

1
2
3
4 **1 Balancing phylogenetic diversity and species numbers in conservation prioritization, using a case**
5 **2 study of threatened species in New Zealand**

6
7
8
9
10 **4 Joseph R. Bennett^{a*}, Graeme Elliott^b, Belinda Mellish^c, Liana N. Joseph^d, Ayesha I. T. Tulloch^a,**
11 **5 William J. M. Probert^{a,e}, Martina M. I. Di Fonzo^a, Joanne M. Monks^c, Hugh P. Possingham^{a,f},**
12 **6 Richard Maloney^c**

13
14
15 ^a Centre for Biodiversity and Conservation Science, University of Queensland, Brisbane 4072, Australia

16
17 ^b Department of Conservation, Private Bag 5, Nelson 7010, New Zealand

18
19 ^c Department of Conservation, Private Bag 4715, Christchurch Mail Centre, Christchurch 8140, New
20 Zealand

21
22 ^d Wildlife Conservation Society, 2300 Southern Boulevard, Bronx, New York 10460, USA

23
24 ^e Center for Infectious Disease Dynamics, Pennsylvania State University, 208 Mueller Lab, University
25 Park, PA 16802, USA

26
27 ^f School of Life Sciences, Silwood Park Imperial College London, Ascot, Berkshire, UK

28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180
181
182
183
184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
240
241
242
243
244
245
246
247
248
249
250
251
252
253
254
255
256
257
258
259
260
261
262
263
264
265
266
267
268
269
270
271
272
273
274
275
276
277
278
279
280
281
282
283
284
285
286
287
288
289
290
291
292
293
294
295
296
297
298
299
300
301
302
303
304
305
306
307
308
309
310
311
312
313
314
315
316
317
318
319
320
321
322
323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339
340
341
342
343
344
345
346
347
348
349
350
351
352
353
354
355
356
357
358
359
360
361
362
363
364
365
366
367
368
369
370
371
372
373
374
375
376
377
378
379
380
381
382
383
384
385
386
387
388
389
390
391
392
393
394
395
396
397
398
399
400
401
402
403
404
405
406
407
408
409
410
411
412
413
414
415
416
417
418
419
420
421
422
423
424
425
426
427
428
429
430
431
432
433
434
435
436
437
438
439
440
441
442
443
444
445
446
447
448
449
450
451
452
453
454
455
456
457
458
459
460
461
462
463
464
465
466
467
468
469
470
471
472
473
474
475
476
477
478
479
480
481
482
483
484
485
486
487
488
489
490
491
492
493
494
495
496
497
498
499
500
501
502
503
504
505
506
507
508
509
510
511
512
513
514
515
516
517
518
519
520
521
522
523
524
525
526
527
528
529
530
531
532
533
534
535
536
537
538
539
540
541
542
543
544
545
546
547
548
549
550
551
552
553
554
555
556
557
558
559
560
561
562
563
564
565
566
567
568
569
570
571
572
573
574
575
576
577
578
579
580
581
582
583
584
585
586
587
588
589
590
591
592
593
594
595
596
597
598
599
600
601
602
603
604
605
606
607
608
609
610
611
612
613
614
615
616
617
618
619
620
621
622
623
624
625
626
627
628
629
630
631
632
633
634
635
636
637
638
639
640
641
642
643
644
645
646
647
648
649
650
651
652
653
654
655
656
657
658
659
660
661
662
663
664
665
666
667
668
669
670
671
672
673
674
675
676
677
678
679
680
681
682
683
684
685
686
687
688
689
690
691
692
693
694
695
696
697
698
699
700
701
702
703
704
705
706
707
708
709
710
711
712
713
714
715
716
717
718
719
720
721
722
723
724
725
726
727
728
729
730
731
732
733
734
735
736
737
738
739
740
741
742
743
744
745
746
747
748
749
750
751
752
753
754
755
756
757
758
759
760
761
762
763
764
765
766
767
768
769
770
771
772
773
774
775
776
777
778
779
780
781
782
783
784
785
786
787
788
789
790
791
792
793
794
795
796
797
798
799
800
801
802
803
804
805
806
807
808
809
810
811
812
813
814
815
816
817
818
819
820
821
822
823
824
825
826
827
828
829
830
831
832
833
834
835
836
837
838
839
840
841
842
843
844
845
846
847
848
849
850
851
852
853
854
855
856
857
858
859
860
861
862
863
864
865
866
867
868
869
870
871
872
873
874
875
876
877
878
879
880
881
882
883
884
885
886
887
888
889
890
891
892
893
894
895
896
897
898
899
900
901
902
903
904
905
906
907
908
909
910
911
912
913
914
915
916
917
918
919
920
921
922
923
924
925
926
927
928
929
930
931
932
933
934
935
936
937
938
939
940
941
942
943
944
945
946
947
948
949
950
951
952
953
954
955
956
957
958
959
960
961
962
963
964
965
966
967
968
969
970
971
972
973
974
975
976
977
978
979
980
981
982
983
984
985
986
987
988
989
990
991
992
993
994
995
996
997
998
999
1000

* Corresponding author: j.bennett5@uq.edu.au

18 **Abstract**

19 Funding for managing threatened species is currently insufficient to assist recovery of all species, so
20 management projects must be prioritized. In attempts to maximize phylogenetic diversity conserved,
21 prioritization protocols for threatened species are increasingly weighting species using metrics that
22 incorporate their evolutionary distinctiveness. In a case study using 700 of the most threatened species in
23 New Zealand, we examined trade-offs between emphasis on species' evolutionary distinctiveness
24 weights, and the numbers of species prioritized, as well as costs and probabilities of success for recovery
25 projects. Increasing emphasis on species' evolutionary distinctiveness weights in the prioritization
26 protocol led to greater per-species costs and higher risk of project failure. In a realistic, limited-budget
27 scenario, this resulted in fewer species prioritized, which imposed limits on the total phylogenetic
28 diversity that could be conserved. However, by systematically varying the emphasis on evolutionary

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

29 distinctiveness weight in the prioritization protocol we were able to minimize trade-offs, and obtain
30 species groups that were near-optimal for both species numbers and phylogenetic diversity conserved.
31 Phylogenetic diversity may not equate perfectly with functional diversity or evolutionary potential, and
32 conservation agencies may be reluctant to sacrifice species numbers. Thus, we recommend prioritizing
33 species groups that achieve an effective balance between maximizing phylogenetic diversity and number
34 of species conserved.

35 **Keywords:** conservation planning; prioritization; threatened species; evolutionary distinctiveness;
36 phylogenetic diversity; New Zealand

37 **Introduction**

38 Global biodiversity loss is accelerating (Butchart et al., 2010), and current funding levels are inadequate
39 to reverse this trend (McCarthy et al., 2012). Funding tends to be allocated unevenly, with taxonomic
40 biases towards charismatic vertebrate species (Martin-Lopez et al., 2009; Laycock et al., 2011). Both
41 scientists and conservation agencies increasingly recognize that systematic prioritization schemes must be
42 developed to efficiently allocate funding to minimize biodiversity loss (e.g. Bottrill et al., 2008; Wilson et
43 al., 2011; IUCN, 2013). A number of frameworks exist for prioritizing threatened species management
44 based on criteria such as threat level (Master, 1991; Carter et al., 2000), socio-political significance
45 (Rodríguez et al., 2004), ecological importance, and potential for recovery (Marsh et al., 2007).

46 Phylogenetic diversity is considered a key component of biodiversity, reflecting life's evolutionary
47 heritage, its functional diversity and potentially its ability to adapt to future conditions (Vane-Wright et
48 al., 1991; Cadotte and Davies, 2010). Thus, the evolutionary distinctiveness of species has repeatedly
49 been proposed as a key consideration in conservation prioritization, under the assumption that distinct
50 species with few extant relatives are more important to maintaining phylogenetic diversity than species
51 from diverse lineages, which are assumed to have greater genetic redundancy (e.g. May, 1990; Vane-
52 Wright et al., 1991; Crozier, 1997).

