fundamentally different from equivalent processes on areas dominated by younger landscapes (Hopper 2009; Mucina & Wardell-Johnson 2011). Thus the complexity of processes and interactions in landscapes with Gondwanan heritage that have become degraded require much higher levels of investment than do sites in more recently derived landscapes (Hopper 2009; Wardell-Johnson et al. 2015*a*).

SWA's Gondwanan landscapes have a rich human heritage of some 45,000 years (Hallam 1975) with social values (Wardell-Johnson 2011) entwined over millennia. These deep-time values add a cultural dimension (Hill et al. 1999; Lennon 2012) to Gondwanan heritage (Hopper et al. 1996) providing a distinctive perspective to conservation, rehabilitation, and restoration. The values of European agriculture and resource extraction have impacted in the past 200 years (Jarvis 1981; Saunders et al. 1991). Conservation and restoration responses vary with landscape, but share a common goal to develop and implement ecological solutions. We summarize the Gondwanan heritage of SWA; then outline the large, complex challenges posed by recent (since 1826), rapid transformation across four interconnected landscapes. Finally, we outline restoration responses arguing for: an active approach to conservation; the critical importance of remnants (especially protected areas); and a Gondwanan perspective to inform restoration practice.

South-western Australia's Gondwanan Heritage

The isolated, predominately Mediterranean-climate region (MCR) of SWA comprises nine bioregions totalling 44 million hectares (Table 1; Fig. 1). SWA is the least topographically complex of the MCRs, making it vulnerable to the interactive effects of climate change (Wardell-Johnson et al. 2011). Old weathered landscapes (Fig. 2) predominate with their biogeographic influence extending to adjacent areas (Rix et al. 2014; Mason et al. 2016). Knowledge of the rich and endemic biota of SWA environments is expanding rapidly. Since 1970 the estimated number of plant species in the region has more than doubled, from 3,600 to almost 8,000 (Hopper & Gioia 2004). Knowledge of the impressive diversity of short-range endemic fauna (Harvey et al. 2011) has also expanded. High levels of local endemism, species richness, and turnover are associated with the biota of this region (Hopper & Gioia 2004; Rix et al. 2014; Fig. 2).

Low nutrient environments in SWA favor species persistence over high dispersability (Hopper 2009). Predominating plant taxa include: long-lived shrubs; geophytes such as sundews and orchids (Fig. 3F); plants with unusual growth forms (e.g. fire-resistant arborescent monocots, Fig. 3C) and distinctive nutritional strategies (e.g. parasitism; cluster roots; carnivory, Fig. 3B); and large, long-lived trees (Fig. 2A). Fauna are predominantly sedentary, exemplified by short-range endemism (SRE; Harvey et al. 2011; Rix et al. 2014; Fig. 3). Diverse, complex ecological processes have enabled adaptation to nutrient-poor conditions in old, fire-prone landscapes (Mucina & Wardell-Johnson 2011), remarkable tolerance to salinity, and capacity to persist as small populations (Hopper 2009; Harvey et al. 2011).

The Scale of the Problem and History of Degradation

Landscape patterns changed profoundly followed the arrival of Aboriginal people (Hallam 1975), with European occupation in 1826 elevating anthropogenic impact (Jarvis 1981). Introduction of animals, plants, and microbes (Shearer et al. 2007; Woinarski et al. 2014), deforestation and logging (Calver & Wardell-Johnson 2004, 2016), topsoil and carbon removal (Wardell-Johnson et al. 2011), nutrient enrichment (Box S1, Supporting Information), and further changes in fire regimes (Gosper et al. 2013; Wardell-Johnson et al. 2015*a*) have resulted in loss of habitat, fragmentation (Saunders et al. 1991), and a trajectory of extinctions (Woinarski et al. 2014). Although the biota shows evolutionary resilience to disturbances (e.g. fire, drought), many taxa are vulnerable to rapidly evolving, contemporary human-induced disturbances (Hopper 2009). Although many invertebrate (Harvey et al. 2011) and some vertebrate (e.g. Wardell-Johnson & Roberts 1993; Box S2) taxa are able to persist as small populations, or in small remnants (Mason et al. 2016), mobile taxa such as most birds and remaining mammals are further compromised by habitat fragmentation (Kitchener et al. 1980, 1982). All nine bioregions have been dramatically altered, with differences in degradation and level of protection between bioregions (Figs. 1 & 2; Tables 1 & 2).

