**Title:** Incorporating evolutionary perspectives into conservation thinking - chapter 1 (placeholder)

Potential journals:

1. Coral Reefs
2. Marine Biology
3. Journal of Fish Biology

**Authors:** Elliott Schmidt1 and Jennifer Donelson1

**Affiliations:** 1 College of Science and Engineering, James Cook University, Australia

**Conflict of Interest:** Authors declare no conflict of interest.

**Keywords:** *Acanthochromis polyacanthus*, intraspecific variation, latitudinal gradient, temperature, physiology

# Abstract

# Introduction

The response of species to climate change is determined by the collective response of populations (Bennett et al. 2019; McKenzie et al. 2020). How populations response to environmental change will likely vary along geographic and environmental gradients due to variation in traits that has evolved via genetic adaptation and phenotypic plasticity (Sorte et al. 2011; Des Roches et al. 2018; Bennett et al. 2019; Plumb et al. 2020). Temperature conditions, particularly among ectotherms, are hypothesized to produce macro-ecological patterns that reflect thermal constraints on organism’s biochemistry and physiology (Somero 2010; Pereira et al. 2017). Co-gradient variation across thermal clines, whereby genetic and environmental influences on phenotype are aligned (e.g., populations exposed to higher temperatures have high optimal performance temperatures), has been demonstrated in a wide variety of taxa (plants [Aitken and Bemmels 2016; Mahony et al. 2020], insects [Hoffmann et al. 2003; Barton et al. 2014], crustaceans [Kuo and Sanford 2009; Sorte et al. 2011; Yampolsky et al. 2014], and fish [see review by Conover et al. 2009]). However, optimal performance temperatures often do not follow the trajectory of environmental gradients (Conover et al. 2009). Counter-gradient variation, whereby genetic and environmental influences on phenotypes are opposed, occurs when phenotypic and genetic divergence are decoupled to maximize fitness (Schmid and Guillaume 2017; Stamp and Hadfield 2020). Counter-gradient variation has been recorded in several taxa (lizards [Angilletta et al. 2004; Hodgson and Schwanz 2019], turtles [Snover et al. 2015], and fish [Gardiner et al. 2010]); however, the extent to which phenotypic plasticity and genetic differentiation contribute to counter-gradient variation varies (Stamp and Hadfield 2020).

Population responses to warming temperatures will likely differ depending on occupied thermal niches. Low-latitude environments characterized by stable temperatures near physiological maximums favor specialized (narrow) thermal niche breadths that primarily evolve through genetic adaptation (i.e., selection for particular phenotypes) rather than plasticity – Climate Variability Hypothesis (CVH) (Janzen 1967; Stevens 1989) (*but see* (Overgaard et al. 2011; Chiono and Paul 2023)). Narrow thermal niche breadths, limited plasticity, and evidence of hard ceilings for upper thermal tolerance (Gunderson and Stillman 2015; Sandblom et al. 2016; Morgan et al. 2020), suggest that low-latitude populations are more vulnerable to shifting temperatures than high-latitude conspecifics (Stillman 2003; Deutsch et al. 2008; Tewksbury et al. 2008; Somero 2010; Sunday et al. 2011). High-latitude populations, that experience variable environmental conditions are predicted to retain greater benefits from maintaining high levels of phenotypic plasticity in physiological than low-latitude conspecifics (Janzen 1967; Stevens 1989); however empirical evidence remains scarce (but see, Molina-Montenegro and Naya 2012; Naya et al. 2012; Donelson et al. 2019). Wider thermal niche breadths have been repeatedly reported in high-latitude populations (Sunday et al. 2011; Shah et al. 2017; Stuart-Smith et al. 2017; McKenzie et al. 2020); however, heat-tolerant phenotypes present in low-latitude populations may be unattainable within high-latitude populations (for example see (Kelly et al. 2012). Therefore, locally adapted populations may possess thermal niches that are narrower than the species as a whole (Kelly and Griffiths 2021).

Intraspecific-variation in thermal performance between populations within marine systems has not received the same attention as terrestrial systems; despite marine organisms having greater confinement to thermal tolerance limits (Sanford and Kelly 2011; Sunday et al. 2011; Pinsky et al. 2019; Lenoir et al. 2020). What we know from the terrestrial is... XXXX. Marine systems have previously been viewed as demographically open networks with minimal dispersal barriers; however, a growing body of evidence suggests that oceanographic features, life history traits, and larval dispersal/establishment ability can act as challenges to gene flow and promote local adaptation (Sanford and Kelly 2011). To date studies that have addressed intraspecific variation in marine species have focused on invertebrates (see review Sanford and Kelly., 2011) including copepods (Kelly et al. 2012; Pereira et al. 2017; Sasaki and Dam 2019), porcelain crabs (Stillman 2002), intertidal snails (Kuo and Sanford 2009; Sorte et al. 2011), and coral (van Oppen et al. 2014); few broach the topic among marine fish.

Thermal intraspecific variation patterns in marine fishes are variable depending on study species. In a common garden experiment (Marcil et al. 2006) found differences in morphological traits between two different Atlantic cod (*Gadus morhua*) populations that experience different thermal environments during early life stages; intraspecific variation patterns followed a counter-gradient variation pattern across a large (<1000 km) spatial scale. Whereas, (Pratchett et al. 2013) compared aerobic physiology metrics among low- and high-latitude populations of coral trout (*Plectropomus leopardus*), and found no significant differences between populations. Further analysis found little genetic variation between coral trout populations across the Great Barrier Reef (GBR) owing to spatial and temporal variation in larval recruitment (Van Herwerden et al. 2009; Taboun et al. 2021). (Gardiner et al. 2010) and (Donelson and Munday 2012) compared thermal performance and acclimation capacity, respectively, between low- and high-latitude populations of a tropical coral reef damselfish, *Acanthochromis polyacanthus*. (Gardiner et al. 2010) found evidence that high-latitude populations maintained higher aerobic capacity than low-latitude populations at warmer temperatures – counter-gradient variation. (Donelson and Munday 2012) reported that high-latitude populations displayed increased acclimation capacity (i.e., developmental plasticity) compared to low-latitude populations – supporting the CVH. Findings from (Gardiner et al. 2010) and (Donelson and Munday 2012) suggests that *A. polyacanthus* provide an opportunity to understand how intraspecific variation will affect the responses to warming temperatures within a non-commercial coral reef fish; a topic that has received little attention to date.

Intraspecific thermal variation within *A.* polyacanthus is evident; however, robust genetic variation between *A. polyacanthus* populations (Doherty et al. 1994; Planes et al. 2001; Van Herwerden and Doherty 2006) suggests that existing physiological studies provide a coarse understanding of *A. polyacanthus’s* thermal landscape. (Gardiner et al. 2010) and (Donelson and Munday 2012) both focused on a single high-latitude population (Heron Island), however, genetic analysis suggests high levels of genetic differentiation between populations throughout *A. polyacanthus’s* range; particularly within the higher latitudes of their distribution. Therefore, to increase the resolution of *A. polyacanthus’s* thermal landscape and allude to a greater understanding of intraspecific variation within marine environments, further exploration is needed. This study compared thermal performance curves of key physiological traits within *A. polyacanthus* from three different populations among two regions of the GBR, Cairns (low-latitude) and Mackay (high-latitude), that experience different thermal profiles. We tested the hypothesis for counter-gradient variation across a thermal gradient between a low latitude and a novel high-latitude region. Based on evidence of greater phenotypic plasticity among low latitude populations(Donelson and Munday 2012), populations from the high latitude region are expected to have increased thermal tolerance and performance at warmer temperatures than populations from the low-latitude region. However, co-gradient variation represents a valid alternative hypothesis considering the limited amount of research available on the topic and observed genetic differences between the high latitude populations examined in this study and the high-latitude population examined by past research.

# Methods

## Sampling

The tropical damselfish, *Acanthochromis polyacanthus* (Bleeker 1855), ranges from the southern Great Barrier Reef (GBR) to the central Philippines (spanning 30° of latitude). *A. polyacanthus* populations are thought to have propagated the Indo-Pacific proceeding Pleistocene (2.6 Ma- 11.7 ka) bottlenecks as rising sea levels reestablished dispersal corridors between reefs (Van Herwerden and Doherty 2006; Ludt and Rocha 2015). However, eventually such dispersal corridors ceased to function as water levels began to reach present-day levels. *A. polyacanthus* perform parental care during embryonic and early life development, in socially monogamous pairs, where eggs are defended by both parents until fry are large enough to disperse into the surrounding habitat(Robertson 1973). This unusual life history trait, among marine fish, coupled with *A. polyacanthus* inability to disperse between reefs separated by depths greater than 10m (Miller-Sims et al. 2008), creates conditions that should promote local adaptation(Sanford and Kelly 2011); a broad geographic distribution across thermally variable environments, where gene flow is limited.

