

1 SUPPORTING INFORMATION

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3 **Genetic diversity and kelp forest vulnerability to climatic**
4 **stress**

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31 Appendix S1: Statistical results from GLMM

32 Appendix S2: Ocean temperatures during the 2011 marine heat wave

33 Appendix S3: Physical and biological predictor variables

34 Appendix S4 Conceptual models

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37 **Appendix S1: Statistical results from GLMM**

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39 **Table S1.** Results of linear mixed modelling of the relationships between latitude and genetic
 40 diversity (expected heterozygosity and number of alleles), physiological versatility (CV of
 41 quantum efficiency and maximum electron transfer rate), resilience and heat wave impact. Each
 42 analysis included 'Region' as a random effect to account for any spatial correlation among sites
 43 within regions. Analyses were undertaken in *nlme* package using R v.3.2.2. r^2 values were
 44 calculated using the *sem.model.fits* function based on the formulas of Nakagawa and Schielzeth
 45 (2013).

46

Fixed effect	Marginal r^2	Conditional r^2	t	P
Expected heterozygosity	0.742	0.806	4.647	0.002
Number of alleles	0.583	0.599	3.783	0.007
Quantum efficiency	0.438	0.524	2.557	0.037
Maximum electron transfer rate	0.363	0.363	2.505	0.041
Resilience	0.676	0.803	3.586	0.009
HW impact	0.841	0.841	7.616	<0.001

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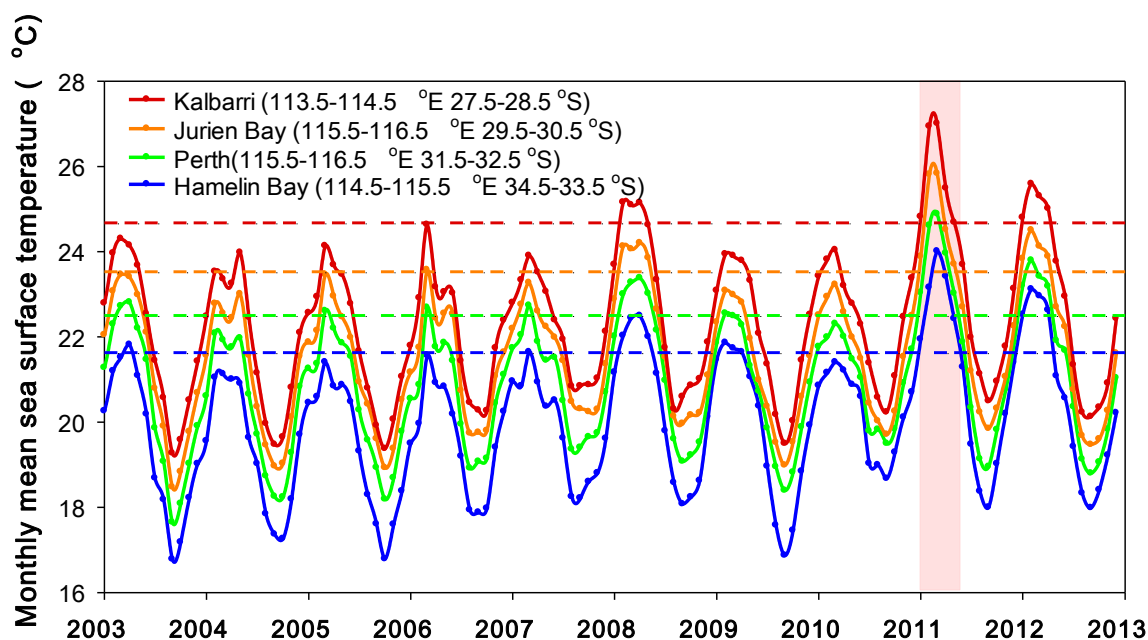
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50 Appendix S2: Ocean temperatures during the 2011 marine heat wave

51 Temperature conditions experienced by the 12 kelp forests were derived from blended SST data
 52 provided by the National Weather Service and the NOAA Operational Model Archive
 53 Distribution Systems (NOMADS) (Wernberg *et al.* 2013). Monthly mean sea surface
 54 temperatures, and temperatures for the climatological period 1981-2010, were extracted for four
 55 regions encompassing the 12 kelp forests from Kalbarri (27.5°S 113.5°E to 28.5°S 114.5°E),
 56 Jurien Bay (29.5°S 114.5°E to 30.5°S 115.5°E), Perth (31.5°S 115.5°E to 32.5°S 116.5°E) and
 57 Hamelin Bay (33.5°S 114.5°E to 34.5°S 115.5°E). These SST's closely reflect temperatures at 8
 58 - 12 m depth on the reefs where the kelps are found (Smale & Wernberg 2009). Moreover,
 59 bottom temperatures vary <5% between individual reefs within our regions (Smale & Wernberg
 60 2009).