For expedience, we group SWA's nine bioregions into four major landscapes defined by European landuse patterns and associated disturbance and management regimes. Each of these interconnected landscapes show distinct disturbance history, providing particular challenges. For effective restoration practice, we advocate landscape, rather than land-use description by a re-focus from human-defined use-landscapes to ecological landscapes. These landscapes are: the Swan Coastal Plain Bioregion (coastal urban/peri-urban landscapes); the South-west forests (Jarrah Forest and Warren Bioregions); the Wandoo Woodlands (Western Australian wheatbelt), which includes the Avon, Mallee, Esperance Plains, and Geraldton Sandplains Bioregions; and the Great Western Woodlands (Goldfields), encompassing the Coolgardie and Hampton Bioregions (GWW, Tables 1 & 2; Fig. 1). The dominant biota has been impacted by different disturbance regimes (Gosper et al. 2013; Wardell-Johnson et al. 2015*a*), and a range of restoration

Table 1. Characteristics of the nine bioregions in the south-western part of the Mediterranean Forests, Woodlands and Scrub Ecoregion (Olson et al. 2001) of Australia (SWA). [a]Interim Biogeographic Regionalisation for Australia (IBRA), Version 7 (subregions) https://www.environment.gov.au/fed/catalog/main/home.page (accessed 26 Jan 2016). [b]*Allocasuarina huegeliana*; [c]*Acacia acuminata*; [d]*Eucalyptus loxophleba*; [e]*E.* spp.; [f]*E. marginata*; [g]*Corymbia calophylla*; [h]*E. wandoo*; [i]*Melaleuca* sp.; [j]*Eucalyptus occidentalis*; [k]*E. diversicolor*; [l]*E. gomphalocephala*; [m]*A. binervia*.

Bioregion[a]	*Geology*	*Vegetation*	*Climate, Mean Annual Rainfall (MAR)*	*Vulnerability*
Avon (AVW)	Dissected plateau of Tertiary laterite in the Yilgarn Craton	Proteaceous shrub-heaths on residual lateritic uplands and derived sandplains, mixed eucalypt, [b]rock sheoak and [c]jam-[d]york gum, woodland on Quaternary alluvials and elluvials	Semiarid warm Mediterranean	Largely deforested for agriculture
Mallee (MAL)	Archean and Proterozoic granite of the Yilgarn Craton, Eocene limestone, playa lakes	[e]Mallee over myrtaceous and proteaceous heath	Semiarid, warm, dry, Mediterranean (7–8 dry months). MAR 300–500 mm	Extensively deforested for agriculture
Esperance Plains (ESP)	Bremer Sedimentary Basin and Albany-Fraser Orogen of Yilgarn Craton, Eocene marine sediment	Heaths, coastal dune shrubs, mallees, mallee-heaths, and granite heaths	Temperate Mediterranean. MAR 500–800 mm	Extensively deforested for agriculture
Geraldton Sandplains (GES)	Central and northern Perth Basin, Pinjarra Orogen, and southern section of Carnarvon Basin	Proteaceous shrub-heaths with emergent mallees, Extensive [d]york gum and *Acacia* woodlands on alluvial outwash plains, proteaceous heath and *Acacia* shrubs on coastal sands and limestone	Semiarid warm Mediterranean	Extensively deforested for agriculture
Jarrah Forest (JAF)	Duricrusted Plateau of Yilgarn Craton, elluvial and alluvial deposits and Mesozoic sediments	[f]Jarrah–[g]marri forest in the west, grading into marri–[h]wandoo woodlands in the east. *Banksia* low woodlands on sand sheets, heath on granite rocks, [i]paperbarks, and [j]swamp yate in south-east	Temperate Mediterranean. MAR 500–1,200 mm	Inland margins and valleys extensively deforested for agriculture
Warren (WAR)	Dissected undulating Leeuwin Complex, Southern Perth Basin, intrusions of Yilgarn Craton, western parts of Albany Orogen	Tall open-forests dominated by [k]karri. Open-forest on poorer soils. Wide valley floors with sedges and shrubs. Coastal woodlands and heaths. Shrub-heaths on swampy plains.	Temperate Mediterranean (3–4 dry months). MAR 800–1,400 mm	Limited deforestation for agriculture
Swan Coastal Plain (SWA)	Dandaragan Plateau and Perth Coastal Plain	*Banksia* and [l]tuart woodlands on sandy soils, [e]sheoak-marri woodlands on outwash plains, and [i]paperbark in swampy areas. *Banksia*, [f]jarrah–[g]marri woodland, and shrub-heaths on laterite.	Warm Mediterranean. MAR 600–1,000 mm	Extensively deforested for agriculture and urbanization
Coolgardie (COO)	Granite strata of Yilgarn Craton with Archaean greenstone intrusions in parallel belts	[e]Mallees and shrubs on sandplains and lateritic uplands, playas and granite outcrops, diverse woodlands shrubs rich in endemic Proteaceae in the west, *Acacia* spp. in the east	Arid to semiarid warm Mediterranean	Some deforestation, extensive mining and grazing
Hampton (HAM)	Marine dunes and limestone escarpments	[e]Mallee, eucalypt, and [m]myall (mulga)	Arid to semiarid	Approximately 50% grazed