1
2
3
4 53 In attempts to shift the emphasis of conservation programmes from maximizing the total number of
5
6 54 species conserved to maximizing conserved phylogenetic diversity, a variety of prioritization schemes
7
8 55 have been proposed that weight species according to metrics incorporating their evolutionary
9
10 56 distinctiveness. Redding and Mooers (2006) proposed a scheme that weights species according to the
11
12 57 ‘equal splits’ distinctiveness metric, which divides evolutionary time of a branch equally among daughter
13
14 58 branches, as well as probability of extinction. Isaac et al. (2007) designed a similar scheme, which
15
16 59 weights species according to a slightly different measure of evolutionary distinctiveness (see *Methods*
17
18 60 below) and International Union for Conservation of Nature (IUCN) threat status. Other methods (e.g.
19
20 61 Vane-Wright et al., 1991; Faith, 1992, 2008) consider phylogenetic complementarity of the prioritized
21
22 62 suite of taxa, with the goal of choosing a species group that protects as much total phylogenetic diversity
23
24 63 as possible. Rosauer et al. (2009) and Cadotte and Davies (2010) proposed methods that explicitly
25
26 64 consider both evolutionary distinctiveness and species ranges when prioritizing areas to maximize
27
28 65 retained phylogenetic diversity. Cofré and Marquet (1999) designed a conservation priority index that
29
30 66 includes an ordinal metric of taxonomic singularity, which assigns higher values to taxa with fewer
31
32 67 closely-related species. Their metric also considers endemism and additional aspects such as threat status
33
34 68 and geographic distribution. Joseph et al. (2009) devised a method that integrates prioritization of species
35
36 69 based on distinctiveness as well as cost, probability of project success and expected change to probability
37
38 70 of species’ survival.
39
40
41
42
43
44
45 71 Given limited budgets, a shift in emphasis towards conserving phylogenetic diversity of a planning area
46
47 72 by prioritizing evolutionarily distinct species may result in trade-offs leading to fewer individual species
48
49 73 being conserved. If conserving maximum phylogenetic diversity in a planning area is the primary goal,
50
51 74 this trade-off may be unimportant. However, the evolutionary distinctiveness of species may not be a
52
53 75 perfect reflection of their long-term ecological importance. In particular, phylogenetic clustering of
54
55 76 extinction risk in some older lineages (Gaston and Blackburn, 1997; Vamosi and Wilson, 2008) raises the
56
57 77 possibility that such lineages may be maladapted to current conditions, and that prioritizing according to
58
59
60
61
62
63
64
65

1
2
3
4 78 evolutionary distinctiveness could sacrifice the rapid evolutionary potential contained in some diverse,
5
6 79 recently-radiated clades. Although conserving phylogenetic diversity may be an important consideration
7
8
9 80 in setting conservation priorities, the trade-offs with other factors such as cost and probability of
10
11 81 management success must also be explored.

12
13
14 82 The potential for such trade-offs when conserving phylogenetic diversity versus species richness was
15
16 83 noted by Davies and Buckley (2011), who found a disconnect between patterns of species richness and
17
18 84 phylogenetic diversity in Neotropical mammals. In addition, Joseph et al. (2009) found in limited tests
19
20 85 that a prioritization strategy that weighted species based exclusively on their evolutionary distinctiveness
21
22 86 could lead to fewer species being prioritized for management versus other strategies. Such trade-offs have
23
24 87 not previously been demonstrated in realistic prioritization scenarios involving an entire suite of
25
26
27 88 threatened species being considered for prioritization.

28
29
30 89 Here, we use systematic prioritization scenarios from a dataset of 700 of the most threatened species in
31
32 90 New Zealand to examine trade-offs when there is increasing emphasis on species' evolutionary
33
34
35 91 distinctiveness. We examine the relationships between emphasis on individual species' evolutionary
36
37 92 distinctiveness, and number of species prioritized, cost and probability of project success. We also
38
39 93 examine the relationships between the total evolutionary distinctiveness weights of prioritized species (a
40
41 94 measure of the phylogenetic diversity conserved) and the number of species conserved, cost and
42
43 95 probability of project success. We examine these patterns using three alternative evolutionary
44
45 96 distinctiveness weights: an iteratively-updated method that accounts for endemism, an additional
46
47 97 iteratively-updated method that incorporates probability of extinction, and a static method that accounts
48
49 98 for threat level. Our aim is to derive efficient prioritization solutions that minimize the potential loss of
50
51 99 both phylogenetic and species diversity, recognizing the potential importance of conserving both aspects
52
53
54
55 100 of biodiversity.

56
57
58 101 **2. Methods**

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

102 *2.1. Dataset*

103 We designed prioritization scenarios using potential recovery projects for 700 of the most threatened
104 species in New Zealand, encompassing all species in New Zealand’s ‘Threatened’ and ‘At Risk’
105 categories that have declining populations (Hitchmough et al., 2005). Each species had an associated
106 ‘project’, which included the specific actions that, based on expert opinion, would be necessary to ensure
107 reasonable probability (~95%) of the species’ persistence over 50 years, as well the costs, assumed
108 benefits and probability of project success. The New Zealand government has used this dataset to help
109 prioritize budget allocations (NZ Department of Conservation, 2011), using a protocol developed by
110 Joseph et al. (2009). New Zealand represents an excellent test case for prioritization, as it is undergoing
111 an extinction crisis that may forecast future global patterns (Jenkins, 2003), and for which there is
112 currently insufficient funding to protect all threatened species.

113 *2.2. Prioritization Protocol*

114 We used the project prioritization protocol (PPP) framework of Joseph et al. (2009), which ranks the
115 efficiencies of threatened species projects based on species’ evolutionary distinctiveness weight, project
116 benefits to species, probabilities of project success, and cost:

$$E_i = \frac{W_i \times B_i \times S_i}{C_i} , \quad 1$$

117
118
119
120 where E_i is the project efficiency for species i ; W_i is the species’ evolutionary distinctiveness weight; B_i is
121 the project benefit to the species, defined as the difference between the estimated probabilities that a
122 species will be secure in 50 years with and without the project; S_i is the estimated probability of project
123 success; and C_i is the cost of all actions associated with the species project. Costs of actions that benefit
124 multiple species are shared among the beneficiaries. Values were assigned to B_i , S_i and C_i through

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

125 consultation with >100 threatened species experts. Further details regarding estimation of these
126 parameters are found in Joseph et al. (2009).

127 The prioritization process begins with all species being funded, then sequentially removes species with
128 the lowest project efficiencies until pre-determined targets for budget or number of species prioritised are
129 reached. At each stage, cost and phylogenetic weight parameters for remaining species are updated, both
130 of which may increase as species are excluded.

131 *2.3. Evolutionary distinctiveness weights (W_i)*

132 While a variety of methods exist for assigning species weights that incorporate evolutionary
133 distinctiveness (e.g. May, 1990; Vane-Wright et al., 1992; Redding and Mooers, 2006; Isaac et al., 2007),
134 a major distinction among them is whether they consider complementarity of the species group, updating
135 weights according to changes in the prioritized species list, or whether they statically assign
136 distinctiveness weights to species based on original conditions (Faith, 2008). We assessed the effects of
137 systematically increasing evolutionary distinctiveness weights on prioritization outcomes using both types
138 of weights and the following specific methods: 1) a measure developed for prioritization in New Zealand,
139 the ‘phylogeny, threat and endemism’ (PTE) method, which updates based on threat status changes as
140 species are removed from prioritization and emphasizes threatened endemics; 2) an additional method,
141 expected phylogenetic diversity (expected PD; Faith, 2008) that updates as species are removed from
142 prioritization and incorporates probabilities of extinction; and 3) the ‘evolutionary distinct and globally
143 endangered’ (EDGE) static method of Isaac et al. (2007). We chose the PTE method because it is
144 currently used in prioritization of species recovery programs in New Zealand and it updates weights
145 according to changes in the prioritized species list, and we chose the expected PD measure because it
146 demonstrates an alternative approach that incorporates estimates of extinction probabilities, and also
147 updates weights as species are removed from prioritization. For the sake of brevity, we present detailed
148 methods and results for expected PD in the Appendix. We chose EDGE because it is a static measure that

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

149 has been used extensively to demonstrate prioritization for large suites of species (e.g. Collen et al., 2011;
150 Isaac et al., 2012). In addition, these measures do not explicitly consider species ranges, which was a
151 necessary criterion since species ranges have not been fully characterized for many threatened New
152 Zealand species, particularly marine species that are difficult to survey. For all three measures, the lack of
153 a detailed phylogenetic tree across our diverse group of threatened species necessitated the use of species'
154 taxonomic relationships as a surrogate for evolutionary distinctiveness. Although this approach is less
155 precise than methods using phylogenetic branch lengths and thus may suffer from errors where taxonomy
156 inaccurately or imprecisely reflects phylogenetic relatedness (Cadotte and Davies, 2010), it has been
157 shown to be a reasonably robust measure of distinctiveness for conservation prioritization (Crozier et al.,
158 2005; Rodrigues et al., 2011).