Adult *A. polyacanthus* were collected via professional collectors from June to December 2021 from six different reefs and two different regions (central GBR [Cairns] and southern GBR [Mackay]). Three reefs from locations around Cairns including, Tongue Reef ([-16.341, 145.773]), Vlassof Cay ([-16.657, 145.990]), and Sudbury Reef ([-16.996, 146.202]), as well as from inshore islands and reefs in proximity to Mackay including: Cockermouth Island ([-20.772, 149.390]), Keswick Island ([-20.908, 149.406]), and Chauvel Reef ([southern; -20.863, 150.363]; **Figure 1**). Cairns and Mackay collection regions are separated by ~400 kilometers (spanning ~5° in latitude).

In total 55 fish were sampled over the duration of the experiment (**Supplemental table 1**). Fish were sampled from Tongue Reef (*n =8*), Sudbury Reef (*n =11*), Vlassof Cay (*n =10*), Cockermouth Island (*n =10*), Keswick Island (*n =6*), and Chauvel Reef (*n =10*). However, not all fish survived the duration of the experiment. From the initial 55 fish, 38 completed all experimental assays including: resting metabolic rate, maximum metabolic rate, aerobic scope, immunocompetence, hematocrit, and enzyme activation analysis.

Adult fish were held in separate 60L opaque aquariums (56L x 35W x 30H) inside an environmentally controlled aquarium room at the Marine and Aquaculture Research Facility at James Cook University (Townsville, Australia). Each aquarium contained a shelter (half a terra-cotta pot), constant aeration, and water flow (2 L/min) at set experimental conditions (see below). Fish were transferred to the experiment room that was used for trials on May 25th, 2022. Respirometry trials occurred from June 6th, 2022 – August 17th, 2022.

## Thermal conditions

To understand local thermal conditions for reefs within Cairns and Mackay locations were examined using temperature data collected via AIMS Temperature Logger data series, at a of depth 10-15m, for a subset of reefs (**Supplemental table 2**) from each region (Australian Institute of Marine Science (AIMS) 2020; **Supplemental figure 1**). Experimental temperatures for repeated aerobic physiology and immune response testing included the approximate daily mean summer temperature for both Mackay (~27°C) and Cairns (~28.5°C) regions, as well as 30°C (mid-2100 century; SSP2-4.5, SSP3-7.0, and SSP5-8.5), and 31.5°C (end of 2100 century; SSP2-4.5 and SSP5-8.5)(Masson-Delmotte et al. 2021). Testing began at coolest temperature of 27°C, and once aerobic physiology and immune response testing was complete, fish were warmer to the next temperature of +1.5°C, at a rate of +0.5°C/day for three consecutive days. Fish were then provided an additional five days to adjust to the new temperature treatment before the next sampling period began. This process was repeated for all testing temperatures.

## Aerobic physiology

Routine and maximum metabolic rate were determined via measuring the rate of oxygen consumption using intermittent flow respirometry. Chambers were 1.5 L in volume and custom built from PVC pipe and acrylic (**Supplemental figure 2**). Experimental setup consisted of two sumps (260L), with continuous water exchange and aeration, each containing four submerged respirometry chambers placed in parallel. Chambers were opaque except for the lid, so that fish could not view each other. Each respirometry chamber unit contained an independent brushless DC recirculation pump (flow rate 240 L h-1), vinyl tubing (composing ~1% of the total water volume), and an inline oxygen sensor probe (multichannel FireSting-O2, PyroScience GmbH, Aachen, Germany). Oxygen sensor probes were calibrated to 0% air, using sodium sulphite (Na2SO3) saturated seawater, at the beginning of the experiment and when spot material was replaced. 100% air calibrations were conducted at the beginning of each trial. During flush periods a pump (AQUAPRO, AP750LV; 750 L h-1) was used to flush each set of four chambers simultaneously. Heaters (2 kilowatt) and temperature sensors (Semitec 103AT-11 IP67) were used to ensure that experimental temperatures remained within +/-0.3°C of experimental temperature set points. Minimal background respiration was achieved through UV filteration, particle filtration (100 µm bag filters), and daily cleaning of equipment (bleach diluted to 200 ppm with fresh water. Fish were deprived of food for 18-24 h before aerobic respiration trials began. Trials were conducted in a fully lit room to eliminate metabolic costs associated with digestion and photoperiod.

Maximum oxygen consumption (MO2max) was used as a proxy for maximum metabolic rate (Norin and Clark 2016). To achieve maximum oxygen consumption fish were placed in a swim tunnel for 10 min. During the initial 5 min interval, the speed of water flow through swim tunnel was slowly increased until fish displayed a changed in gait swimming behavior, defined as a transitioning behavior from predominately pectoral swimming to body/tail undulations (**Supplemental video 1**). The speed of the swim tunnel that produced this intermediary transitional swimming behavior was maintained for the second 5 min interval. Immediately after the 10 min swimming period, fish were collected by hand, and transferred to respiration chambers. Pilot studies (unpublish data, Schmidt) determined that highest MO2max levels were achieved with the immediate transfer of from the swim tunnel to respiration chambers, rather than including an intermediary air exposure period. Therefore, no air exposure time was included prior to fish being transferred into respiration chambers. The time between fish being placed in respiration chambers and the of data being recorded (i.e., start of the wait period) was less than 10 s. MO2max was measured over 30 s intervals via rolling regressions within the *‘*auto\_rate’ function included in the R package ‘*respR’* (v2.0.1). The steepest slope (highest oxygen consumption rate) with an *r2* threshold of 0.95 was used to determine MO2max. MO2max was measured prior to routine metabolic rate (MO2routine).

Fish were randomly placed in respirometry chambers for 3.5 – 6 h ( =4.67 h) to measure MO2routine. Oxygen consumption was measured continuously over cycles consisting of a 15 second wait, 225 second measurement, and 180 flush period. Air percentage never dropped below 80% air saturation. Oxygen consumption rates were measured over a 220 min interval with an *r2* threshold of 0.95.MO2routine was measured by taking the mean of the lowest 3 oxygen consumption slopes. Background respiration was measured at the start of each trial by measuring oxygen consumption within empty chambers for at least three consecutive cycles. Background respiration levels were typically accounted for <2% of measured oxygen usage rates and were therefore ignored. The mass of fish was measured at the end of all respiratory trials, after fish had been euthanized and patted dry with paper towel to avoid the inclusion of excess moisture. The net respirometer volume of chambers ranged from 1:123 to 1:36 (ratio =1:60; **Supplemental figure 3**) depending on the size of each fish. Oxygen consumption rates were converted from percent air saturation values to mg h-1 via the *‘convert\_rate’* function within the R package *respR* (Harianto et al. 2019). Absolute aerobic scope (AAS) was calculated by subtracting MO2routine fromMO2max.

## Immune response

To test the sensitivity of the immune system, subcutaneous phytohemagglutinin injections were used to produce a (localized) cell-mediated response (e.g., inflammation, T-cell proliferation, infiltration of immune cells; (Martin et al. 2006; LaMonica et al. 2021). PHA swelling response provides useful information on individual’s immune system status *in vivo*, while limiting additional stress other than that derived from handling (Merino et al. 1999). Tissue swelling 24-hours post-injection is mediated via complex immunological cascade, however, is primarily driven via the congregation of leukocytes to the injection site (Martin et al. 2006). Fish were injected in the caudal peduncle with 0.03 mL of phytohemagglutinin (Phytohemaglutinin; L8754 Sigma-Aldrich, 45 ug 10 uL-1) dissolved in phosphate buffer saline (PBS), made to a ratio of 1 mg PHA to 1 mL PBS. The immunocompetence of fish was determined by measuring the injection area with pressure sensitive calipers (Mitutoyo ABS Digimatic; accuracy 0.1mm) pre-injection, and ~18-24 hours post-injection. The difference in localized swelling pre- and post-injection was used as a proxy for immunocompetence.

## Fish sampling

Whole blood and tissue samples (i.e., white muscle tissue) were collected 10 days after all aerobic physiology and immune responses trails were completed at the final testing temperature (31.5°C). Whole blood was collected from the caudal vein via heparin-coated 25-gauge surgical needles. Fish were then euthanized via cervical dislocation. White muscle tissue samples were dissected from tissue between the dorsal fine and lateral line; once obtained tissue samples were stored in liquid nitrogen and then transferred to a -80°C freezer.