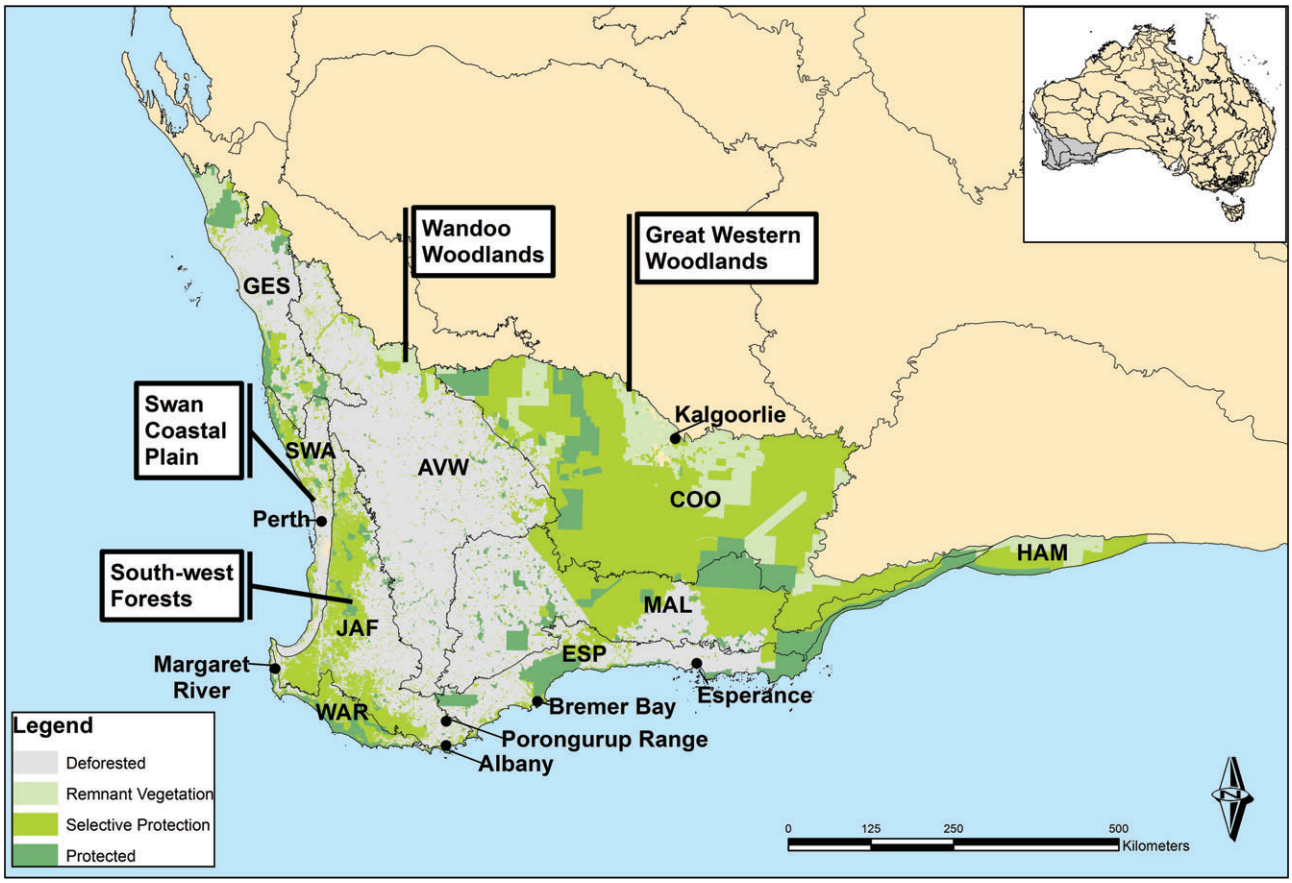

Figure 1. The south-western part of the Mediterranean Forests, Woodlands, and Scrub Ecoregion of Australia (SWA). This area is also the South-western Australian Global Biodiversity Hotspot. This area encompasses nine bioregions, which for expedience we have grouped into four landscape types (see text for details). Also shown is the extent of protected areas, selective protection, unprotected remnants, and areas deforested (see Table 2 for details). Municipal landmarks are also shown.

responses is necessary. Considerable variation exists within and between bioregions, and across these landscapes.

Swan Coastal Plain

Urbanization is centered on the Perth metropolitan area (PMA—where 74% of Western Australians live), more than doubling since the 1970s (WWF-Australia 2010). Extensive associated ecological impact extends beyond the bioregion (How & Dell 2000; Horwitz et al. 2009). Although the PMA is less than 0.24% of the State's area, human impact has costly environmental, social, and economic consequences. Increased population and changed social values have increased resource demands, including water usage in a warming drying climate (Bates et al. 2008). Water supply dams are increasingly ineffective, with ground water abstraction presenting significant threats to biodiversity (Horwitz et al. 2009, Box S2). Environmental degradation, social exclusion, and high costs of services have led to public safety concerns, with requirements for increasing resources for disaster management (Nechyba & Walsh 2004). Urban expansion and changed settlement patterns have reduced natural or semi-natural vegetation on the Swan Coastal Plain to only 34.7%, with only 10% in protected areas (Table 2).