159 The PTE method of evolutionary distinctiveness weighting was designed to fulfil the following criteria:
160 1) to account for threatened species within the same lineages, since risk to sister species increases risk to
161 phylogenetic lineages (Faith, 2008), and species with lineages containing many threatened species should
162 be weighted higher to help conserve a representative group of species; 2) to update values as species are
163 managed and threats change, rather than statically partition distinctiveness weight (e.g. Isaac et al., 2007);
164 and 3) to include endemism as an important consideration for threatened taxonomic groups, to reflect the
165 fact that a planning area (in our case, New Zealand) bears the responsibility for conserving the
166 evolutionary history of its endemic lineages.

167 The PTE method uses the following formula:

$$W_i = R_i \times M_i , \quad 2$$

169 where W_i is the evolutionary distinctiveness weight of species i . R_i (representativeness of species i) is
170 calculated as follows:

$$R_i = 1 + \sum_{z=s,g,f} T_{iz} \frac{A_{iz}}{B_{iz}} , \quad 3$$

1
2
3
4 172 where s , g and f are species, genus and family taxonomic levels; $T_{iz} = 1$ for each level if all taxa at this
5
6 173 level are threatened in the planning area and $T_{iz} = 0$ otherwise; A_{iz} is the number of threatened taxa at this
7
8 174 level, within the next-highest taxonomic level (for $z=s$, number of threatened species in the genus; for
9
10 175 $z=g$, number of threatened genera in the family; for $z=f$, number of threatened families in the order); and
11
12 176 B_{iz} is the total number of taxa at this level, within the next-highest taxonomic level (for $z=s$, the total
13
14 177 number of species in the genus, etc.). The addition of 1 to the summed proportion of threatened taxa
15
16 178 scales ensures $W_i \geq 1$ in Equation 1, allowing tests on evolutionary distinctiveness weight outlined below.
17
18 179 Thus, a species from a genus containing three species, two of which are threatened, would have $R_i = 1 +$
19
20 180 $2/3 + 0 + 0 = 1.66$, while the sole species from a genus in a family containing another genus that is secure
21
22 181 would have $R_i = 1 + 1/1 + 1/2 + 0 = 2.5$. This formula gives greater weight to threatened species from
23
24 182 lineages containing a greater proportion of threatened taxa, in recognition of the risk to the evolutionary
25
26 183 distinctiveness of these lineages. Species from more diverse lineages receive relatively low weight, unless
27
28 184 their lineages contain a high proportion of threatened taxa.
29
30
31
32
33

34 185 M_i is a multiplier for endemism of threatened taxa, which was added to recognize species that are
35
36 186 endemic to New Zealand, and thus wholly dependent on the planning area for survival:
37
38

$$39 \quad M_i = 1 + \sum_{z=s,g,f} U_{iz}, \quad 4$$

40
41
42 188 where $U_{iz} = 1$ if all threatened taxa at a given level are endemic to the planning area. Thus, an endemic
43
44 189 species whose entire genus is threatened and endemic, but whose family is not endemic, would have $M_i =$
45
46 190 $1 + 1 + 1 + 0 = 3$, while a threatened non-endemic species would have $M_i = 1 + 0 + 0 + 0 = 1$. When
47
48 191 calculating the initial W_i for a given species, closely-related species that are retained in the prioritized list
49
50 192 are considered to be managed and therefore secure. However, species' W_i are re-calculated with each
51
52 193 iteration of the prioritization algorithm. As species are dropped from the prioritized list, they are
53
54 194 considered threatened and W_i for remaining species are updated accordingly.
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 195 EDGE weighting was designed to prioritize species by both evolutionary distinctiveness and threat level
5
6 196 (Isaac et al., 2007). We calculated EDGE weights using the following formula:

$$10 \quad 197 \quad W_i = 1 + EDGE_i \quad , \quad 5$$

11
12 198 where W_i is the EDGE measure of evolutionary distinctiveness weight of species i , with a value of 1
13
14 199 added to scale the minimum W_i to 1. EDGE assigns static, one-time species weights based on the
15
16
17 200 following formula:

$$20 \quad 201 \quad EDGE_i = \ln(1 + ED_i) + GE_i \times \ln(2) \quad , \quad 6$$

21
22
23 202 where ED_i is the evolutionary distinctiveness of species i , calculated as the sum of all branch lengths
24
25 203 divided for each branch by the number of subtended species (Isaac et al., 2007), and GE_i is the threat
26
27 204 status of the species, assigned a number of one to four. We used New Zealand threat categories
28
29
30 205 (Hitchmough et al., 2005, 2012; see Appendix Table A1 for details) instead of the IUCN Red List
31
32 206 Categories used by Isaac et al. (2007) because some New Zealand species have not yet been ranked by the
33
34 207 IUCN. Since we were using taxonomic relationships as a surrogate for phylogenetic relationships, branch
35
36 208 lengths were assumed to be one. As opposed to the original EDGE approach that uses EDGE as the sole
37
38
39 209 criterion in developing proposed species priority lists, we incorporated EDGE-based W_i into the Joseph et
40
41 210 al. (2009) prioritization framework in Equation 1 above.

44 211 *2.4. Tests on evolutionary distinctiveness weight*

45
46
47 212 We examined the trade-offs incurred when the emphasis on evolutionary distinctiveness weight of
48
49 213 individual species is systematically increased vis-à-vis other parameters, and when the total
50
51 214 distinctiveness weight conserved by the prioritized species (a measure of the phylogenetic diversity
52
53 215 conserved) increases. To do so, we ran sets of prioritization protocols that progressively increased the
54
55
56 216 emphasis on species' W_i in Equation 1 using an exponent:

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

$$E_i = \frac{W_i^{x \times B_i \times S_i}}{C_i},$$

7

217 where x is the exponent used to emphasize evolutionary distinctiveness weight in prioritization iterations.
218 Increasing x increased the emphasis on evolutionary distinctiveness weight in the prioritization protocol,
219 allowing us to efficiently test scenarios ranging from no consideration of distinctiveness to strong
220 emphasis on distinctiveness weights. The exponent was incrementally increased from zero to five, in
221 increments of 0.125 from zero to one, and 0.25 from one to five, and the prioritization protocol was run at
222 each increment. An exponent of zero represents no consideration of evolutionary distinctiveness weight
223 (x=0 so $W_i^x = 1$ for all species i); an exponent of one represents emphasis on distinctiveness weight as
224 calculated in Equation 1; an exponent of five strongly favours species with larger distinctiveness weights.
225 Increasing x also increased the total evolutionary distinctiveness weight conserved by the prioritized
226 species group (calculated as the sum of W_i for all prioritized species), allowing us to explore potential
227 trade-offs in phylogenetic diversity conserved versus number of species prioritized and mean probability
228 of project success.
229

230 We ran this analysis for W_i based on PTE, EDGE, and expected PD, using two budget scenarios: 1) a
231 fixed maximum annual budget of \$30M NZD, which reflects recent budgets allocated by the New
232 Zealand government for conserving threatened species (NZ DOC, 2013); and 2) a flexible budget to
233 ensure a prioritization target of 300 species, which is the number of species currently prioritized for
234 management by the New Zealand Department of Conservation (NZ DOC, 2012). Analyses were
235 conducted using R v. 2.15.2 (R Development Core Team, 2012); data and code are available on request
236 from the corresponding author. For the \$30M scenarios we plotted the exponent on W_i and total
237 distinctiveness weight (summed W_i of prioritized species) versus number of species prioritized and mean
238 probability of project success. For the 300 species scenarios, we plotted the exponent on W_i and total
239 distinctiveness weight versus total annual budget and mean probability of project success. To compare
240 these results with those obtained considering only evolutionary distinctiveness weight, we also ran the

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

241 prioritization protocol for \$30M and 300 species constraints using only W_i to rank species ignoring cost
242 and feasibility. In addition, to determine whether results might be influenced by dependencies among
243 input variables, we examined relationships among input variables using linear models.