## Hematocrit

Microcapillary tubes (75mm Drummond Hemata-clad plain) were used to centrifuge blood samples at 10,000 rpm for 60 seconds to separate red cells from blood plasma. The proportion of blood volume occupied by red blood cells (hematocrit) was recorded by usinga ruler to first measure the space of the microcapillary tube that was occupied by the total blood volume (packed red blood cells and blood plasma), followed by measuring the space occupied by just packed red blood cells. Hematocrit scores were calculated using the following formula:

## Enzyme activity

White muscle tissue was used to examine the maximal enzyme activity of lactate dehydrogenase (LDH) and citrate synthase (CS). Testing temperatures of 20°C, 30°C, 40°C, and 50°C were used to determine maximal enzyme activity and the associated thermal performance curve. White muscle tissue was used for the maximal enzyme activity analysis because, it’s anaerobic capacity has been shown to correlate to whole organism oxygen consumption, and it plays an important role in bursts of high-speed swimming (Sullivan and Somero 1980). Additionally, white muscle tissue compromises most of the body mass for *A. polyacanthus*. White tissue samples were extracted from fish immediately after fish had been euthanized, placed in liquid nitrogen, and then transferred to a -80°C freezer for storage.

The maximal enzyme activity method used here was adapted from previous studies (Thibault et al. 1997; Seebacher et al. 2003; Lang et al. 2021). Samples were defrosted on ice. A sterile scalpel blade was used to extract a tissue sample (20-40 mg). Extracted tissue samples were homogenized via a microtube homogenizer (BeadBug 3, Benchmark Scientific, Model D1030-E) in a 1:10 dilution with a buffer consisting of 50 mmol L-1 4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid (HEPES), 1 mmol L-1 ethylenediaminetetraacetic acid (EDTA), 0.01% Triton X-100, and 99.99% Milli-Q water, and adjusted to pH 7.4 with sodium hydroxide (NaOH). A subset of homogenized tissue was extracted for LDH, and CS. Homogenized tissue samples used for the LDH assay were centrifuged (Eppendorf Centrifuge 5424, Hamburg, Germany) at 150 rpm for <3 s. Homogenized tissue samples used for the CS assay were not centrifuged to allow mitochondria to be retained within the supernatant.

Absorbance readings were measured with a spectrophotometer every 2 s, with 20 readings over 13 min (UV5, Mettler-Toledo, Columbus, OH). Testing temperatures were maintained with a Loop L100 circulation thermostat (Lauda, Lauda-Königshofen, Germany). All samples were measured in triplicate and included a blank control.

LDH was assayed in 0.5 mmol L-1 of β*-*nicotinamide adenine dinucleotide reduced disodium salt hydrate (NADH)-TRIS solution (pH 7.4). and 50 mmol L-1 of sodium-pyruvate-NADH-Tris solution (pH 7.4). NADH absorbance was measured at a wavelength of 340 nm (Seebacher 2003). CS was assay in 2 mmol L-1 5,5’-dithobis-(2-nitronemzoic acid) (DTNB)-ethanol solution, 12 mmol L-1 acetyl coenzyme A-lithium salt-Milli-Q solution, and 50 mmol L-1 oxaloacetic acid-Tris solution (pH 8.0). DTNB absorbance was measured at a wavelength of 412 nm (Seebacher 2003; Blank 2004).

The mean slope was used to determine maximal enzyme activity. Background activity was subtracted from sample absorbance slopes when background activity exceeded 5% of sample absorption levels. Final maximal enzyme activity levels were calculated in units per milligram tissue (U mg-1 tissue) using the following formula where: represents the mean absorption of tested sample in triplicate, represents to the light path length (cm), represents the molar absorptivity/extinction coefficient (M-1 cm-1), represents tissue sample concentration (mg/ml), and represents volume.

## Statistical analysis

Generalized linear mixed effect models were used to test for differences in metabolic, immune, hematocrit, and enzyme activity, responses between low- and high-latitude populations to temperature. All aerobic metabolic models were run using a gaussian distribution. To model metabolic responses including MO2routine, MO2max, and MO2net, independent variables including, region and temperature were modelled as fixed factors with an interaction; fish mass (centered) was used as a covariate. Individual identification codes for each fish were used as a random factor due to repeated measures. The model for MO2routine included the additional covariate of testing runtime. The same fixed variables, region and temperature, were used for modelling PHA immunocompetence response, and enzyme (LDH) activity. However, for the PHA swelling response model instead of a gaussian distribution, a gamma distribution was used with an inverse link. For the enzyme analysis for lactate dehydrogenase model tissue mass (centered) was used instead of fish mass. To model the (combined region) correlation between lactate dehydrogenase activity and temperature, temperature was modelled as a continuous numerical variable and third order polynomial, tissue mass (centered; fixed), and individual fish identification codes as a random factor. Hematocrit was modelled as a linear regression with percent packed blood cells as the dependent factor and region as an independent variable.

All statistical analysis was conducted in R (v 4.2.2). GLMMs were run using the ‘glmmTMB’ function within the ‘*glmmTMB’* (v.1.1.5). Model selection occurred using the function ‘AICc’ via the *‘MuMin’* (v.1.47.1). Visual and statistical performance of models was checked via both the ‘check\_model’ function in the *‘performance’* (v. 0.10.0) package and the ‘simulateRedisuals’ and ‘testResiduals’ functions in the ‘*DHARMa’* (v. 0.4.6) package. The *‘emmeans’* (v. 1.8.2) package was used to extract estimated marginal means from models that were used to tested for statistical significance. All figures were made using the ‘*ggplot2*’ (v. 3.4.0) package.

# Results

## Aerobic physiology

MO2rest displayed a positive relationship with temperature, but no significant differences were seen in MO2rest when comparing fish from low- and high-latitude regions at 27°C, 28.5°C, 30°C, or 31.5°C. (**Figure 2a**). At the lowest two temperatures, 27°C and 28.5°C, MO2routine was most similar between regions (*p*27 =0.58, [CI: -0.45, 0.78]; *p*28.5 =0.90, [CI: -0.67, 0.59]). MO2Rest was significantly higher at 30°C and 31.5°C, than at 27°C and 28.5°C for fish from high-latitude populations (*p*Leading27v30 <0.0022, [CI: -1.78, -0.29]; *p27–31.5* <0.0001, [CI*27–31.5*: -2.17, -0.66]; *p*Leading28.5v30 =0.035, [CI: -1.53, -0.039]; *p*Leading28.5v31.5 =0.0006, [CI*28.5–31.5*: -1.91, -0.40]) region. The largest increase in RMR (14%) between temperatures within high-latitude region fish was observed between 28.5°C and 30°C. In the low-latitude region MO2Rest similar differences were seen (*p*Core27v30 =0.0077, [CI: -1.50, -0.17]; *pCore27v31.5* <0.0001, [CI: -2.07, -0.66]; *p*Core28.5v30 <0.0001, [CI: -1.99, -0.65]), however there was no significant difference between 28.5°C and 30°C. The largest increase in RMR (14%) with low-latitude region fish was observed between 30°C and 31.5°C (*pCore30v31.5 <*0.01, [CI: -1.50, -0.17]).

MO2max and temperature displayed diverging patterns between low- and high-latitude regions (**Figure 2b**). A positive relationship was seen between MO2max and temperature among fish from low-latitude populations; steadily increasing between temperature intervals (27-28.5°C: 10%; 28.5-30°C: 6%; 30-31.5°C: 3%). Fish from high-latitude populations differences between temperature intervals were <2%, producing a flat response, where MO2max values were constantly ~14.2 MgO2 hr-1. Low-latitude fish had significantly higher MO2max compared to Mackay region fish at 30°C (*p* <0.05, [CI: 0.030, 3.62]; 13% increase; 1.90 MgO2 hr-1) and 31.5°C (*p* <0.05, [CI: 0.22, 3.86]; 15% increase; 2.10 MgO2 hr-1).

Significant differences in AAS were seen between regions at warmer temperatures 30°C (*p* <0.01*,* [CI: 0.56, 4.01]) and 31.5°C (*p* <0.05*,* [CI: 0.28, 3.78]; **Figure 2c**). This enhanced AAS possessed by low-latitude region fish by a difference of 2.28 MgO2 hr-1 at 30°C and 2.03 MgO2 hr-1 31.5°C represented a difference of 28% and 27%, respectively. Optimal AAS for low- and high-latitude populations was 30°C (10.31 MgO2 hr-1) and 28.5°C (8.57 MgO2 hr-1), respectively; +1.5°C above the average summer temperature in each region. Interestingly, low-latitude region fish showed similar AAS values at 28.5°C (9.63 MgO2 hr-1) and 31.5°C (9.58 MgO2 hr-1). At lower temperatures, 27°C and 28.5°C, no significant differences were observed between regions (*p27* =0.76; *p28.5* =0.20).