Restoring the Swan Coastal Plain. Rebuilding Gondwanan heritage in Swan Coastal Plain landscapes will be achieved by identifying key sites of ecological integrity and providing them with protection. These landscapes must be conserved by managing human settlement patterns to emphasize high density, climate-appropriate housing, and urban settlements to sustain and restore ecological integrity. Reducing the urban footprint by minimising ecological resource demands, desalination replacing ground-water extraction, and removal of ineffective water supply dams can reduce impacts of local water use on ecological landscapes and neighboring bioregions (see Nilsson et al. 2005). Pets and invasive species must be intensively managed if urban areas are to act as conservation hubs for vulnerable species such as Carnaby's Cockatoo (Fig. 3A; Box 1). Existing social capital generated by dense human populations and ongoing environmental actions such as Bushcare and Coastcare groups in urban regions provide significant opportunities to focus, connect, and improve local restoration efforts. Urban management legislation must reduce the demands of

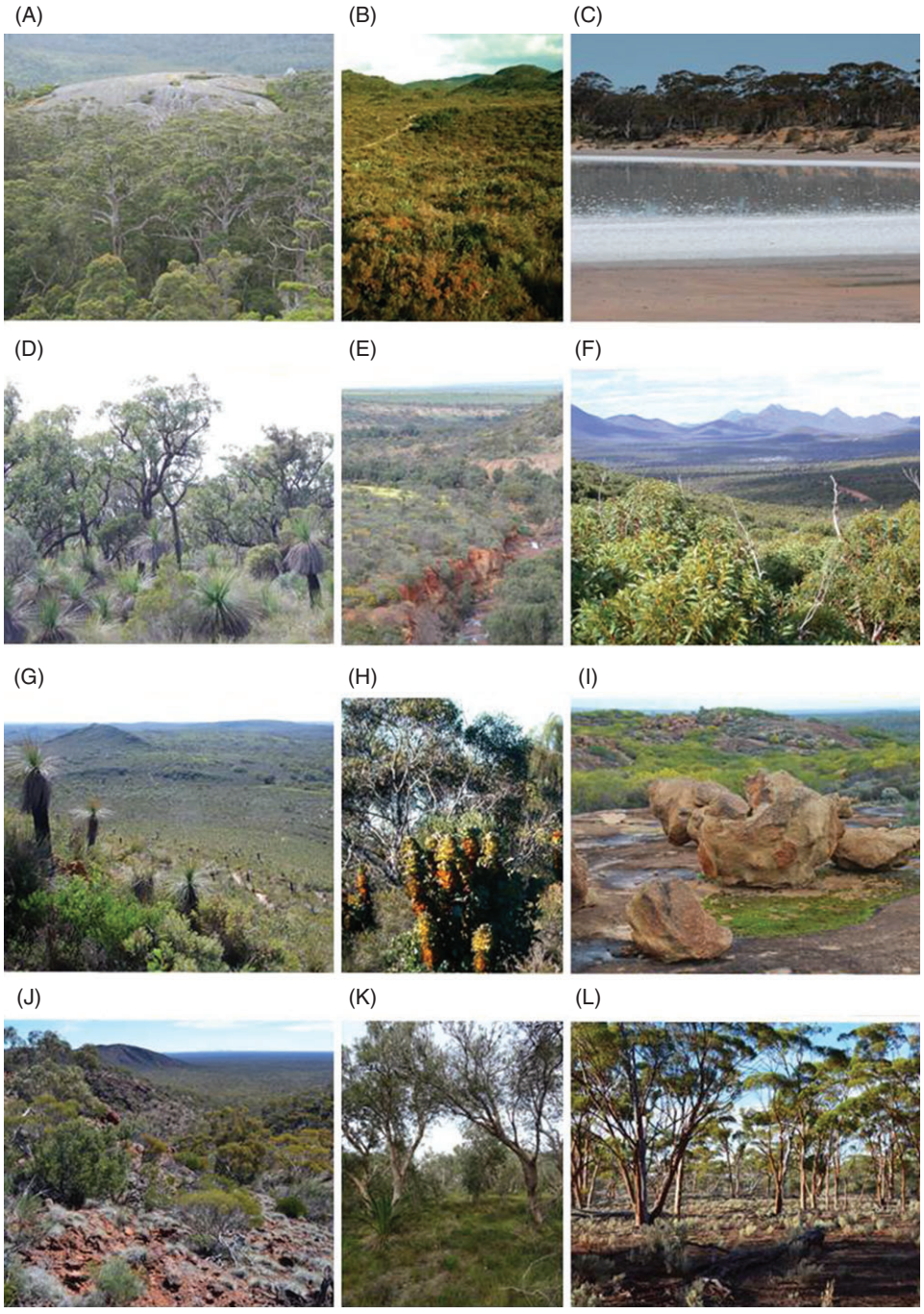

Figure 2. Examples of major habitats and landscape features in the Mediterranean Forests, Woodlands, and Scrub Ecoregion of Australia (SWA). (A) Granite outcrop and tall open-karri (*Eucalyptus diversicolor*) forest in the high rainfall Warren Bioregion. (B) Coastal shrubland in the d'Entrecasteaux dune systems, Warren Bioregion. (C) Salt lake and woodlands, Lake Dundas in the Great Western Woodlands, Coolgardie Bioregion. (D) Jarrah (*E. marginata*) open-forest, with *Xanthorrhoea preissii*, Jarrah Forest Bioregion. (E) York gum (*E. loxophleba*) and jam (*Acacia acuminata*) woodland, Geraldton Sandplains Bioregion. (F) Mallee Heathland in the Stirling Ranges, Mallee Bioregion. (G) Shrub heathlands with *Kingia australis*, Mt Lesueur, Geraldton Sandplains Bioregion. (H) Mallee shrubland with *Hakea victoria*, Esperance Plains Bioregion. (I) Granite outcrop and *Acacia* shrubland, Chiddacooping, Avon Wheatbelt Bioregion. (J) Mallee shrublands, Helena Aurora Range, Great Western Woodlands, Coolgardie Bioregion. (K) Banksia (*B. menziesii, B. attenuata,* with *Macrozamia reidlei*) woodland, Swan Coastal Plain Bioregion. (L) Salmon Gum (*Eucalyptus salmonophloia*) woodland, Great Western Woodlands, Coolgardie Bioregion. Photo can be credited: (A, B, D–L) Grant Wardell-Johnson; (C) Amanda Keesing.