244 3. Results

245 3.1. \$30M budget scenario

246 As we increased the emphasis on individual species' distinctiveness weights (i.e., increased x in Equation
247 7), the number of species prioritized for a \$30M budget progressively decreased for PTE, EDGE and
248 expected PD methods, while the total distinctiveness weight conserved initially increased (Fig. 1;
249 Appendix, Fig. A1). However, for the PTE method total distinctiveness weight conserved reached an
250 asymptote, after which relatively constant total distinctiveness weight was conserved in progressively
251 fewer species (Fig. 1c). For EDGE and expected PD, gains in total distinctiveness weight were reversed
252 when the emphasis on evolutionary distinctiveness of species rose to a certain level ($x = 3.75$ for EDGE),
253 as increases due to more distinct species being prioritized could not compensate for losses due to fewer
254 species being prioritized (Fig. 1d; Appendix, Fig. A1, Table A2). This difference between the methods
255 occurred because dropped species in the PTE method are assumed to not contribute to future phylogenetic
256 diversity, and thus weights increase more than for EDGE (which is static), or expected PD (for which the
257 additional weight in retained species is multiplied by the extinction probabilities of all related dropped
258 species). Retention of species with greater complementarity in PTE thus helped to compensate for loss of
259 total PTE distinctiveness weight as species were dropped. At each successive increase (via exponent x) on
260 species' W_i , newly-retained species at this level contributed a mean of 13.0 (± 1.4 SE) to the total PTE
261 weight. Mean PTE weight of these species prior to updating when others were removed was 3.4 (± 0.3
262 SE).

263 For PTE, an exponent on W_i of 1.25 offered the best compromise between maximum species retained and
264 maximum total distinctiveness weight conserved, with 296 species retained (versus a maximum across all

1
2
3
4 265 iterations of 301 species), and total PTE weight of 581 (versus a maximum of 603; Fig 1e). For EDGE, an
5
6 266 exponent on W_i of 1.5 offered the best compromise, with 305 species retained (versus a maximum across
7
8
9 267 all iterations of 306 species), and total EDGE weight of 722 (versus a maximum of 724; Fig 1f). For all
10
11 268 methods, mean probability of project success for prioritized species was lowest at the highest degree of
12
13 269 emphasis on W_i (Appendix, Fig. A2). The iterations offering the largest combined proportion of
14
15 270 maximum species retained and total distinctiveness weight conserved also offered an optimal or near-
16
17 271 optimal compromise with mean probability of project success (Appendix, Table A2).
18
19
20
21 272 For PTE and EDGE methods, correlations among input variables were non-significant or trivial
22
23 273 (Appendix, Table A3), and thus results for both the \$30M and 300 species scenario were not dependent
24
25 274 on relationships among input variables. However, expected PD was highly correlated with the benefit
26
27 275 parameter B (the difference between estimated probabilities that species will be secure with and without
28
29 276 their projects), because its formula incorporated B_i from Equation 1 as an estimate of extinction
30
31 277 probability (Appendix, Table A3).
32
33
34

35 278 3.2. 300 species scenario

36
37
38 279 With a fixed target of 300 species prioritized, increased emphasis on individual species' evolutionary
39
40 280 distinctiveness weight and increased total distinctiveness weight conserved were both accompanied by
41
42 281 increased annual budget and decreased mean probability of success (Fig. 2 Appendix, Fig. A3, A4). For
43
44 282 the EDGE method, a 21% increase in estimated annual cost from \$36.9 million to \$44.8 million (for a
45
46 283 1.3% increase in total distinctiveness weight) occurred when the exponent on W_i increased from 3.5 to
47
48 284 3.75. This cost increase was driven largely by the addition of the critically-endangered shrub
49
50 285 *Carmichaelia carmichaeliae*, which contributed ~50% of the added cost and ~20% of the total
51
52 286 evolutionary distinctiveness weight of the five species added at this level.
53
54
55
56

57 287 As the degree of emphasis on W_i increased, total distinctiveness weight conserved by the 300 retained
58
59 288 species reached an asymptote for the PTE method, but continued to increase for EDGE (Fig. 2). This was
60
61
62
63
64
65

1
2
3
4 289 due to two differences in how the distinctiveness weights are calculated. In the PTE method, updating of
5
6 290 distinctiveness weight for retained species meant that species added as emphasis on W_i increased
7
8 291 contributed diminishing additional distinctiveness weight to the complementary core group of species
9
10 292 (Appendix, Fig. A5). However, the static partitioning of distinctiveness weight in EDGE meant that
11
12 293 complementarity of species groups was not considered. In addition, the influence of threat level in EDGE
13
14 294 calculation resulted in greater numbers of critically endangered species being prioritized as the degree of
15
16 295 emphasis on W_i increased (Appendix, Fig. A4), with total EDGE distinctiveness weight increasing
17
18 296 accordingly. Results for the expected PD method were intermediate between the PTE and EDGE methods
19
20 297 (Appendix, Fig. A3, A5).
21
22
23
24

25 298 For the 300 species scenario, total distinctiveness weight conserved per dollar spent was optimal at
26
27 299 intermediate levels of total distinctiveness weight. The optimum value for PTE, the was 19.7 PTE units
28
29 300 per million NZD at an exponent on W_i of 1.3, while for EDGE it was 24.5 EDGE units per million NZD
30
31 301 at an exponent of 1.5 (Appendix, Table A4).
32
33
34

35 302 *3.3. W_i -only rankings*

36
37

38 303 For PTE, EDGE and expected PD \$30M scenarios, species rankings using only W_i resulted in
39
40 304 considerably lower total evolutionary distinctiveness weight conserved, numbers of species conserved and
41
42 305 mean probabilities of success than any of the runs considering other factors (Appendix, Table A5).
43
44

45 306 Scenarios for 300 species using only W_i resulted in the maximum total weight that could be conserved in
46
47 307 300 ranked species (Appendix, Table A5). However, mean probabilities of success were low, and annual
48
49 308 budgets were nearly four times recent annual budgets for conserving threatened species in the planning
50
51 309 area (NZ DOC, 2013).
52
53

54 310 **4. Discussion**

55
56

57 311 Given limited funding, there is potential tension between conservation objectives emphasizing either the
58
59 312 number of species secured or phylogenetic diversity conserved. Within the objective of maximizing
60
61
62
63
64
65

1
2
3
4 313 phylogenetic diversity conserved, there is also potential tension between prioritizing species according to
5
6 314 their evolutionary distinctiveness weights, and maximizing the total distinctiveness (i.e., phylogenetic
7
8 315 diversity) among all prioritized species (Faith, 2008). We examined trade-offs among these objectives
9
10 316 using a dataset of 700 of New Zealand's most threatened species that has been used to prioritize funding
11
12 317 for conservation projects. Our tests used three types of evolutionary distinctiveness weights, and included
13
14 318 the additional realistic constraints of project costs, benefits and probabilities of success.
15
16
17
18 319 Our tests showed that increasing the emphasis on the distinctiveness weight of individual species in
19
20 320 prioritization leads to sacrifices the number of species that can be managed with a fixed budget. These
21
22 321 sacrifices limited the total distinctiveness weight that could be conserved in a chosen suite of species, as
23
24 322 the addition of more distinct (and more expensive) species was offset by the removal of greater numbers
25
26 323 of less distinct species. Fortunately, the trade-off between total distinctiveness weight conserved and
27
28 324 number of species that could be managed for a set budget was convex for all methods of measuring
29
30 325 distinctiveness weight, and near-optimal total distinctiveness weight could be retained while retaining a
31
32 326 near-optimal total number of species. In scenarios where a fixed number of species was chosen regardless
33
34 327 of budget, costs increased as individual species' weight was given greater priority, especially at the
35
36 328 highest level of emphasis, for which relatively small increases in total distinctiveness weight conserved
37
38 329 were often accompanied by large budget increases.
39
40
41
42
43
44 330 There are strong arguments for considering the importance of evolutionary history in prioritizing the
45
46 331 conservation of species (Cadotte et al., 2010; Collen et al., 2011). Prioritizing species according to
47
48 332 weights based on evolutionary distinctiveness may help to conserve the functional diversity of life,
49
50 333 including its resilience to environmental change, and its genetic capacity to evolve as new conditions arise
51
52 334 (Vane-Wright et al., 1991; Cadotte and Davies, 2010). Indeed, where resources are limited and
53
54 335 conserving phylogenetic diversity is the primary consideration, a potentially attractive approach could be
55
56 336 prioritizing the minimum number of species necessary to achieve near-maximum attainable total
57
58 337 distinctiveness weight, thereby allowing more focussed, efficient conservation efforts.
59
60
61
62
63
64
65