61 In early 2011 (austral summer), the west coast of Australia experienced an extreme marine heat
 62 wave driven by an exceptionally strong flow of the Leeuwin Current and high air-sea heat fluxes
 63 (Feng *et al.* 2013; Wernberg *et al.* 2013). The marine heat wave resulted in ocean temperatures
 64 warmer than anything in 140-years of records from the Hadley Centre (Wernberg *et al.* 2013)
 65 and 215 years of records from local coral cores (Zinke *et al.* 2014). In the years immediately
 66 prior to the heat wave, summer temperatures were within the warmest temperatures generally
 67 experienced (i.e., below the maximum climatological value), but during the heat wave, temperate
 68 reefs experienced extended periods of temperatures 2-3 °C higher than normal (Fig. S1).



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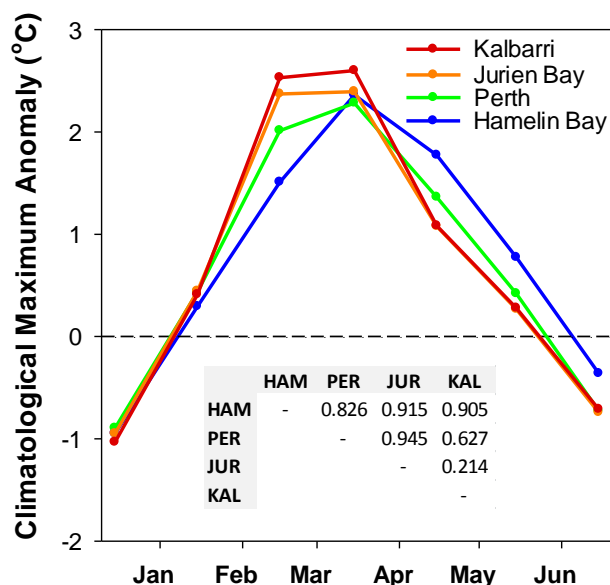
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71 **Fig. S1.** Ocean temperatures from January 2003 to December 2012. Monthly mean SST (solid
 72 lines) and maximum monthly mean temperatures for the climatological year 1981-2010 (broken
 73 lines). The five months (January to May 2011) encompassing the 2011 marine heatwave are
 74 highlighted in pale red.

75

76 The heat wave peaked at slightly different times along the coast but warming profiles were
 77 similar in different regions (Fig. S1, Fig. S2). The satellites recorded marginally higher warming
 78 anomalies in Kalbarri (Fig. S2) but the highest absolute temperature anomalies have been
 79 reported from Jurien Bay (Pearce & Feng 2013), where kelp loss was only partial. Importantly,
 80 positive climatological maximum anomalies (CMA's) (i.e., conditions where ocean temperatures
 81 exceeded the climatological maximum temperature) prevailed for ~5 months throughout the
 82 coastline and there were no statistically significant differences between regions in CMA's over
 83 the duration of the heatwave (pair-wise t-tests, $P > 0.213$, Fig. S2).

84 Climatological maximum anomalies are more conservative, and provide a better measure of
 85 climatically stressful conditions, than simple temperature anomalies (Selig *et al.* 2010). In
 86 contrast to temperature anomalies, which provide the deviation from a fixed point in time,
 87 CMA's take into account that higher temperatures might normally occur at a different time of the
 88 year. That is, they report deviations from the maximum temperatures normally experienced at
 89 any time of the year (Selig *et al.* 2010). Here we report monthly CMA's as indicative of
 90 spatiotemporally broad patterns of heat exposure. Nevertheless, integrating and averaging
 91 inherently evens out short-term or localized extremes (Smale & Wernberg 2009), which might
 92 show different patterns that could also be important. Currently, there is a very limited
 93 understanding of what characteristics of a marine heatwave is detrimental to kelp forests and
 94 most other marine organisms (Hobday *et al.* 2016). Here we analyse cumulative climatological
 95 maximum anomalies because cumulative heat exposure (e.g., degree heating weeks) has proven
 96 to be a strong predictor for coral reefs (Selig *et al.* 2010) and this measure also takes into account
 97 that a heatwave can exhibit different characteristics in different locations (Hobday *et al.* 2016).