Figure 3. Examples of animal, plant, and fungal taxa endemic to the Mediterranean Forests, Woodlands and Scrub Ecoregion of Australia (SWA). (A) Carnaby's black-Cockatoo (*Calyptorhynchus latirostris*—Cacatuidae) and *Banksia sessilis* (Proteraceae), Jarrah Forest Bioregion. (B) Albany Pitcher plant (*Cephalotus folicularis*—Cephalotaceae) and the widespread high rainfall taxon, Bog Clubmoss (*Lycopodiella serpentina*—Lycopodiaceae), Warren Bioregion. (C) An arborescent monocot, *Dasypogon hookeri* (Dasypogonaceae), Jarrah Forest Bioregion. (D) Red Moort, *Eucalyptus cernua* (Myrtaceae), Mallee Bioregion. (E) *Anthocercis sylvicola* (Solanaceae), Warren Bioregion. (F) Eastern Queen of Sheba (*Thelymitra speciosa*—Orchidaceae), Stirling Range, Mallee Bioregion. (G) Good's Banksia (*Banksia goodii*—Proteaceae), Jarrah Forest Bioregion. (H) *Descolea* sp. (Cortiniaraceae), Warren Bioregion. (I) Mygalomorph spider (*Aganippe* sp.—Idiopidae), Avon Wheatbelt Bioregion. (J) Sunset Frog (*Spicospina flammocaerulea*—Myobatrachidae), Warren Bioregion. (K) Marbled Gecko (*Christinus marmoratus*—Gekkonidae), Jarrah Forest Bioregion. (L) Honey possum (*Tarsipes rostratus*—Tarsipedidae), Esperance Plains Bioregion. (M) Red-eared Firetail Finch (*Stagonopleura oculata*—Estrildidae), Warren Bioregion. Photo can be credited: (A) Leighton DeBarros, Sea Dog films; (B,C, E-H, J, K) Grant Wardell-Johnson; (D) Keith Bradby; (I) Leanda Mason; (L) Amanda Keesing.

Table 2. Area and percentage of area protected; selectively protected, unprotected; and deforested within each bioregion of south-western Australia (SWA). [a]Interim Biogeographic Regionalisation for Australia (IBRA), Version 7 (subregions), https://www.environment.gov.au/fed/catalog/main/home.page (accessed 26 Jan 2016); [b]Calculated as the percentage of *National Park*, *Nature Conservation* and *Strict Nature Reserves* areas within each IBRA. Land-use data was Version 5 (1997), Western Australia, http://www.agriculture.gov.au/abares/aclump/land-use/data-download (accessed 26 Jan 2016). More recent land use mapping was not updated over the full IBRA extent; [c]Calculated as the percentage of *species management area*, *managed resource protection*, *remnant native cover*, *traditional indigenous uses*, and *other minimum intervention areas* within each IBRA (see note '*b*' for dataset); [d]Calculated as the percentage of *Livestock Grazing in Native Environments* within each IBRA; [e]Area deforested calculated as the percentage of cleared land used for *Agriculture and Plantations (Dryland and Irrigated), Other Intensive Uses*, and *Artificial Water Bodies*.