1
2
3
4 338 However, such an approach has three potential flaws. First, it relies on an accurate quantification of
5
6 339 phylogeny and distinctiveness. In our case, realistic prioritization across a full suite of threatened species
7
8 340 necessitated the use of taxonomic relationships as a proxy for phylogenetic relationships. While this
9
10 341 technique may be useful for conservation prioritization (Crozier et al., 2005; Rodrigues et al., 2011), it is
11
12 342 also accompanied by considerable uncertainty. Even meticulously constructed phylogenies are subject to
13
14 343 debate and revision (e.g. Wiens et al., 2010; Pagel, 2012). Second, the link between functional and
15
16 344 phylogenetic diversity is strong in some cases (e.g. Cadotte et al., 2008), but not in others (e.g. Kluge and
17
18 345 Kessler, 2010), potentially weakening the argument for conserving phylogenetic diversity as a proxy for
19
20 346 functional diversity (Winter et al., 2012). Third, positive relationships between evolutionary
21
22 347 distinctiveness and extinction probability for some groups (Redding and Mooers, 2006; Vamosi and
23
24 348 Wilson, 2008) but not others (Verde Arregoitia et al., 2013), indicate that the link between phylogenetic
25
26 349 distinctiveness and ability to adapt to emerging conditions is unclear. In addition, highly-radiated lineages
27
28 350 sometimes show remarkable adaptability to change (Schluter, 2001, Seehausen, 2004).
29
30
31
32
33
34 351 Including evolutionary distinctiveness weight in prioritization schemes also introduces an additional
35
36 352 parameter that must be traded off with other important considerations. In our prioritization scenarios,
37
38 353 increasing emphasis on distinctiveness weight was generally accompanied by increases in cost and
39
40 354 decreases in mean probability of project success across species. Lower probabilities of project success
41
42 355 indicate greater risk that some species, and their associated evolutionary distinctiveness, may be lost
43
44 356 despite being prioritized for management intervention.
45
46
47
48 357 Exploring a range of emphasis on distinctiveness weight allowed us to find species combinations that
49
50 358 were a useful compromise between species-based and phylogenetic approaches. For the PTE method with
51
52 359 a \$30M budget, the prioritized suite of species that offered the best compromise between the number of
53
54 360 species prioritized and total distinctiveness weight conserved represented 98% of the maximum species
55
56 361 number and 96% of the maximum total distinctiveness weight attained across all iterations. For EDGE
57
58 362 and expected PD, the compromise group represented ~99% of the maximum number of species and
59
60
61
62
63
64
65

1
2
3
4 363 maximum total distinctiveness weight of all iterations. Where our goal was to conserve 300 species,
5
6 364 exploring the range of emphases on distinctiveness weights revealed a useful compromise between total
7
8 365 distinctiveness weight conserved and money spent. Given the potential benefits and uncertainties in either
9
10 366 a phylogenetic or species-based approach, we suggest that exploring a range of possible compromises is
11
12 367 preferable to using either approach in isolation. While extreme approaches strongly emphasizing species
13
14 368 numbers sacrificed conserved distinctiveness weight, and extreme approaches emphasizing
15
16 369 distinctiveness weight sacrificed species numbers, the optimal combinations of both approaches were
17
18 370 near-optimal for both distinctiveness weight and number of species prioritized.
19
20
21
22
23 371 Despite broad agreement among tests using PTE, EDGE and expected PD on compromises between
24
25 372 species numbers and evolutionary distinctiveness weight, there were differences in results among the
26
27 373 methods that were indicative of the contrasting ways in which each method calculates distinctiveness
28
29 374 weight. The PTE method explicitly includes complementarity based on threats to related species and
30
31 375 updates this measure as species are dropped from prioritization, while EDGE statically partitions
32
33 376 distinctiveness weight. Expected PD is intermediate between PTE and EDGE. It updates weights as
34
35 377 species are dropped; however, it multiplies the contributions of dropped species to retained species'
36
37 378 updated weights by the dropped species' probabilities of extinction. For the \$30M scenario and the PTE
38
39 379 method, species losses at higher emphases on distinctiveness weight were compensated by increased
40
41 380 weight assigned to retained species. This did not occur for EDGE or expected PD.
42
43
44
45
46 381 As noted by Faith (2008), static partitioning without considering complementarity may lead to inefficient
47
48 382 prioritization. Permanent assignment of low priority to species from a diverse lineage may mean that no
49
50 383 species from such a lineage is prioritized, putting the entire lineage at risk. Likewise, permanent
51
52 384 assignment of high priority to all species from a highly-distinct lineage would not reflect the total
53
54 385 phylogenetic diversity at risk once one or more species in the lineage are made secure. For example, Isaac
55
56 386 et al. (2012) derived a global EDGE-based prioritization list for threatened amphibians, of which the top
57
58 387 five species were in the genus *Epicrionops*. If one or more of these species were protected to the point
59
60
61
62
63
64
65

1
2
3
4 388 where the highly-distinct *Epicrionops* genus itself was safe, the other *Epicrionops* species could move
5
6 389 down the list of priorities if threats to other lineages posed greater threat to global phylogenetic diversity.
7
8
9
10 390 In addition, if non-prioritized threatened species are likely to go extinct, the importance of secure species
11
12 391 to the survival of lineages may be misconstrued if evolutionary distinctiveness weights are not updated to
13
14 392 reflect the insecurity of the non-prioritized species. Updating based on complementarity and threat in the
15
16 393 PTE method is therefore prudent in that it assumes non-prioritized threatened species may not contribute
17
18 394 to future diversity, and responsibility for persistence of phylogenetic diversity rests with prioritized or
19
20 395 non-threatened relatives. Although non-prioritized species may still persist without management, their
21
22 396 continued survival and the persistence of their associated evolutionary distinctiveness cannot be assumed.
23
24
25 397 The expected PD method offers a less conservative approach, by considering extinction probabilities for
26
27 398 dropped species. Depending on the timescale of planning and the perception of accuracy in extinction
28
29 399 probability estimates, either technique may be appropriate.
30
31
32
33 400 Another key difference among the PTE, EDGE and expected PD methods is that PTE calculations
34
35 401 consider endemism of threatened taxa. Again, this is a cautious, prudent approach, especially in the New
36
37 402 Zealand context. Though ideally conservation efforts should be prioritized globally (Wilson et al., 2006;
38
39 403 Brooks et al., 2006), individual planning areas routinely bear the burden of conserving their threatened
40
41 404 species, and therefore the responsibility for survival of their endemics. As a centre of endemism
42
43 405 (Mittermeier et al., 1998; Wallis and Trewick, 2009), New Zealand bears a disproportionate responsibility
44
45 406 for conserving threatened endemics. By weighting prioritization towards threatened endemic taxa, the
46
47 407 PTE method helps to prioritize the only chance of survival for these lineages.
48
49
50
51 408 In other planning areas, where threatened species ranges cross political boundaries, the strategy for
52
53 409 considering endemism may need to be more nuanced. For example, Cofré and Marquet (1999) included
54
55 410 an ordinal measure of endemism in a ranking system for species conservation, with species found in
56
57 411 fewer countries receiving a higher endemism score. In some cases, species may not be endemic to a
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

412 planning area, but may be shared with areas lacking environmental protection, where their survival cannot
413 be assumed (e.g. Abbitt et al., 2000). In such cases, managers may still wish to weight such species as if
414 they were endemic in prioritization protocols. Finally, there may be ecological, social or political
415 considerations that can influence weighting of species in either quantitative or informal prioritization
416 processes. For example, there may be strong impetus for preserving keystone species (Soulé et al., 2005),
417 iconic species (Schwartz, 2008), or those that are economically important or part of cultural traditions
418 (Rodríguez et al., 2004).

419 **5. Conclusion**

420 The earth is experiencing a biodiversity crisis for which current funding and political will is sufficient to
421 do little more than attenuate (Butchart et al., 2010; McCarthy et al., 2012). Thus, scarce resources must be
422 prioritized to focus on projects that minimize biodiversity loss within current constraints (Bottrill et al.,
423 2008). Since the unique genetic information contained in threatened species is valuable from both
424 practical and philosophical standpoints (Cadotte et al., 2010), it is important to include evolutionary
425 distinctiveness weights in prioritizing threatened species for conservation. Indeed, as detailed
426 understanding of phylogenetic relationships among species improves, there may be increasing incentive at
427 global and local levels to explicitly rank species according to their evolutionary distinctiveness.