## Immune response

Immune swelling response exhibited a curved response in both low- and high-latitude populations that peaked at 28.5°C (**Figure 3**), however, no significant differences were found between regions at tested temperatures (*p27* =0.19; *p28.5* =0.62; *p30* =0.59; *p31.5* =0.80). Combined results between regions showed that immune response was lowest at 31.5°C, showing a decrease of 60%, 75%, and 53% compared to 27°C (*p* <0.0001*,* [CI: 0.43, 1.42]), 28.5°C (*p* <0.0001*,* [CI: 0.87, 1.88]), and 30 °C (*p* <0.01*,* [CI: 0.23, 1.30]), respectively. At 28.5°C immune response was also significantly higher than responses produced at 27°C (*p* <0.05*,* [CI: -0.90, -0.0016]) and 30°C (*p* <0.01*,* [CI: 0.12, 1.10]).

## Hematocrit

No significant difference was observed in hematocrit levels between low- and high-latitude populations at 31.5°C (*p* =0.058; **Supplemental figure 4**). Packed red blood cells composed 22.4% and 25.9% of whole blood for low- and high-latitude populations, respectively.

## Enzyme analysis

Lactate dehydrogenase activity was positively correlated with temperature (*p* <0.0001, [CI: 1.94, 2.45], *R2 =*0.79; **Figure 4a**), however, no significant differences were seen in LDH activity between regions at any of the tested experimental temperatures for lactate dehydrogenase activity: 20°C (*p* =0.54), 30°C (*p* =0.48), 40°C (*p* =0.42), and 50°C (*p* =0.53). Citrate synthases was negatively correlated with temperature (*p* <0.0001, [CI: -144, -73]; **Figure 4b**). Similar to LDH, no significant differences were identified between CS activity between regions at tested experimental temperatures: 20°C (*p* =0.90), 30°C (*p* =0.76), 40°C (*p* =0.72), and 50°C (*p* =0.33).

# Discussion

How populations will respond to climate change will depend on experienced local environmental conditions. If environmental and genetic influence are aligned (co-gradient variation) low-latitude populations living in warmer conditions are expected to respond to warming temperatures more adeptly than high-latitude populations. However, high-latitude populations that may experience greater environmental variability may be able to compensate performance at warmer conditions via greater investment in phenotypic plasticity (CVH; counter-gradient variation; Janzen 1967; Stevens 1989). Results from this study detected co-gradient variation when comparing AAS between low- and high-latitude *A. polyacanthus* populations. Immune response and hematocrit were similar between populations. Findings suggest that AAS is adapted to local regional conditions, and therefore, intraspecific variation in thermal performance needs to be accounted for when modelling responses to climate change.

## Aerobic physiology

Fish from low-latitude populations demonstrated significantly higher aerobic physiology capacity at warmer temperatures than conspecifics from high-latitude populations – evidence of co-gradient variation. Furthermore, low-latitude populations showed higher thermal optimal temperatures than high-latitude conspecifics. Differences in AAS between regions was driven by low-latitude population’s ability to increase their MO2max at warmer temperatures; offsetting increases in MO2rest. Alternatively, fish from high latitude populations displayed plateaued MO2max values at warmer temperatures and therefore experienced lower AAS was primarily driven by increasing MO2Rest values. Improved capacity for oxygen at higher temperatures suggests low-latitude populations are adapted to optimize AAS, compared to high-latitude conspecifics. AAS serves as a proxy for the limits of oxygen demanding processes (e.g., motor activity, reproductive output, growth) that can be performed simultaneously (Clark et al. 2013) and is expected to be the primary mechanism that determines how fish will respond to climate change (Pörtner and Knust 2007; Pörtner et al. 2017). Therefore, at warmer temperatures low-latitude fish are expected to have increased fitness over high-latitude populations.

Evidence of co-gradient variation suggests that for the populations examined in this study genetic and environmental influences on AAS are aligned. However, the primary driver of counter-gradient variation is differences in phenotypic plasticity and therefore may be dependent on differences in experienced in thermal variation among populations. However, for many fish habitat depth may be more predictive of experience thermal variability than latitude. Therefore, marine species may display both co- and counter-gradient variation among populations, with the determining factor being fine scale biogeography rather than latitude. Gardiner et al. (2010) identified counter-gradient variation between *A. polyacanthus* populations when comparing low-latitude populations (i.e., Lizard Island) and a high-latitude population that exists further south than the high-latitude populations examining in this study. When examining fine scale biogeography, Gardiner et al. (2010) sampled high-latitude populations from shallow lagoons, whereas this study had fish collected from ~6-12 meters on coral reef shelfs. Reef flats and lagoons experience greater short-term thermal variability via exposure to semidiurnal tidal oscillations compared to reef slopes that are exposed the open ocean and hence more thermally stable (Brown et al. 2023). Thermally variable lagoonal reef sites at Heron Island have been shown experience greater daily temperature maxima, mean temperature, and magnitude of diel variation; during heatwave years daily temperature maximums were recorded at 36.5°C within thermally variable locations (Brown et al. 2023). Therefore, fish sampled by Gardiner et al. (2010) may have experienced thermal conditions with a greater variability and magnitude than low-latitude reef-shelf populations; these conditions would favor greater investment in phenotypic plasticity and therefore contributed to increased AAS compared to examined low-latitude populations. In combination with Gardiner et al. (2010), findings from this study suggests that *A. polyacanthus* may exhibit both co- and counter gradient variation among populations, depending on the population in question, elucidating the importance of incorporating macro- and fine-scale biogeography in understanding intraspecific variation between populations.

Results display patterns representing local adaptation, however, failed to show significant differences at regional average summer temperatures, that are predicted to drive thermal local adaptation. However, local adaptation can be difficult to see when testing at intermediate temperatures that are shared between populations (Pilakouta et al. 2020). Within this current study significant differences between regions were only identified once temperatures exceeded conditions that high-latitude populations experience. Increasing the range of testing temperatures to include cooler conditions that low-latitude populations rarely or do not experience, but high-latitude populations do (e.g., 20-23°C), may identify ‘local vs. foreign’ as well as ‘home vs away’ criterion (Kawecki and Ebert 2004) between populations more conclusively.

## Immune response

Immune response was dependent on temperature, however, fish from low- and high-latitude showed similar responses. The warmest temperature tested, 31.5°C, resulted in the lowest immune response. Similar responses have been observed in rabbitfish (*Siganus doliatus*), where no immune response was detected at 31.5°C (LaMonica et al. 2021). Evidence to date suggests that as temperatures increase and/or heatwaves increase in frequency and magnitude, thermal conditions will begin to compromise the immune response of fish. Immunological research into measuring and understanding PHA responses in fish remains scarce compared to other taxa. Within bird species PHA swelling responses have been shown to be less costly than other behaviors (e.g., molting, breeding; Martin et al. 2006). If similar conditions exist within fish, a limited ability to mount immune responses at 31.5°C suggests that more energetic behaviors, such as reproduction, will cease around similar temperatures.

Peak PHA swelling at 28.5°C suggests evidence for the multiple performances – multiple optima (MPMO) hypothesis proposed by Clark et al. (2013). Under the MPMO hypothesis different physiological functions possess different optimal temperatures. Whereas results from this study identified 30.0°C as optimal for AAS among low-latitude populations, swelling response was optimal at 28.5°C. Therefore, while future warming conditions of +1.5°C may provide advantages associated with AAS among low-latitude populations, it may come at the cost of immune response. Among high-latitude fish 28.5°C was optimal for both AAS and immune response. However, it is important to note that AAS among high-latitude fish showed little difference between tested temperatures.

Repeated PHA injections may represent acquired immune response rather than innate immune response. Previous research on repeated PHA injections in blue-footed boobies (*Sula nebouxii*) detected an average increase of 90% between first and second PHA injections; attributing the increase from the second injection to acquired T-mediated immunity (Santiago-Quesada et al. 2015). Increased swelling at 28.5°C compared to swelling at 27°C may be an artefact of the acquired immune system rather than temperature, however, measurements at 30°C and 31.5°C represent acquired immune system.

## Hematocrit

Red blood cells showed no indication of intraspecific variation at 31.5°C. Hematocrit ratios can be used to estimate oxygen carrying capacity in blood and are predicted to increase to compensate for oxygen demand at higher temperatures when physiological processes on energetically expensive. However, results within the literature have demonstrated mixed outcomes. When examining juvenile chinook salmon (*Oncorhynchus tshawytscha*) Munoz et al. (2018) were able to demonstrate a positive correlation between CTmax and hematocrit. However, results similar to this study were identified in Atlantic Salmon (*Salmo salar*), where CTmax ratios was unexpectedly shown to be negatively related to CTmax and showed no correlation with relative ventricle mass (Bartlett et al. 2022). Additionally, hematocrit was shown to be unresponsive in both *Caesion cuning* and *Cheilodipterus quinquelineatus* when exposed to elevated temperatures (+3.0°C above ambient temperature) for 5-weeks (Johansen et al. 2021). While increasing hematocrit may provide an opportunity to increase oxygen carrying capacity, it does not appear to be a ubiquitous response among marine fish species exposed to elevated temperatures.