	Protected[b]		*Selectively Protected*[c]		*Unprotected Remnant Vegetation*[d]		*Deforested*[e]		*Total Area*	
Bioregion[a] *[Landscape]*	*ha*	*%*	*ha*	*%*	*ha*	*%*	*ha*	*%*	*ha*	*%*
Avon (AVW)	162,033	1.7	693,790	7.3	286,136	3.0	8,369,564	88.0	9,511,522	21.7
Mallee (MAL)	1,325,861	17.9	2,460,289	33.2	18,039	0.2	3,611,908	48.7	7,416,097	17.0
Esperance Plains (ESP)	823,609	28.3	438,252	15.1	584	<0.1	1,645,245	56.6	2,907,690	6.6
Geraldton Sandplains (GES)	479,800	15.3	478,424	15.2	259,932	8.3	1,920,933	61.2	3,139,090	7.2
[Wandoo Woodlands]	2,791,303	12.1	4,070,755	17.7	564,691	2.5	15,547,650	67.7	22,974,399	52.5
Jarrah Forest (JAF)	226,211	5.0	2,051,484	45.6	0	0.0	2,224,148	49.4	4,501,843	10.3
Warren (WAR)	262,074	31.0	428,511	50.9	105,432	<0.1	151,491	18.0	947,508	2.2
[South-west Forests]	488,285	9.0	2,479,995	45.5	105,432	1.9	2,375,639	43.6	5,449,351	12.5
[Swan Coastal Plain] (SWA)	149,303	10.0	368,837	24.7	2,059	<0.1	973,969	65.3	1,492,109	3.4
Coolgardie (COO)	1,436,161	11.1	8,427,049	65.4	2,805,116	21.8	223,856	1.7	12,892,182	29.5
Hampton (HAM)	114,430	10.7	544,869	51.2	405,462	38.1	0	0.0	1,064,761	2.4
[Great Western Woodlands]	1,550,591	11.1	8,971,918	64.3	3,210,578	23.0	223,856	1.6	13,956,943	31.9
Total area	4,979,483	11.4	15,891,506	36.3	3,775,279	8.6	19,121,115	43.7	43,767,382	100

growth and development to protect biodiversity hotspots and build ecological integrity through active restoration.

South-west Forests

Rainfall declines of about 15–20% in the South-west Forest landscapes since 1970 are projected to continue (Bates et al. 2008). The Jarrah Forest Bioregion has just over half of pre-European vegetation remaining (Table 2), but only 5% in protected areas, reflecting society's immediate resource focus (Calver & Wardell-Johnson 2004). Jarrah (*Eucalyptus marginata*) forest in particular has been structurally transformed by on-going mining and logging (Wardell-Johnson et al. 2015*a*). By contrast, the Warren Bioregion includes a high proportion of protected area (Table 2), though mostly recently gazetted. Over a third of the tall forest (predominantly Karri, *Eucalyptus diversicolor*) existing at the time of European settlement (190,000 of about 250,000 hectares) has been ecologically compromised as a result of clearfelling (with regeneration) since 1967. In addition, climate change threatens ecological integrity, with declines in vertebrate fauna (Box 1) and introduced plants potentially invading moister, more fertile sites (e.g. Box S1). Approved mining leases or State agreements (principally for bauxite, gold, and coal) cover 45% of State forest (CCWA 2012) constituting a significant potential landscape transformation to rehabilitated mine-sites and industrial-scale logging in the future.

Restoring South-west Forests. Rebuilding Gondwanan heritage in South-west Forest landscapes will be achieved by recognizing the high biodiversity significance of these forested ecosystems and managing them to maintain their high refugial capacity (Keppel et al. 2015). In areas that have been mined, the State government-sanctioned focus must shift from rebuilding a Jarrah forest overstorey for timber supplies, to restoring the understorey and protecting surrounding habitat (Wardell-Johnson et al. 2015*a*). State-of-the-Science rehabilitation (Koch 2007; Standish et al. 2015; Willyams 2015) can be harnessed to rebuild integrity that restores a diverse understorey. Protecting old growth characteristics is urgently required in forest management under the trending drying climate (Wardell-Johnson et al. 2015*a*). Societal rancor (Routley & Routley 1974; Lindenmayer et al. 2015) suggests a need for change in governance processes to integrate a broader set of interests and values in decision-making in SWA forested landscapes (e.g. Stevensen 2000; Box S1).

Wandoo Woodland

The Wandoo Woodland (WW) landscapes are diverse, extending across four bioregions. Deforestation and land use changes (particularly agriculture) have contributed to pronounced alterations in ecological functioning (Saunders et al. 1991; George et al. 1995; Box 1). Significant alterations occurred between 1905 and 1995, with the bulk of more fertile soils alienated between 1905 and 1931 (Jarvis 1981). Government policy, broad-scale fertilizer application, commodity prices, and periods of above average rainfall resulted in less fertile soils being converted to agriculture between 1948 and 1969. In this period over 400,000 hectares of public land was alienated and deforested annually (Jasper 1984). Almost 68% of the region has been deforested, including 88% of the Avon Wheatbelt Bioregion. Significant nutrient inputs are required to maintain agricultural viability. Rising water tables (George et al. 1995) have increased salt loads at the soil surface, diminished quality of the land for

agriculture, and compromised adjacent remnants, including protected areas (Saunders et al. 1991). Although 12% of this region is in protected areas, the spread is uneven, and less than 2% of the Avon Wheatbelt Bioregion (Table 2) is protected.