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 99 **Fig. S2.** Climatological Maximum Anomalies (CMA's) for the five months encompassing the
 100 2011-marine heat wave (CMA > 0; highlighted in red in Fig. S1) and two-tailed P-values
 101 (insert) from pair-wise comparisons of CMA's between all regions for the months January to
 102 May (CMA > 0).

104 **Appendix S3: Physical and biological predictor variables**

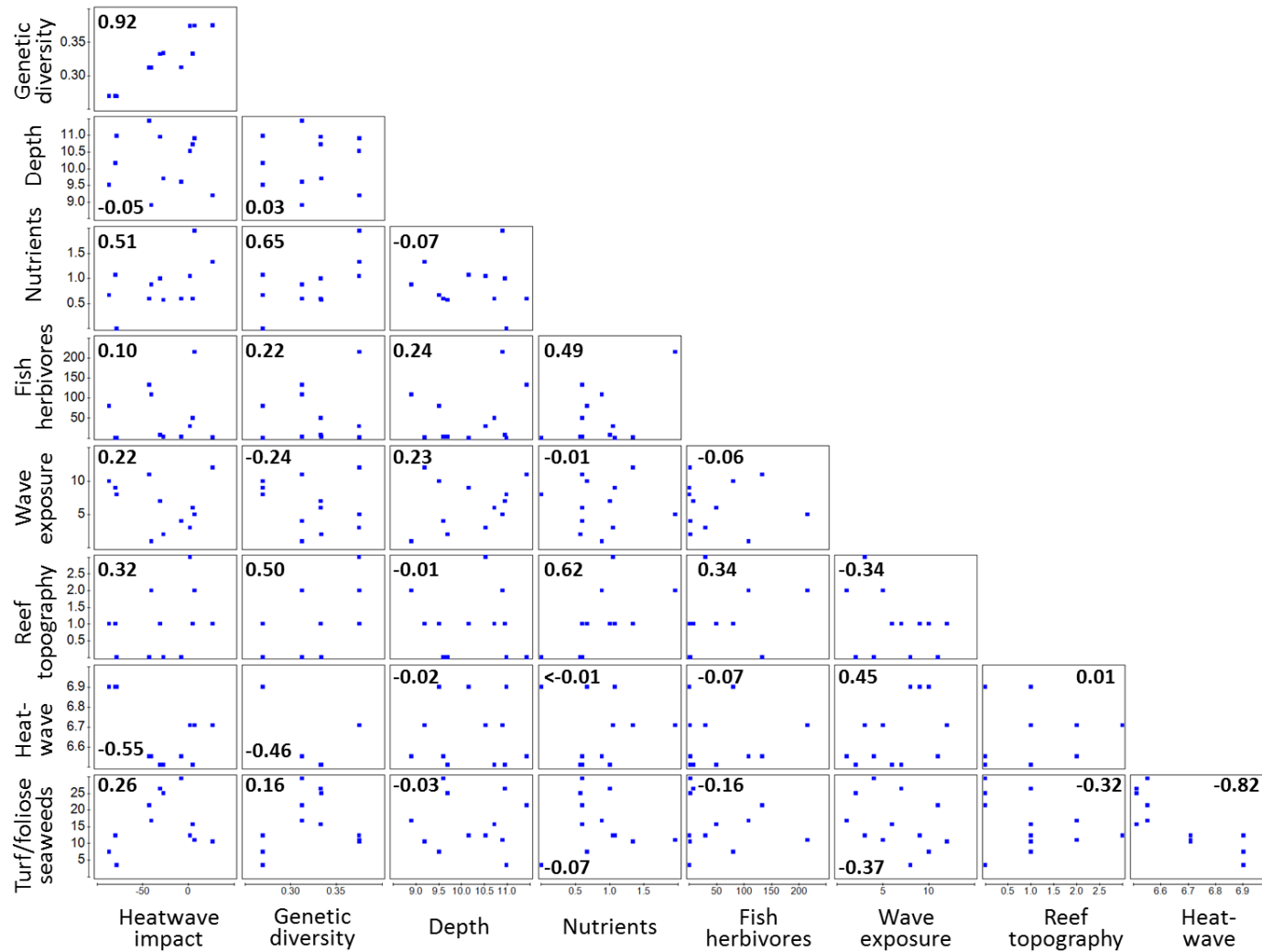
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106 **Table S2.** *Potential biological and environmental predictors of heatwave impacts. Data and their co-linearity are shown in Fig. S3.*