## Enzyme analysis

LDH and CS activity were significant correlated with temperature, positive and negatively, respectively; however, neither enzyme showed significant differences between low- and high-latitude populations. LDH and CS are proxy representation for anerobic glycolysis [citation] and aerobic capacity that can achieved via the citric acid cycle [citation], respectively. The transition from aerobic to anaerobic process is expected among ectotherms that experience warming thermal conditions, and has been previously identified in crown-of-thorns sea starts (*Acanthaster spp.*; Lang et al. 2021). However, a lack of significant difference between regions suggests that enzymatic performance within white muscle of *Acanthochromis polyacanthus*, does not contribute to organismal differences that were demonstrated via AAS. The anaerobic capacity of white muscle tissue has been shown to correlate to whole organism oxygen consumption, and it plays an important role in bursts of high-speed swimming (Sullivan and Somero 1980). However, enzymatic activity relevant to whole organismal response may be more prevalent in mitochondrial-rich muscle tissue-types, such as heart tissue that is associated with cardiac function, that has been previously shown to be a central determining mechanism for thermal, tolerances, local adaptation, and plasticity in fish (Farrell 2009; Ekström et al. 2017; Nyboer and Chapman 2018; Pichaud et al. 2019). Heart tissue may be more ideal for future enzymatic analysis, however, within small coral reef fish the lack of obtainable tissue mass can prove challenging.

## Conservation implications

Determining spatial patterns of thermal adaptation underlie the ability to predict population responses to climate change (Sorte et al. 2011; Moran et al. 2016). Species distribution models frequently assign all populations identical thermal ranges, however, such approaches risk inaccurately projecting species trajectories under climate change scenarios. Findings from this experiment demonstrated different aerobic physiology capacity among *A. polyacanthus* populations from low- and high-latitude regions as well as a decline in immune response within both regions as temperatures exceed 28.5°C. Models that assume all *A. polyacanthus* populations occupy the same environmental niche, in regard to AAS, as low-latitude populations risk underestimating the impact of elevated temperatures on high-latitude populations; vice-versa, models that assume that all *A. polyacanthus* populations occupy the environmental niche of high-latitude populations would risk underestimating the ability of low-latitude populations to response to climate change. Furthermore, when results from this study are examined concurrently with Gardiner et al. (2010), evidence suggests that fine scale biogeographic features that contribute to experience environmental variability can create pockets of adaptive heterogeneity. While large scale latitudinal patterns, such as co-gradient variation, may be present among populations that experience similar climatic variability, neighboring populations that experience difference environmental conditions (e.g., shallow lagoons) may display alternative responses to climate change different than responses predicted by broad scale biogeographical (e.g. latitude) patterns (also see Pallarés et al. 2023). These findings suggest that the adaptive landscape of species within marine environments may resemble a heterogenous matrix of populations with varying levels of adaptability, and therefore, the necessity to sample numerous populations in different environments to understand species’ adaptive landscape. Such an understanding would not only allow for more accurate predictive modelling but would also yield benefits for translocation-based conservation techniques such as assisted gene flow that rely on the introduction of beneficial traits as well as genetic compatibility between populations.

## Limitations and future research

Main limitations of this study reside in the 1) ever-changing nature of traits that are subjected to evolutionary processes, 2) researchers’ decision to focus on warmer, rather than cooler, temperatures to detect local adaptation, and 3) absence of equatorial populations. In this study physiological traits were measured between low- and high-latitude populations at a single time point, however, thermal breadths are not static (Kelly et al. 2012). Genetic adaptation and phenotypic plasticity will both impact how populations will respond to environmental changes via shifts in thermal performance. This current study was limited to current thermal tolerances; however, future research should explore genetic and plastic differences between populations to determine future adaptive potential among populations from each region via multi-generational experiments. Previous studies on *A. polyacanthus*, have detected genetic (Doherty et al. 1994; Planes et al. 2001; Van Herwerden and Doherty 2006) and plastic (Donelson and Munday 2012) differences between populations, suggesting that adaptive potential between examined regions are unlikely to be analogous.

Experimental temperatures in this study were chosen based on regional mean summer average temperatures as well as mid- and end-of-century predicted future ocean warming temperatures; physiological responses at cooler temperatures were not explored. Projected future ocean warming temperatures were chosen to explore population responses to future conditions, however, previous research on sticklebacks (*Gasterosteus aculeatus*) demonstrated that measuring aerobic physiology outside of thermal norms can reveal cryptic variation and local adaptation that may be otherwise unnoticed at intermediate temperatures (Pilakouta et al. 2020). Additionally, the exploration of aerobic physiology at cooler temperatures may have better revealed ‘local vs. foreign’ as well as ‘home and away’ criterion, outlined by Kawecki and Ebert (2004), used to detect local adaptation.

Lastly, this study was unable to source fish from known equatorial populations for *A. polyacanthus’s* range. Trailing edge populations are suggested to be living closest to their thermal limits and therefore possess greatest thermal tolerance as well as sensitivity to change in temperature; however, to date no *A. polyacanthus* have not explored comparisons between equatorial, low-latitude, and high-latitude populations. Future research should aim to include trailing edge populations within experiments to understand the extent of thermal tolerance within *A. polyacanthus*, and adaptive populations within populations that are predicted to be most sensitive to climate change.

## Conclusions

Population’s ability to respond to climate change will depend on experienced environmental conditions. Results from this study identify co-gradient variation between low- and high-latitude populations when examining AAS among populations found within habitats that possess similar fine-scale biogeographic features. However, previous *A.* polyacanthus research has identified counter-gradient variation, suggesting that *A. polyacanthus* populations represent a heterogenous matrix influenced by broad and fine-scale biogeographical features; further highlighting the need to understand intra-population variation within marine species. Assuming all populations will respond similarly to climate change will lead to inaccurate modelling and estimations of species vulnerability, and risk resource managers failing to provide effective conservation management solutions.

# Acknowledgements

Authors would like to acknowledge the JCU aquarium facility for technical assistance. Thank you to Jasmine Cane and Yogi Yasutake Cross for helping with fish sampling and dissections. Thank you to Lauren Fleming, Esther Bernard, and Alexa Ferrante for helping with the daily aquarium maintenance and husbandry with fish used in this experiment. Additional thank you to the collectors that helped with acquiring fish sampled in this experiment including Cairns Marine, Salty Pets, and FishCube.

# Competing Interests

Authors declare no competing interests.

# Funding and ethics

Funding was provided by \_\_\_\_\_ and, Australian Society for Fish Biology, and the JCU Centre of Excellence for Coral Reef Studies. Research was completed under JCU ethics approval A2764.

# References

Aitken SN, Bemmels JB (2016) Time to get moving : Assisted gene flow of forest trees. Evol Appl 9:271–290 doi:10.1111/eva.12293

Angilletta MJ, Oufiero CE, Sears MW (2004) Thermal adaptation of maternal and embryonic phenotypes in a geographically widespread ectotherm. Int Congr Ser 1275:258–266 doi:10.1016/j.ics.2004.07.038

Atkins KE, Travis JMJ (2010) Local adaptation and the evolution of species’ ranges under climate change. J Theor Biol 266:449–457 doi:10.1016/j.jtbi.2010.07.014

Australian Institute of Marine Science (AIMS) (2020) AIMS Sea Water Temperature Observing System (AIMS Temperature Logger Program).