428 However, species' evolutionary distinctiveness is not the only consideration: other aspects such as cost
429 and probability of project success must be taken into account. Given that there are still many uncertainties
430 in phylogenetic trees as well as links between evolutionary distinctiveness and potential adaptive ability,
431 it is also prudent to seek a balance between a phylogenetic and species-based approach. For better or
432 worse, 'species' is also the currency with which governments and conservation agencies often measure
433 conservation progress. Conservation planners have been slow to incorporate evolutionary distinctiveness
434 into prioritization schemes (Collen et al., 2011; Isaac et al., 2007; 2012), perhaps due to a perceived lack
435 of compelling justification for phylogenetic approaches (Winter et al., 2012), or continued allegiance to

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

436 traditional methods. As we have shown, a combined approach that minimizes loss in both species and
437 phylogenetic diversity is possible.

438 **Acknowledgements**

439 We thank Shaun O’Connor, Jodie Densem, Katherine Gareau, Simone Cleland, Pete Corson, Nick
440 Singers, Colin O’Donnell, Peter de Lange, Rod Hitchmough, Debbie Freeman, Warren Chinn, Don
441 Newman and the dedicated work of the more than 100 threatened species experts for their support in
442 parameterizing the prioritization protocol. This research was conducted with the support of funding from
443 the Australian Government’s National Environmental Research Program, the Australian Research
444 Council Centre of Excellence for Environmental Decisions, the New Zealand Department of
445 Conservation, the Cedar Tree Foundation and the David H. Smith Conservation Research Fellowship
446 Program. Two anonymous referees provided constructive comments that improved the quality of this
447 paper.

448 **References**

449 Abbitt, R. J. F., Scott, J. M., Wilcove, D. S. 2000. The geography of vulnerability: incorporating
450 species geography and human development patterns into conservation planning. *Biol.*
451 *Cons.* 96, 169-175. (doi:10.1016/S0006-3207(00)00064-1)

452 Bottrill, M. C. Joseph, L. N., Carwardine, J., Bode, M., Cook, C., Game, E. T., Grantham,
453 H., Kark, S., Linke, S., McDonald-Madden, E., Pressey, R. L., Walker, S., Wilson, K. A.,
454 Possingham, H. P. 2008. Is conservation triage just smart decision making? *Trends Ecol.*
455 *Evol.* 23, 649–54. (doi:10.1016/j.tree.2008.07.007)

456 Brooks, T. M., Mittermeier, R. A., da Fonseca, G. A. B., Gerlach, J., Hoffmann, M., Lamoreux,
457 J. F., Mittermeier, C. G., Pilgrim, J. D., Rodrigues, A. S. L. 2006. Global biodiversity
458 conservation priorities. *Science* 313, 58–61. (doi:10.1126/science.1127609)

459 Butchart, S. H. M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J. P. W., Almond, R.
460 E. A., Baillie, J. E. M., Bomhard, B. Brown, C. Bruno, J., Carpenter, K. E., Carr, G. M.,
461 Chanson, J., Chenery, A. M., Csirke, J., Davidson, N. C., Dentener, F., Foster, M., Galli,
462 A., Galloway, J. N. Genovesi, P., Gregory, R. D., Hockings, M., Kapos, V., Lamarque, J.-
463 F., Leverington, F., Loh, J. McGeoch, M. A., McRae, L., Minasyan, A., Hernández
464 Morcillo, M., Oldfield, T. E. E., Pauly, D. Quader, S., Revenga, C., John R. Sauer, J. R.,

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

465 Skolnik, B., Spear, D., Stanwell-Smith, D., Stuart, S. N., Symes, A., Tierney, M., Tyrrell,
466 T. D., Vié, J.-C., Watson, R. 2010. Global biodiversity: indicators of recent declines.
467 Science 328, 1164–8. (doi:10.1126/science.1187512)

468 Cadotte, M. W. and Davies, J. T. 2010. Rarest of the rare: advances in combining evolutionary
469 distinctiveness and scarcity to inform conservation at biogeographical scales. *Divers.*
470 *Distrib.* 16, 376–385. (doi:10.1111/j.1472-4642.2010.00650.x)

471 Cadotte, M. W., Cardinale, B. J., Oakley, T. H. 2008. Evolutionary history and the effect of
472 biodiversity on plant productivity. *Proc. Natl. Acad. Sci. USA* 105, 17012–7.
473 (doi:10.1073/pnas.0805962105)

474 Carter, M. F., Hunter, W. C., Pashley, D. N., Rosenberg, K. V. 2000. setting conservation
475 priorities for landbirds in the united states : the partners in flight approach. *Auk* 117,
476 541–548. (doi: 10.1642/0004-8038(2000)117[0541:SCPFLI]2.0.CO;2)

477 Cofré, H., Marquet, P. A. 1999. Conservation status, rarity, and geographic priorities for
478 conservation of Chilean mammals: an assessment. *Biol. Cons.* 88, 53-68.
479 (doi:10.1016/S0006-3207(98)00090-1)

480 Collen, B., Turvey, S. T., Waterman, C., Meredith, H. M. R., Kuhn, T. S., Baillie, J. E. M., Isaac,
481 N. J. B. 2011. Investing in evolutionary history: implementing a phylogenetic approach
482 for mammal conservation. *Phil.Trans. R. Soc. B* 366, 2611–22.
483 (doi:10.1098/rstb.2011.0109)

484 Crozier, R. H. 1997. Preserving the Information Content of Species: Genetic and Conservation
485 Phylogeny. *Ann. Rev. Ecol. Syst.* 28, 243–268. (doi:10.1234/12345678)

486 Crozier, R. H., Dunnett, L. J., Agapow, P-M. 2005. Phylogenetic biodiversity assessment based
487 on systematic nomenclature. *Evol. Bioinform. Online* 1, 11–36.

488 Davies, T. J. and Buckley, L. B. 2011. Phylogenetic diversity as a window into the evolutionary
489 and biogeographic histories of present-day richness gradients for mammals. *Phil.Trans. R.*
490 *Soc. B* 366, 2414–25. (doi:10.1098/rstb.2011.0058)

491 Faith, D. P. 1992. Conservation evaluation and phylogenetic diversity. *Biol. Cons.* 61, 1–10.
492 (doi:10.1016/0006-3207(92)91201-3)

493 Faith, D. P. 2008. Threatened species and the potential loss of phylogenetic diversity:
494 conservation scenarios based on estimated extinction probabilities and phylogenetic risk
495 analysis. *Conserv. Biol.* 22, 1461–70. (doi:10.1111/j.1523-1739.2008.01068.x)

496 Gaston, K. and Blackburn, T. M. 1997. Evolutionary age and risk of extinction in the global
497 avifauna. *Evol. Ecol.* 11, 557–565. (doi: 10.1007/s10682-997-1511-4)