Restoring the Wandoo Woodland (WW). Rebuilding Gondwanan heritage in Wandoo Woodland landscapes will be achieved by protecting sites where introduced species and industrial agriculture have not destroyed ecological integrity. The parlous state of the environment urges a broad range of approaches, including species and community recovery programs (e.g. Box S2; Woinarski et al. 2014), and voluntary projects (e.g. Box S3). Active conservation strategies and reconnecting protected areas with remnants are critical to restoration in these landscapes. This may be facilitated by drawing on successful Landcare and conservation work (Bradby 1991). Broad-scale compromised ecological integrity urges a shift beyond piecemeal approaches with a greater commitment, drawing on a landscape scale of governance. Repurchasing agricultural land and active and properly resourced conservation measures in protected areas (Bradby et al. 2016) are sought. Integrated, broad-scale, imaginative pest control programs targeting multiple species; and addressing meso-predator release issues or prey-shifting to vulnerable natives (Box 1) will be necessary in landscapes where ecological integrity has been compromised.

Box 1. Wandoo Woodlands: mammal declines, research emphasis, and the importance of introduced predator control to restoration

Protecting Australia's unique assemblage of mammals, of which 86% are endemic, is a challenge. Australia holds the world record for extinctions in the past 200 years (Woinarski et al. 2014). This record demonstrates Australia's poor investment ranking in the 40 most conservation-underfunded countries globally (Waldron et al. 2013).

Deforestation (Saunders et al. 1991) and introduced predators, especially cats (*Felis catus*) and foxes (*Vulpes vulpes*), have a significant impact on medium-sized mammals in all landscapes, but especially in the Wandoo Woodlands (Woinarski et al. 2014). Active conservation strategies such as 1080 poison applications are well documented and very effective for Western Australian conditions (Marlow et al. 2015). Many species of the genus *Gastrolobium* (Fabaceae) are endemic in SWA and naturally accumulate monofluoroacetic acid—the key ingredient in 1080. Thus this poison is fatal to introduced species but not to natives.

Other integrated active conservation measures including captive breeding, translocation (with post-release monitoring), and predator-proof fencing will be essential in restoring ecological integrity for mammal populations (de Tores & Marlow 2012). Despite the proven value of fences in conservation internationally (Moseby et al. 2011; de Tores & Marlow 2012) Australia has been slow on the uptake, relying on small amounts of private investment. The few exemplars in Western Australia cover a very small area but will be increasingly important, despite establishment and monitoring costs (de Tores & Marlow 2012).

Despite significant policy investment in prioritisation, taxon research emphasis has not reflected conservation needs. A limited set of iconic species have attracted interest whereas endemic species of potential conservation significance have attracted little investment (Fleming & Bateman 2016), constraining effective ecological restoration and conservation planning. Active conservation is the key to restoring Australia's unique mammal assemblages, but is dependent on adequate investment and formal protection through governance that links public and private domains in conservation. Photo by S. Dundas

Great Western Woodlands

The Great Western Woodlands (GWW) is the world's most intact temperate woodland extending over 15 million hectares (Watson et al. 2008, Table 2). Although 1.6% is deforested, less than 12% is vested as protected area, reflecting a resource extraction focus (Jarvis 1981). Although tree-cover is largely intact, 20% has been compromised by extensive sheep grazing and introduced species (e.g. camels *Camelus dromedarius* and donkeys *Equus asinus*). Extensive mining commenced in the Kalgoorlie area from the 1890s resulted in intense localized disturbance over about three million hectares (DEC 2010). On-going interests include over 340 working mines (Ye 2008), often in areas of high biodiversity significance (Gibson et al. 2011), posing a significant on-going rehabilitation and restoration legacy. Although there is a low human population density, climate change poses the greatest on-going conservation concern through fire impact (Gosper et al. 2013; Recher & Davis 2013).

Restoring the Great Western Woodlands (GWW). Rebuilding Gondwanan heritage in the Great Western Woodland landscapes will be achieved by identifying key sites of ecological integrity and providing them with protection. Increasing direct involvement of Traditional Owners in GWW management (Bradby et al. 2016) will assist in generating a deep-time cultural knowledge integration with scientific knowledge to generate targeted restoration. Increasing scrutiny of mining proposals and associated mine closure plans will potentially result in improved rehabilitation. However, low levels of civil engagement will require legislative action to ensure restoration outcomes in the area as the value of mining resources declines, and mines are abandoned (Ye 2008). Conservation and restoration approaches concerning fire management and protection will be increasingly important under continued global warming (Gosper et al. 2013; Recher & Davis 2013).