Bartlett CB, Garber AF, Gonen S, Benfey TJ (2022) Acute critical thermal maximum does not predict chronic incremental thermal maximum in Atlantic salmon (Salmo salar). Comp Biochem Physiol -Part A Mol Integr Physiol 266:111143 doi:10.1016/j.cbpa.2022.111143

Barton M, Sunnucks P, Norgate M, Murray N, Kearney M (2014) Co-gradient variation in growth rate and development time of a broadly distributed butterfly. PLoS One 9:1–8 doi:10.1371/journal.pone.0095258

Bennett S, Duarte CM, Marbà N, Wernberg T (2019) Integrating within-species variation in thermal physiology into climate change ecology. Philos Trans R Soc B Biol Sci 374: doi:10.1098/rstb.2018.0550

Bradshaw AD (1984) Ecological significance of genetic variation between populations. In: Dirzo R., Sarukhan J. (eds) Perspectives on plant population ecology. Sinauer, Sunderland, MA, pp 213–228

Brown KT, Eyal G, Dove SG, Barott KL (2023) Fine-scale heterogeneity reveals disproportionate thermal stress and coral mortality in thermally variable reef habitats during a marine heatwave. Coral Reefs 42:131–142 doi:10.1007/s00338-022-02328-6

Chiono A, Paul JR (2023) The Climatic Variability Hypothesis and trade-offs in thermal performance in coastal and inland populations of Mimulus guttatus. Evolution 77:870–880 doi:10.1093/evolut/qpad005

Clark TD, Sandblom E, Jutfelt F (2013) Aerobic scope measurements of fishes in an era of climate change: respirometry, relevance and recommendations. J Exp Biol 216:2771–2782 doi:10.1242/jeb.084251

Conover DO, Clarke LM, Munch SB, Wagner GN (2006) Spatial and temporal scales of adaptive divergence in marine fishes and the implications for conservation. J Fish Biol 69:21–47 doi:10.1111/j.1095-8649.2006.01274.x

Conover DO, Duffy TA, Hice LA (2009) The covariance between genetic and environmental influences across ecological gradients: Reassessing the evolutionary significance of countergradient and cogradient variation. Ann N Y Acad Sci 1168:100–129 doi:10.1111/j.1749-6632.2009.04575.x

Deutsch CA, Tewksbury JJ, Huey RB, Sheldon KS, Ghalambor CK, Haak DC, Martin PR (2008) Impacts of climate warming on terrestrial ectotherms across latitude. Proc Natl Acad Sci U S A 105:6668–6672 doi:10.1073/pnas.0709472105

Doherty PJ, Mather P, Planes S (1994) Acanthochromis polyacanthus, a fish lacking larval dispersal, has genetically differentiated populations at local and regional scales on the Great Barrier Reef. Mar Biol 121:11–21 doi:10.1007/BF00349469

Donelson JM, Munday PL (2012) Thermal sensitivity does not determine acclimation capacity for a tropical reef fish. J Anim Ecol 81:1126–1131 doi:10.1111/j.1365-2656.2012.01982.x

Donelson JM, Munday PL (2015) Transgenerational plasticity mitigates the impact of global warming to offspring sex ratios. Glob Chang Biol 21:2954–2962 doi:10.1111/gcb.12912

Donelson JM, Munday PL, Mccormick MI, Nilsson GE (2011) Acclimation to predicted ocean warming through developmental plasticity in a tropical reef fish. Glob Chang Biol 17:1712–1719 doi:10.1111/j.1365-2486.2010.02339.x

Donelson JM, Munday PL, McCormick MI, Pankhurst NW, Pankhurst PM (2010) Effects of elevated water temperature and food availability on the reproductive performance of a coral reef fish. Mar Ecol Prog Ser 401:233–243 doi:10.3354/meps08366

Donelson JM, Sunday JM, Figueira WF, Gaitán-Espitia JD, Hobday AJ, Johnson CR, Leis JM, Ling SD, Marshall D, Pandolfi JM, Pecl G, Rodgers GG, Booth DJ, Munday PL (2019) Understanding interactions between plasticity, adaptation and range shifts in response to marine environmental change. Philos Trans R Soc B Biol Sci 374:20180186 doi:10.1098/rstb.2018.0186

Ekström A, Sandblom E, Blier PU, Cyr BAD, Brijs J, Pichaud N (2017) Thermal sensitivity and phenotypic plasticity of cardiac mitochondrial metabolism in European perch, Perca fluviatilis. J Exp Biol 220:386–396 doi:10.1242/jeb.150698

Eliason EJ, Clark TD, Hague MJ, Hanson LM, Gallagher ZS, Jeffries KM, Gale MK, Patterson DA, Hinch SG, Farrell AP (2011) Differences in thermal tolerance among sockeye salmon populations. Science (80- ) 332:109–112 doi:10.1126/science.1199158

Endler JA (1977) Geographic variation, speciation, and clines. Princeton University Press, Princeton, New Jersey, USA

Farrell AP (2009) Environment, antecedents and climate change: Lessons from the study of temperature physiology and river migration of salmonids. J Exp Biol 212:3771–3780 doi:10.1242/jeb.023671

García-Ramos G, Kirkpatrick M (1997) Genetic models of adaptation and gene flow in peripheral populations. Evolution (N Y) 51:21–28 doi:10.1111/j.1558-5646.1997.tb02384.x

Gardiner NM, Munday PL, Nilsson GE (2010) Counter-gradient variation in respiratory performance of coral reef fishes at elevated temperatures. PLoS One 5:e13299 doi:10.1371/journal.pone.0013299

Gunderson AR, Stillman JH (2015) Plasticity in thermal tolerance has limited potential to buffer ectotherms from global warming. Proc R Soc B Biol Sci 282: doi:10.1098/rspb.2015.0401

Hampe A, Petit RJ (2005) Conserving biodiversity under climate change: The rear edge matters. Ecol Lett 8:461–467 doi:10.1111/j.1461-0248.2005.00739.x

Harianto J, Carey N, Byrne M (2019) respR - An R package for the manipulation and analysis of respirometry data. Methods Ecol Evol 10:912–920 doi:https://doi.org/10.1111/2041-210X.13162

Hendry AP (2001) Traits in discrete populations: A theoretical framework for empirical tests. Evolution (N Y) 55:459–466

Hereford J (2009) A quantitative survey of local adaptation and fitness trade-offs. Am Nat 173:579–588 doi:10.1086/597611

Van Herwerden L, Doherty PJ (2006) Contrasting genetic structures across two hybrid zones of a tropical reef fish, Acanthochromis polyacanthus (Bleeker 1855). J Evol Biol 19:239–252 doi:10.1111/j.1420-9101.2005.00969.x

Van Herwerden L, Howard Choat J, Newman SJ, Leray M, Hillersøy G (2009) Complex patterns of population structure and recruitment of Plectropomus leopardus (Pisces: Epinephelidae) in the Indo-West Pacific: Implications for fisheries management. Mar Biol 156:1595–1607 doi:10.1007/s00227-009-1195-0

Hodgson MJ, Schwanz LE (2019) Drop it like it’s hot: Interpopulation variation in thermal phenotypes shows counter-gradient pattern. J Therm Biol 83:178–186 doi:10.1016/j.jtherbio.2019.05.016

Hoffmann AA, Sgró CM (2011) Climate change and evolutionary adaptation. Nature 470:479–485 doi:10.1038/nature09670

Hoffmann AA, Sørensen JG, Loeschcke V (2003) Adaptation of Drosophila to temperature extremes: Bringing together quantitative and molecular approaches. J Therm Biol 28:175–216 doi:10.1016/S0306-4565(02)00057-8

Janzen DH (1967) Why mountain passes are higher in the tropics. Am Nat 101:233–249

Jayasundara N, Somero GN (2013) Physiological plasticity of cardiorespiratory function in a eurythermal marine teleost, the longjaw mudsucker, Gillichthys mirabilis. J Exp Biol 216:2111–2121 doi:10.1242/jeb.083873

Johansen JL, Nadler LE, Habary A, Bowden AJ, Rummer J (2021) Thermal acclimation of tropical coral reef fishes to global heat waves. Elife 10:1–30

Jump AS, Peñuelas J (2005) Running to stand still: Adaptation and the response of plants to rapid climate change. Ecol Lett 8:1010–1020 doi:10.1111/j.1461-0248.2005.00796.x

Kawecki TJ, Ebert D (2004) Conceptual issues in local adaptation. Ecol Lett 7:1225–1241 doi:10.1111/j.1461-0248.2004.00684.x

Kelly MW, Griffiths JS (2021) Selection Experiments in the Sea: What Can Experimental Evolution Tell Us About How Marine Life Will Respond to Climate Change? Biol Bull 000–000 doi:10.1086/715109

Kelly MW, Sanford E, Grosberg RK (2012) Limited potential for adaptation to climate change in a broadly distributed marine crustacean. Proc R Soc B 349–356 doi:10.1098/rspb.2011.0542

Kuo ESL, Sanford E (2009) Geographic variation in the upper thermal limits of an intertidal snail: Implications for climate envelope models. Mar Ecol Prog Ser 388:137–146 doi:10.3354/meps08102

LaMonica LE, Fox RJ, Donelson JM (2021) Thermal sensitivity of juvenile rabbitfishes Siganus doliatus and S. lineatus (Siganidae): a key role for habitat? Coral Reefs 40:1307–1320 doi:10.1007/s00338-021-02146-2

Lang BJ, Donelson JM, Caballes CF, Doll PC, Pratchett MS (2021) Metabolic Responses of Pacific Crown-of-Thorns Sea Stars (Acanthaster sp.) to Acute Warming. Biol Bull 241:347–358 doi:10.1086/717049

Lefevre S, Wang T, McKenzie DJ (2021) The role of mechanistic physiology in investigating impacts of global warming on fishes. J Exp Biol 224: doi:10.1242/jeb.238840

Lenoir J, Bertrand R, Comte L, Bourgeaud L, Hattab T, Murienne J, Grenouillet G (2020) Species better track climate warming in the oceans than on land. Nat Ecol Evol 4:1044–1059 doi:10.1038/s41559-020-1198-2