1
2
3
4 498 Hitchmough, R. 2012. The revised New Zealand Threat Classification System. New Zealand
5 499 Department of Conservation, Wellington, NZ.
6
7
8 500 Hitchmough, R., Bull, L., Cromarty, P. 2005. New Zealand Threat Classification System Lists.
9 501 New Zealand Department of Conservation, Wellington, NZ.
10
11
12 502 Isaac, N. J. B., Turvey, S. T., Collen, B., Waterman, C., Baillie, J. E. M. 2007. Mammals on the
13 503 EDGE: conservation priorities based on threat and phylogeny. *PloS ONE* 2, e296.
14 504 (doi:10.1371/journal.pone.0000296)
15
16 505 Isaac, N. J. B., Redding, D. W., Meredith, H. M., Safi, K. 2012. Phylogenetically-informed
17 506 priorities for amphibian conservation. *PloS ONE* 7, e43912.
18 507 (doi:10.1371/journal.pone.0043912)
19
20
21 508 IUCN. 2013. Red List Overview. <http://www.iucnredlist.org/about/red-list-overview>. 28 June
22 509 2013.
23
24
25 510 Jenkins, M. 2003. Prospects for biodiversity. *Science* 302, 1175–7.
26 511 (doi:10.1126/science.1088666)
27
28
29 512 Joseph, L. N., Maloney, R. F., Possingham, H. P. 2009. Optimal allocation of resources among
30 513 threatened species: a project prioritization protocol. *Conserv. Biol.* 23, 328–38.
31 514 (doi:10.1111/j.1523-1739.2008.01124.x)
32
33
34 515 Kluge, J. and Kessler, M. 2011. Phylogenetic diversity, trait diversity and niches: species
35 516 assembly of ferns along a tropical elevational gradient. *J. Biogeog.* 38, 394–405.
36 517 (doi:10.1111/j.1365-2699.2010.02433.x)
37
38
39 518 Laycock, H. F., Moran, D., Smart, J. C. R., Raffaelli, D. G., White, P. C. L. 2011. Evaluating the
40 519 effectiveness and efficiency of biodiversity conservation spending. *Ecol. Econ.* 70, 1789–
41 520 1796. (doi:10.1016/j.ecolecon.2011.05.002)
42
43
44 521 Marsh, H., Dennis, A., Hines, H., Kutt, A., McDonald, K., Weber, E., Williams, S., Winter, J.
45 522 2007. Optimizing allocation of management resources for wildlife. *Conserv. Biol.* 21,
46 523 387–99. (doi:10.1111/j.1523-1739.2006.00589.x)
47
48
49 524 Martín-López, B., Montes, C., Ramírez, L., Benayas, J. 2009. What drives policy decision-
50 525 making related to species conservation? *Biol. Cons.* 142, 1370–1380.
51 526 (doi:10.1016/j.biocon.2009.01.030)
52
53
54 527 Master, L. 1991. Assessing threats and setting priorities for conservation. *Conserv. Biol.* 5, 559–
55 528 563. (doi: 10.1111/j.1523-1739.1991.tb00370.x)
56
57 529 May, R. 1990. Taxonomy as destiny. *Nature* 347, 129–130. (doi:10.1038/347129a0)
58
59
60
61
62
63
64
65

- 1
2
3
4 530 McCarthy, D. P. Donald, P. F., Scharlemann, J. P. W., Buchanan, G. M., Balmford, A., Green, J.
5 531 M. H., Bennun, L. A., Burgess, N. D., Fishpool, L. D. C., Garnett, S. T., Leonard, D. L.,
6 532 Maloney, R. F., Morling, P., Schaefer, H. M., Symes, A., Wiedenfeld, D. A., Butchart, S.
7 533 H. M. 2012. Financial costs of meeting global biodiversity conservation targets: current
8 534 spending and unmet needs. *Science* 338, 946–9. (doi:10.1126/science.1229803)
9
10
11 535 Mittermeier, R., Myers, N., Thomsen, J. B., da Fonseca, G. A. B., Olivieri, S. 1998. Biodiversity
12 536 hotspots and major tropical wilderness areas: approaches to setting conservation priorities.
13 537 *Conserv. Biol.* 12, 516–520. (10.1046/j.1523-1739.1998.012003516.x)
14
15
16 538 NZ Department of Conservation. 2011. New Zealand Department of Conservation Statement of
17 539 Intent 2011-2014. New Zealand Department of Conservation, Wellington, NZ.
18
19
20 540 NZ Department of Conservation. 2012. New Zealand Department of Conservation Statement of
21 541 Intent 2012-2017. New Zealand Department of Conservation, Wellington, NZ.
22
23
24 542 NZ Department of Conservation. 2013. New Zealand Department of Conservation Annual
25 543 Reports Archive. <http://www.doc.govt.nz/publications/about-doc/archive/annual-reports/>.
26 544 15 June 2013.
27
28
29 545 Pagel, M. 2012. First steps for birds. *Nature* 491, 337. (doi: 10.1038/nature11642).
30
31 546 R Development Core Team. 2012. R: a language and environment for statistical computing.
32 547 Vienna, Austria: R Foundation for Statistical Computing.
33
34
35 548 Redding, D. W. and Mooers, A. Ø. 2006. Incorporating evolutionary measures into conservation
36 549 prioritization. *Conserv. Biol.* 20, 1670–16788. (doi:10.1111/j.1523-1739.2006.00555.x)
37
38
39 550 Rodrigues, A. S. L., Grenyer, R., Baillie, J. E. M., Bininda-Emonds, O. R. P., Gittlemann, J. L.,
40 551 Hoffmann, M., Safi, M. K., Schipper, J., Stuart, S. N., Brooks, T. 2011. Complete,
41 552 accurate, mammalian phylogenies aid conservation planning, but not much. *Phil.Trans. R.*
42 553 *Soc. B* 366, 2652–60. (doi:10.1098/rstb.2011.0104)
43
44
45 554 Rodríguez, J. P., Rojas-Suárez, F., Sharpe, C. J. 2004. Setting priorities for the conservation of
46 555 Venezuela's threatened birds. *Oryx* 38, 373–382. (doi:10.1017/S0030605304000730)
47
48
49 556 Rosauer, D., Laffan, S. W., Crisp, M. D., Donnellan, S. C., Cook, L. G. 2009. Phylogenetic
50 557 endemism: a new approach for identifying geographical concentrations of evolutionary
51 558 history. *Mol. Ecol.* 18, 4061–4072. (doi: 10.1111/j.1365-294X.2009.04311.x)
52
53
54 559 Schluter, D. 2001. Ecology and the origin of species. *Trends Ecol. Evol.* 16, 372–380. (doi:
55 560 10.1016/S0169-5347(01)02198-X).
56
57 561 Schwartz, M. W. 2008. The Performance of the Endangered Species Act. *Annu. Rev. Ecol. Evol.*
58 562 *Syst.* 39, 279-299. (doi:10.1146/annurev.ecolsys.39.110707.173538)
59
60
61
62
63
64
65

1
2
3
4 563 Seehausen, O. 2004. Hybridization and adaptive radiation. *Trends Ecol. Evol.* 19, 198–207.
5 564 (doi:10.1016/j.tree.2004.01.003)
6
7
8 565 Soulé, M., E., Estes, J. A., Miller, B., Honnold, D. L. 2005. Strongly Interacting Species:
9 566 Conservation Policy, Management, and Ethics. *BioScience* 55, 168-176.
10 567 (doi:10.1641/0006-3568(2005)055[0168:SISCPM]2.0.CO;2)
11
12
13 568 Vamosi, J. C. and Wilson, J. R. U. 2008. Nonrandom extinction leads to elevated loss of
14 569 angiosperm evolutionary history. *Ecol. Lett.* 11, 1047–53. (doi:10.1111/j.1461-
15 570 0248.2008.01215.x)
16
17
18 571 Vane-Wright, R. I., Humphries, C. J., Williams, P. H. 1991. What to protect?—Systematics and
19 572 the agony of choice. *Biol. Cons.* 55, 235–254. (doi:10.1016/0006-3207(91)90030-D)
20
21 573 Verde Arregoitia, L. D., Blomberg, S. P., Fisher, D. O. 2013. Phylogenetic correlates of
22 574 extinction risk in mammals: species in older lineages are not at greater risk. *Proc. R. Soc.*
23 575 *Lond. B.* 280, 20131092. (doi:10.1098/rspb.2013.1092)
24
25
26 576 Wallis, G. P. and Trewick, S. A. 2009. New Zealand phylogeography: evolution on a small
27 577 continent. *Mol. Ecol.* 18, 3548–80. (doi:10.1111/j.1365-294X.2009.04294.x)
28
29
30 578 Wiens, J. J., Pyron, R. A., Moen, D. S. 2010. Niche conservatism as an emerging principle in
31 579 ecology and conservation biology. *Ecol. Lett.* 13, 1310–24. (doi:10.1111/j.1461-
32 580 0248.2010.01515.x)
33
34
35 581 Wilson, H. B., Joseph, L. N., Moore, A. L., Possingham, H. P. 2011. When should we save the
36 582 most endangered species? *Ecol. Lett.* 14, 886–90. (doi:10.1111/j.1461-
37 583 0248.2011.01652.x)
38
39
40 584 Wilson, K. A., McBride, M. F., Bode, M., Possingham, H. P. 2006. Prioritizing global
41 585 conservation efforts. *Nature* 440, 337–40. (doi:10.1038/nature04366)
42
43 586 Winter, M., Devictor, V., Schweiger, O. 2012. Phylogenetic diversity and nature conservation:
44 587 where are we? *Trends Ecol. Evol.* 28, 199–204. (doi:10.1016/j.tree.2012.10.015)
45
46
47 588

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

589 Figure Captions:

590 Fig. 1 – Effect of increasing emphasis on evolutionary distinctiveness weight (W_i) with a \$30M NZD
591 budget: degree of emphasis on species' distinctiveness weight (exponent x on W_i) versus number of
592 species prioritized for PTE (a) and EDGE (b); degree of emphasis on W_i versus total distinctiveness
593 weight (W) conserved for PTE (c) and EDGE (d); and total distinctiveness weight conserved versus
594 number of species prioritized for PTE (e) and EDGE (f). Grey numbers represent the degree of emphasis
595 on W_i for selected points. Filled squares in (e) and (f) represent iterations with the best compromise
596 between total distinctiveness weight conserved and number of species prioritized. Note that
597 distinctiveness weight is measured differently for PTE and EDGE, and is not directly comparable
598 between these measures.