Conservation, Rehabilitation, and Restoration of Gondwanan heritage

Since European settlement, more than 19 million hectares, or over 43% of the SWA global biodiversity hotspot, has been deforested through agriculture, timber exploitation, mining activities, and human settlement (Fig. 1; Table 2). Of the remaining native vegetation, relatively little occurs in protected areas, with significant areas afforded protected status only after extensive alteration through exploitation (e.g. forestry, mining). SWA now faces escalating impacts of invasive plants, animals and microbes, fragmentation, nitrification, carbon removal, increased salinization, and topsoil degradation (Wardell-Johnson et al. 2011). Over 40 years of warming and drying (especially in higher rainfall areas) exacerbates many of these threats (Wardell-Johnson et al. 2011, 2015*a*).

The Anthropocene has resulted in huge cost to the natural environment (Lewis & Maslin 2015), especially in old landscapes (Hopper 2009; Mucina & Wardell-Johnson 2011). Ill-informed decision-making has played a part, but social expectations and social patterns govern the future of the SWA hotspot (Wardell-Johnson 2011). Future development cannot be based on historic models of social expectations or settlement patterns, because further degradation of ecological integrity impacts on human resilience (United Nations 2015). The future requires integration of Gondwanan heritage to build social stewardship at the local level (Satterfield et al. 2013). This Gondwanan perspective emphasizes the role of civil society in defining a more sustainable ecological future that accounts for the high cost of environmental degradation (United Nations 2015).

It must be acknowledged that even during the most development-focused phase of Australia's history, SWA's biodiversity values were accorded recognition (Calver & Wardell-Johnson 2016). However, conservation programmes were *ad hoc*, with the dominant response being to create protected areas with relatively passive conservation programs. The landscapes outside protected areas faced increased exploitation on an industrial scale (e.g. Box S1). Multiple use (Calver & Wardell-Johnson 2016) and active conservation measures on private land emerged through the Landcare movement during the 1980s. However, the *ad hoc* nature of resourcing, and dependence on volunteers makes these approaches insufficient and unviable as means of restoring ecological integrity at the landscape scale (Maron et al. 2016). Although there has been significant innovation in restoration techniques (SERA 2016), the scale of the challenge demands a mandate for restoration through comprehensive and broadly applied governance (see Stevensen 2000), along with active measures to protect and restore the remnants of relatively intact ecological landscapes (Wardell-Johnson et al. 2015*b*).

While ecologically intact vegetation is important in defining core components of ecological restoration (see Catterall et al. 2004), they are of particular significance in Gondwanan landscapes (Hopper 2009; Harvey et al. 2011). Many native species, especially highly sedentary species, are able to persist in small remnants or small populations despite introduced predators, but will be susceptible to a changing climate (Harvey et al. 2011; Mason et al. 2016). Despite future trajectories of climate change (Lechner et al. 2015) historical reference points are necessary in areas requiring restoration or rehabilitation. As a priority in SWA, restoration programs must conserve remaining private and public remnants (Hopper 2009; Mason et al. 2016) as these sites will form the anchors for future biodiversity. Intensive management (see Willyams 2015) including active protection and long-term integrated pest management programs will contribute to natural increases and re-colonization (Woinarski et al. 2014). Natural increases and the ability to move with a changing climate cannot be left to chance through passive conservation measures. For fauna, active conservation through captive breeding, translocation, baiting of introduced predators, and the use of predator-proof fencing must be applied to protect and restore remnant populations (Moseby et al. 2011; de Tores & Marlow 2012; Box 1).

A Gondwanan stewardship based on temporal and spatial components must be built through integrating deep-time connections including Aboriginal knowledge of the land (Wardell-Johnson 2011; Bradby et al. 2016). Integrating

knowledge systems that account for symbolic and social values in landscapes is important to engage people in landscape management. Maintenance of ecological and economic landscape values is most likely to result from broader values-engagement (Wardell-Johnson 2011). Effective restoration is built on decisions that account for systemic linkages between people and the landscapes to which they are connected (Wardell-Johnson 2011). Areas can then be placed on a restoration trajectory, with biological richness and ecological function increasing over time. These areas improve buffering and connectivity to remnants but landscape-scale vision, stewardship, and commitment are also required (Bradby et al. 2016). This requires a legislative framework of governance that more consistently supports civil society engagement (Stevensen 2000) that links values in restoration strategies.

The breadth of the challenge requires transdisciplinary collaborations that effectively link theory across disciplines with practise. Rehabilitation and restoration of human-impacted landscapes require active engagement with conservation at all sociopolitical levels. While such change may necessitate direct action in some circumstances (Box S1), a legislative mandate to limit legacy costs and coordinate industrial-scale restoration that moves beyond volunteerism (Maron et al. 2016) is urged. Ecological integrity has been so thoroughly compromised in SWA that optimisation or triage is disingenuous. All remnants are now conservation-essential, even those in relatively poor condition. We urge highly developed restoration efforts be integrated with active conservation to protect SWA's inspirational Gondwanan heritage.

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Supporting Information

The following information may be found in the online version of this article:

Box S1. Conservation reliance on community conservation voices in South-west Forests: The WA Forest Alliance advocacy.

Box S2. South-west Forests: Connecting landscapes to conserve the White-bellied Frog.

Box S3. South-west Forests: Who cares about weeds in the Porongurup National Park?

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