Predictor variable	Data description	Data source
Genetic diversity	Expected heterozygosity (H_e) derived from 6 polymorphic loci. Raw values used. Values assigned to each kelp forest by linear regression on latitude ($H_e = 0.0158 \times S^\circ - 0.1643$; $r^2 = 0.77$, $P = 0.0004$).	Coleman <i>et al.</i> (2011)
Reef topography	Counts of large (>2 m vertical relief) topographical features per 25 m transect. Raw values used for each reef.	Tuya <i>et al.</i> (2009)
Fish herbivores	Counts of herbivorous fishes (<i>Kyphosus</i> spp., <i>Odax</i> spp, <i>Parma</i> spp.) observed in 1500 m ² transects over one year prior to the 2011 marine heatwave. Raw values used for each reef.	Tuya <i>et al.</i> (2011)
Heatwave	Cumulative Climatological Maximum Anomaly. Sum of monthly temperatures exceeding the long-term climatological maximum (1981-2010) for each region (in Fig. S2, the area under each curve above zero). Akin to degrees heating weeks as it reports cumulative heat exposure. Kelp forests within a region were assigned identical CCMA's as short-term logger data has shown reef-to-reef differences to be less than 5% (Smale & Wernberg, 2009).	Appendix S2.
Wave exposure	Water motion at each kelp forest ranked from 1-12 based on many years of diving in all kelp forests.	Wernberg, unpublished data
Turf/foliose seaweeds	Measurements of cover of small turf and foliose algae cover along 25 m transects. Raw values used for each kelp forest.	Wernberg <i>et al.</i> (2011b)
Nutrient concentration	Mean NO _x concentration measured in each kelp forest 3 times over ~1 year. Raw values used.	Wernberg <i>et al.</i> (2010)
Depth	Measurements with a scuba depth gauge. Raw values used for each kelp forest.	Wernberg, unpublished data; see also Wernberg <i>et al.</i> (2010)

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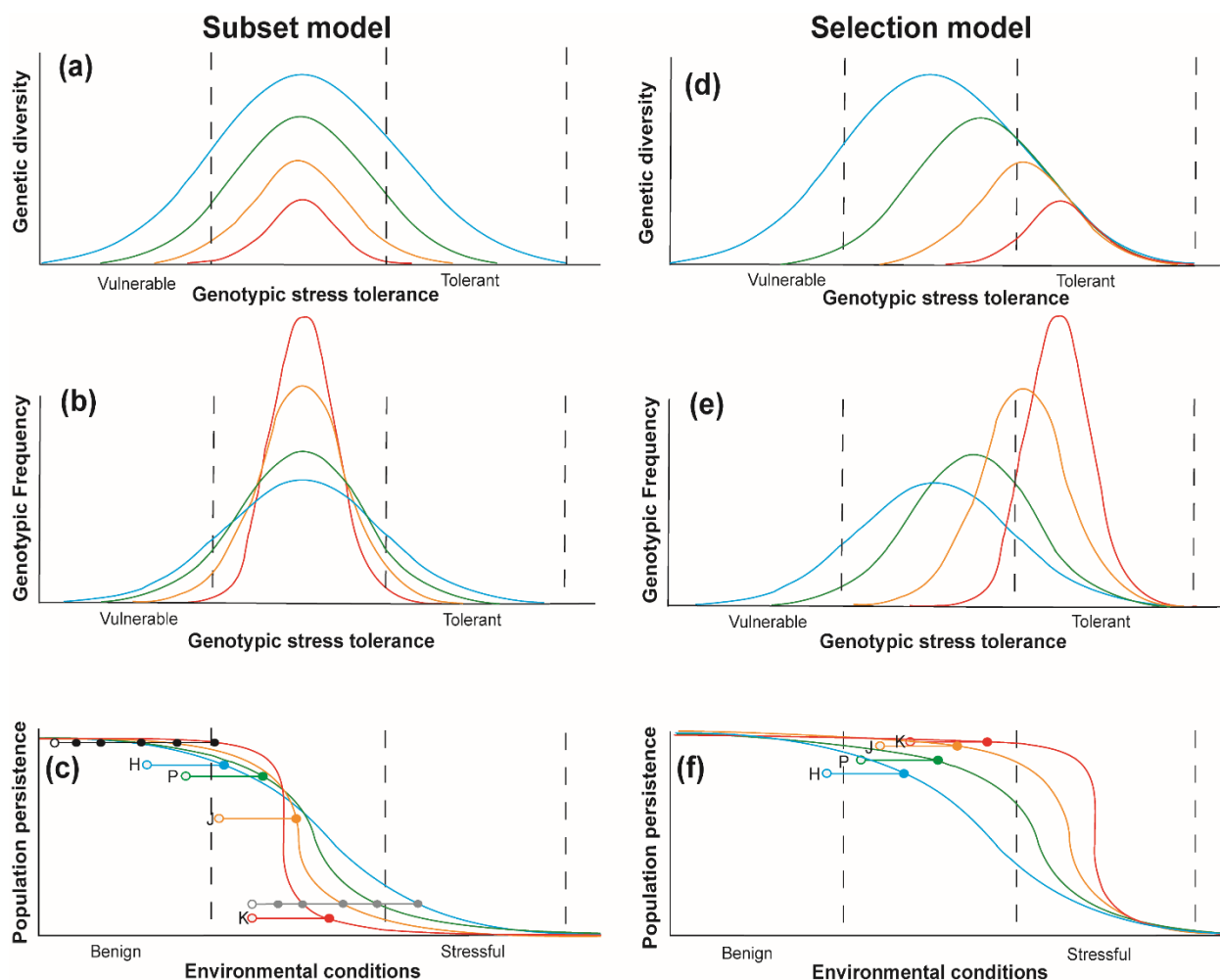
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110 **Fig. S3.** Draftman's plot of potential biological and environmental predictors of heatwave impacts (dependent variable) (cf. Table S2).
 111 Insert in each panel are Pearson's correlation coefficients (r) between each pair of biological and environmental predictor variables,
 112 as well as the dependent variable, heatwave impact, indicating their degree of co-linearity. Contributions from individual predictors
 113 that are highly correlated should be interpreted with caution.