Linhart YB, Grant MC (1996) Evolutionary significance of local genetic differentiation in plants. Annu Rev Ecol Syst 27:237–277 doi:10.1146/annurev.ecolsys.27.1.237

Ludt WB, Rocha LA (2015) Shifting seas: The impacts of Pleistocene sea-level fluctuations on the evolution of tropical marine taxa. J Biogeogr 42:25–38 doi:10.1111/jbi.12416

Mahony CR, MacLachlan IR, Lind BM, Yoder JB, Wang T, Aitken SN (2020) Evaluating genomic data for management of local adaptation in a changing climate: A lodgepole pine case study. Evol Appl 13:116–131 doi:10.1111/eva.12871

Marcil J, Swain DP, Hutchings JA (2006) Countergradient variation in body shape between two populations of Atlantic cod (Gadus morhua). Proc R Soc B Biol Sci 273:217–223 doi:10.1098/rspb.2005.3306

Martin LB, Han P, Lewittes J, Kuhlman JR, Klasing KC, Wikelski M (2006) Phytohemagglutinin-induced skin swelling in birds: Histological support for a classic immunoecological technique. Funct Ecol 20:290–299 doi:10.1111/j.1365-2435.2006.01094.x

Masson-Delmotte Z, A P, SL C, C P, S B, N C, Y C, L G, Al. G, Et (2021) Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report ofthe Intergovernmental Panel on Climate Change. Summary for Policymakers. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp 3–32 doi:10.1017/9781009157896.001.3

McKenzie DJ, Zhang Y, Eliason EJ, Schulte PM, Claireaux G, Blasco FR, Nati JJH, Farrell AP (2020) Intraspecific variation in tolerance of warming in fishes. J Fish Biol 1–20 doi:10.1111/jfb.14620

Merino S, Martínez J, Møller AP, Sanabria L, De Lope F, Pérez J, Rodríguez-Caabeiro F (1999) Phytohaemagglutinin injection assay and physiological stress in nestling house martins. Anim Behav 58:219–222 doi:10.1006/anbe.1999.1127

Miller-Sims VC, Gerlach G, Kingsford MJ, Atema J (2008) Dispersal in the spiny damselfish, Acanthochromis polyacanthus, a coral reef fish species without a larval pelagic stage. Mol Ecol 17:5036–5048 doi:10.1111/j.1365-294X.2008.03986.x

Moffett ER, Fryxell DC, Palkovacs EP, Kinnison MT, Simon KS (2018) Local adaptation reduces the metabolic cost of environmental warming. Ecology 99:2318–2326 doi:10.1002/ecy.2463

Molina-Montenegro MA, Naya DE (2012) Latitudinal Patterns in Phenotypic Plasticity and Fitness-Related Traits: Assessing the Climatic Variability Hypothesis (CVH) with an Invasive Plant Species. PLoS One 7:23–28 doi:10.1371/journal.pone.0047620

Moran E V., Hartig F, Bell DM (2016) Intraspecific trait variation across scales: Implications for understanding global change responses. Glob Chang Biol 22:137–150 doi:10.1111/gcb.13000

Morgan R, Finnøen MH, Jensen H, Pélabon C, Jutfelt F (2020) Low potential for evolutionary rescue from climate change in a tropical fish. PNAS 117:33365–33372 doi:10.1073/pnas.2011419117

Munday PL, Jones GP, Pratchett MS, Williams AJ (2008a) Climate change and the future for coral reef fishes. Fish Fish 9:261–285 doi:10.1111/j.1467-2979.2008.00281.x

Munday PL, Kingsford MJ, O’Callaghan M, Donelson JM (2008b) Elevated temperature restricts growth potential of the coral reef fish Acanthochromis polyacanthus. Coral Reefs 27:927–931 doi:10.1007/s00338-008-0393-4

Munoz NJ, Farrell AP, Heath JW, D NB (2018) Hematocrit Is Associated with Thermal Tolerance and Modulated by Developmental Temperature in Juvenile Chinook Salmon. Physiol Biochem Zool 91: doi:https://doi.org/10.1086/695556

Naya DE, Spangenberg L, Naya H, Bozinovic F (2012) Latitudinal patterns in rodent metabolic flexibility. Am Nat 179: doi:10.1086/665646

Nilsson GE, Crawley N, Lunde IG, Munday PL (2009) Elevated temperature reduces the respiratory scope of coral reef fishes. Glob Chang Biol 15:1405–1412 doi:10.1111/j.1365-2486.2008.01767.x

Norin T, Clark TD (2016) Measurement and relevance of maximum metabolic rate in fishes. J Fish Biol 88:122–151 doi:10.1111/jfb.12796

Nyboer EA, Chapman LJ (2018) Cardiac plasticity influences aerobic performance and thermal tolerance in a tropical, freshwater fish at elevated temperatures. J Exp Biol 221: doi:10.1242/jeb.178087

O’Brien EK, Higgie M, Reynolds A, Hoffmann AA, Bridle JR (2017) Testing for local adaptation and evolutionary potential along altitudinal gradients in rainforest Drosophila: beyond laboratory estimates. Glob Chang Biol 23:1847–1860 doi:10.1111/gcb.13553

van Oppen MJH, Puill-Stephan E, Lundgren P, De’ath G, Bay LK (2014) First-generation fitness consequences of interpopulational hybridisation in a Great Barrier Reef coral and its implications for assisted migration management. Coral Reefs 33:607–611 doi:10.1007/s00338-014-1145-2

Overgaard J, Kristensen TN, Mitchell KA, Hoffmann AA (2011) Thermal tolerance in widespread and tropical Drosophila species: Does phenotypic plasticity increase with latitude? Am Nat 178: doi:10.1086/661780

Pallarés S, Garoffolo D, Rodríguez B, Sánchez‐Fernández D (2023) Role of climatic variability in shaping intraspecific variation of thermal tolerance in Mediterranean water beetles. Insect Sci 1–14 doi:10.1111/1744-7917.13241

Pankhurst NW, Munday PL (2011) Effects of climate change on fish reproduction and early life history stages. Mar Freshw Res 62:1015–1026 doi:10.1071/MF10269

Pereira RJ, Sasaki MC, Burton RS (2017) Adaptation to a latitudinal thermal gradient within a widespread copepod species: The contributions of genetic divergence and phenotypic plasticity. Proc R Soc B Biol Sci 284:2017023 doi:10.1098/rspb.2017.0236

Pichaud N, Ekström A, Breton S, Sundström F, Rowinski P, Blier PU, Sandblom E (2019) Cardiac mitochondrial plasticity and thermal sensitivity in a fish inhabiting an artificially heated ecosystem. Sci Rep 9:1–11 doi:10.1038/s41598-019-54165-3

Pilakouta N, Killen SS, Kristjánsson BK, Skúlason S, Lindström J, Metcalfe NB, Parsons KJ (2020) Multigenerational exposure to elevated temperatures leads to a reduction in standard metabolic rate in the wild. Funct Ecol 34:1205–1214 doi:10.1111/1365-2435.13538

Pinsky ML, Eikeset AM, McCauley DJ, Payne JL, Sunday JM (2019) Greater vulnerability to warming of marine versus terrestrial ectotherms. Nature 569:108–111 doi:10.1038/s41586-019-1132-4

Planes S, Doherty PJ, Bernardi G (2001) Strong genetic divergence among populations of a marine fish with limited dispersal, Acanthochromis polyacanthus, within the Great Barrier Reef and the Coral Sea. Evolution (N Y) 55:2263–2273 doi:10.1111/j.0014-3820.2001.tb00741.x

Plumb WJ, Coker TLR, Stocks JJ, Woodcock P, Quine CP, Nemesio-Gorriz M, Douglas GC, Kelly LJ, Buggs RJA (2020) The viability of a breeding programme for ash in the British Isles in the face of ash dieback. Plants People Planet 2:29–40 doi:10.1002/ppp3.10060

Pörtner HO, Bock C, Mark FC (2017) Oxygen- & capacity-limited thermal tolerance: Bridging ecology & physiology. J Exp Biol 220:2685–2696 doi:10.1242/jeb.134585

Pörtner HO, Knust R (2007) Climate change affects marine fishes through the oxygen limitation of thermal tolerance. Science (80- ) 315:95–97 doi:10.1126/science.1135471

Pratchett MS, Messmer V, Reynolds J, Martin J, Clark TD, Munday PL, Tobin A., Hoey AS (2013) Effects of climate change on reproduction, larval development, and adult health of coral trout (Plectropomus spp.).