599
600 Fig. 2 – Effect of increasing emphasis on evolutionary distinctiveness weight (W_i) with a fixed target of
601 300 species: degree of emphasis on species' distinctiveness weight (exponent x on W_i) versus annual
602 budget for PTE (a) and EDGE (b); degree of emphasis on W_i versus total distinctiveness weight (W)
603 conserved for PTE (c) and EDGE (d); and total distinctiveness weight conserved versus annual budget for
604 PTE (e) and EDGE (f). Grey numbers represent the degree of emphasis on W_i for selected points. Filled
605 squares in (e) and (f) represent iterations with the highest total distinctiveness weight per dollar spent.

606

Figure 1

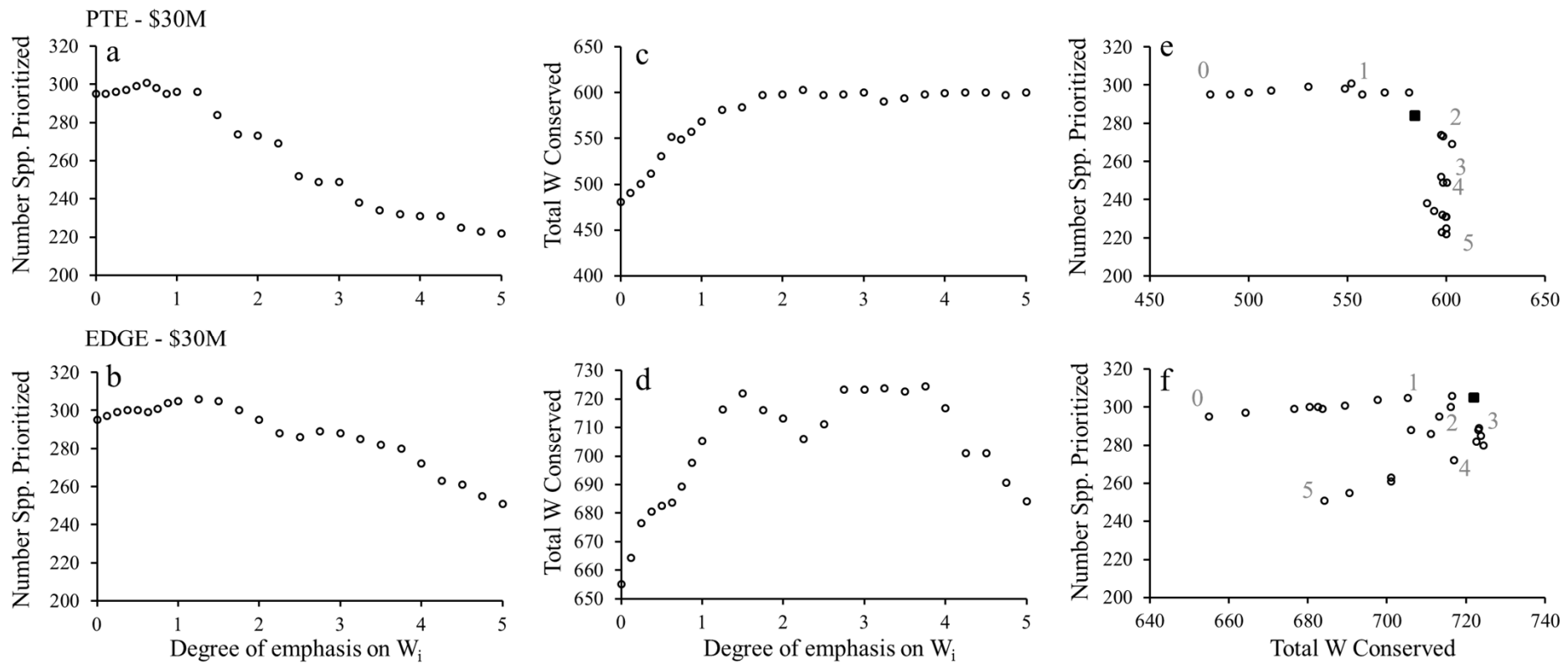
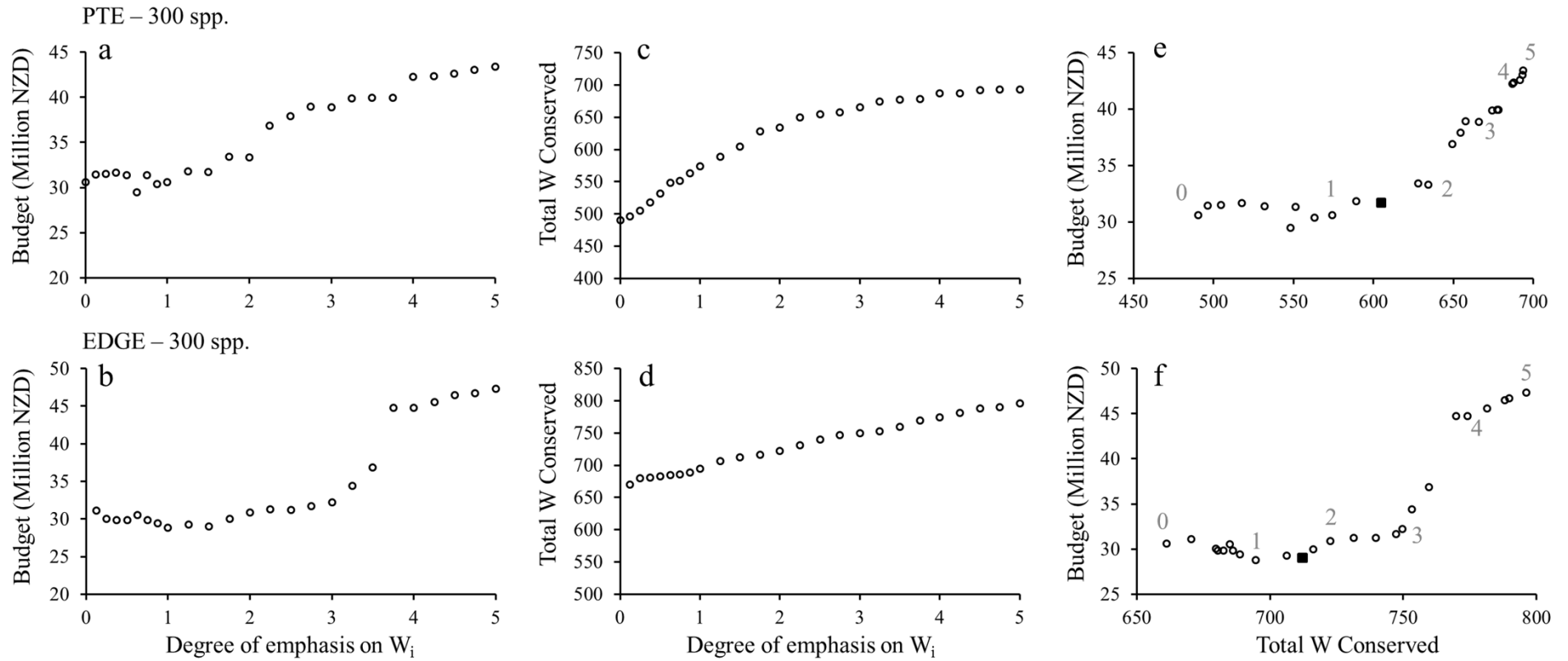


Figure 2



Appendix

[Click here to download Additional File: bennett et al - appendix_v3.docx](#)