114 **Appendix S4 Conceptual models**

115 We speculate that two conceptual models (a 'subset' and an 'selection' model) may explain
116 possible relationships between genetic diversity and population impacts of perturbations in these
117 kelp forests (Fig. S4). Both models assume that individual genotypes vary in their stress
118 tolerance, broadly defined as their capacity to resist and/or recover from a perturbation, and that
119 their frequency of occurrence in the population follows a Gaussian distribution. Under the
120 'subset model', genetic diversity arises through non-selective processes (Hampe & Petit, 2005;
121 Coleman et al., 2011), such that populations with low genetic diversity represent a narrow subset
122 of genotypes compared to high diversity populations, while the genotypic population mean stress
123 tolerance remains constant (Fig. S4a, b). Encountering increasingly stressful environmental
124 conditions, low diversity populations transition from high (due to the absence of vulnerable
125 genotypes) to low persistence as the environment exceeds the tolerance limits of intermediate
126 genotypes (Fig. S4b, c). In contrast, diverse populations undergo more gradual decline in
127 population persistence, due to the presence of both vulnerable and stress-tolerant genotypes.
128 Under the 'selection model', low genetic diversity arises through selection of stress tolerant
129 genotypes (Frankham, 2005; Hampe & Petit, 2005), such that genotypic mean population
130 tolerance increases with loss of diversity (Fig. S4d, e). Consequently, under all but the most
131 benign or extreme conditions, the 'selection model' predicts greater population resistance to
132 perturbation and higher persistence of low relative to high diversity populations (Fig. 4f),
133 whereas the opposite is true for the 'subset model' (Fig. S4c). In both cases, however, the
134 response of low-diversity populations will be abrupt and catastrophic once the population
135 threshold is exceeded (Fig. S4c, f).

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138 **Figure S4.** Conceptual models of effects of genetic diversity on population responses to
 139 perturbation along an environmental gradient. Theoretical distribution of genetic diversity (a,
 140 d), population genotype frequencies (b, e) and population survival (c, f) under a 'subset' and an
 141 'selection' origin of genetic diversity. In (c) and (f), different population endpoints (filled circles)
 142 are illustrated as a function of initial conditions (open circles) and magnitude of perturbation
 143 (length of the horizontal line). The colored examples (H, P, J, K) illustrate responses at our four
 144 regions (Hamelin Bay, Perth, Jurien Bay and Kalbarri, respectively), where genetic diversity
 145 and initial conditions differed (Fig. S1), but the magnitude of perturbation (monthly mean
 146 thermal stress anomaly) was similar (Fig. S2). The black and grey lines illustrate the general
 147 cases where variation in initial conditions, anomaly size and genetic diversity have no effect
 148 (black) or interact to produce complex patterns of influence on population survival (grey).

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152 **Appendix S5 Additional references**

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