Richardson JL, Urban MC, Bolnick DI, Skelly DK (2014) Microgeographic adaptation and the spatial scale of evolution. Trends Ecol Evol 29:165–176 doi:10.1016/j.tree.2014.01.002

Robertson DR (1973) Field Observations on the Reproductive Behaviour of a Pomacentrid Fish, Acanthochromis polyacanthus. Z Tierpsychol 32:319–324 doi:10.1111/j.1439-0310.1973.tb01108.x

Des Roches S, Post DM, Turley NE, Bailey JK, Hendry AP, Kinnison MT, Schweitzer JA, Palkovacs EP (2018) The ecological importance of intraspecific variation. Nat Ecol Evol 2:57–64 doi:10.1038/s41559-017-0402-5

Rodgers GG, Donelson JM, Munday PL (2017) Thermosensitive period of sex determination in the coral-reef damselfish Acanthochromis polyacanthus and the implications of projected ocean warming. Coral Reefs 36:131–138 doi:10.1007/s00338-016-1496-y

Sandblom E, Clark TD, Gräns A, Ekström A, Brijs J, Sundström LF, Odelström A, Adill A, Aho T, Jutfelt F (2016) Physiological constraints to climate warming in fish follow principles of plastic floors and concrete ceilings. Nat Commun 7:1–8 doi:10.1038/ncomms11447

Sanford E, Kelly MW (2011) Local Adaptation in Marine Invertebrates. Ann Rev Mar Sci 3:509–35 doi:10.1146/annurev-marine-120709-142756

Santiago-Quesada F, Albano N, Castillo-Guerrero JA, Fernández G, González-Medina E, Sánchez-Guzmán JM (2015) Secondary phytohaemagglutinin (PHA) swelling response is a good indicator of T-cell-mediated immunity in free-living birds. Ibis (Lond 1859) 157:767–773 doi:10.1111/ibi.12295

Sasaki MC, Dam HG (2019) Integrating patterns of thermal tolerance and phenotypic plasticity with population genetics to improve understanding of vulnerability to warming in a widespread copepod. Glob Chang Biol 25:4147–4164 doi:10.1111/gcb.14811

Schmid M, Guillaume F (2017) The role of phenotypic plasticity on population differentiation. Heredity (Edinb) 119:214–225 doi:10.1038/hdy.2017.36

Seebacher F, Guderley H, Elsey RM, Trosclair PL (2003) Seasonal acclimatisation of muscle metabolic enzymes in a reptile (Alligator mississippiensis). J Exp Biol 206:1193–1200 doi:10.1242/jeb.00223

Shah AA, Gill BA, Encalada AC, Flecker AS, Funk WC, Guayasamin JM, Kondratieff BC, Poff NLR, Thomas SA, Zamudio KR, Ghalambor CK (2017) Climate variability predicts thermal limits of aquatic insects across elevation and latitude. Funct Ecol 31:2118–2127 doi:10.1111/1365-2435.12906

Snover ML, Adams MJ, Ashton DT, Bettaso JB, Welsh HH (2015) Evidence of counter-gradient growth in western pond turtles (Actinemys marmorata) across thermal gradients. Freshw Biol 60:1944–1963 doi:10.1111/fwb.12623

Somero GN (2010) The physiology of climate change: How potentials for acclimatization and genetic adaptation will determine “winners” and “losers.” J Exp Biol 213:912–920 doi:10.1242/jeb.037473

Sorte CJB, Jones SJ, Miller LP (2011) Geographic variation in temperature tolerance as an indicator of potential population responses to climate change. J Exp Mar Bio Ecol 400:209–217 doi:10.1016/j.jembe.2011.02.009

Spinks RK, Munday PL, Donelson JM (2019) Developmental effects of heatwave conditions on the early life stages of a coral reef fish. J Exp Biol 222: doi:10.1242/jeb.202713

Stamp MA, Hadfield JD (2020) The relative importance of plasticity versus genetic differentiation in explaining between population differences; a meta-analysis. Ecol Lett 23:1432–1441 doi:10.1111/ele.13565

Stevens GC (1989) The Latitudinal Gradient in Geographical Range: How so Many Species Coexist in the Tropics. Am Nat 133:240–256

Stillman JH (2002) Causes and consequences of thermal tolerance limits in rocky intertidal porcelain crabs, genus Petrolisthes. Integr Comp Biol 42:790–796 doi:10.1093/icb/42.4.790

Stillman JH (2003) Acclimation capacity underlies susceptibility to climate change. Science (80- ) 301:65 doi:10.1126/science.1083073

Stuart-Smith RD, Edgar GJ, Bates AE (2017) Thermal limits to the geographic distributions of shallow-water marine species. Nat Ecol Evol 1:1846–1852 doi:10.1038/s41559-017-0353-x

Sullivan KM, Somero GN (1980) Enzyme activities of fish skeletal muscle and brain as influenced by depth of occurrence and habits of feeding and locomotion. Mar Biol 60:91–99 doi:10.1007/BF00389152

Sunday JM, Bates AE, Dulvy NK (2011) Global analysis of thermal tolerance and latitude in ectotherms. Proc R Soc B Biol Sci 278:1823–1830 doi:10.1098/rspb.2010.1295

Taboun ZS, Walter RP, Ovenden JR, Heath DD (2021) Spatial and temporal genetic variation in an exploited reef fish: The effects of exploitation on cohort genetic structure. Evol Appl 14:1286–1300 doi:10.1111/eva.13198

Tewksbury JJ, Huey RB, Deutsch CA (2008) Ecology: Putting the heat on tropical animals. Science (80- ) 320:1296–1297 doi:10.1126/science.1159328

Thibault M, Blier PU, Guderley H (1997) Seasonal variation of muscle metabolic organization in rainbow trout (Oncorhynchus mykiss). Fish Physiol Biochem 16:139–155 doi:10.1007/BF00004671

Wu NC, Seebacher F (2022) Physiology can predict animal activity, exploration, and dispersal. Commun Biol 5:1–11 doi:10.1038/s42003-022-03055-y

Yampolsky LY, Schaer TMM, Ebert D (2014) Adaptive phenotypic plasticity and local adaptation for temperature tolerance in freshwater zooplankton. Proc R Soc B Biol Sci 281:20132744 doi:10.1098/rspb.2013.2744

Zarco-Perello S, Pratchett M, Liao V (2012) Temperature-growth performance curves for a coral reef fish, Acanthochromis polyacanthus. Galaxea, J Coral Reef Stud 14:97–103 doi:10.3755/galaxea.14.97

# Figures

# Table

# Supplemental Material

## Supplemental figures

## Supplemental tables

**Climate change has begun to shift environmental conditions away from historic thermal regimes that populations evolved under**. As climate continues to shift species may struggle to keep pace(Jump and Peñuelas 2005).

Evolutionary processes have previously been ignored when projecting species responses to climate change due to the thought that they were too slow to influence measurable demographic effects (Kelly and Griffiths 2021). However, species may overcome this obstacle via large effective population sizes and fecundity rates, whereby (if the necessary genetic variation is available) strong selection pressures could produce sizeable changes in allele frequency within a single generation/cohort (Kelly and Griffiths 2021). Therefore, important to consider evolutionary process that will influence past and future populations responses to climate change. **This information should come later maybe even just have in discussion??**

**Local adaptation occurs within metapopulations when native genotypes are better adapted to local environment conditions than foreign genotypes** (Linhart and Grant 1996; Kawecki and Ebert 2004; Hereford 2009). Through gene x environment interactions, local adaptation may arise in spatially heterogenous environments if divergent selection can overcome the homogenizing effects of gene flow and temporal instability in selective forces (Endler 1977; Bradshaw 1984; García-Ramos and Kirkpatrick 1997; Hendry 2001; Kawecki and Ebert 2004; Richardson et al. 2014). Isolated populations are particularly susceptible to local adaptation... Metapopulations may therefore be comprised of a mosaic of locally adapted populations that have evolved optimized traits suited to local environments.

**Thermal conditions across latitudinal gradients can shaped the fitness landscape via locally adapted traits.** ~~Local adaptation typically thought of \_\_\_\_\_, but can also be in the form of thermal tolerances (Aitkens and Travis 2010). The pervasive nature of temperature at various biological levels (e.g. cellular biochemistry, physiological processes), particularly among ectotherms, suggests that it can impose strong divergent selection pressures on populations (Pereira et al. 2017).~~ Moreover, temperature-dependent clines (i.e. local adaptation) between populations represent diverging evolutionary histories that can elucidate how populations will respond to climate change (Somero 2010; Hoffmann and Sgró 2011; Pereira et al. 2017).

Local adaptation, phenotypic plasticity, and genetic arhectiture represent threes components that much be analysed together to understand future responses.

However, recent evidence suggests that the rapid pace of climate change can disrupt local adaptation processes via shifting selection pressures (Hoffmann and Sgró 2011).

**The ability to response to shifting selection pressure will depend on the genetic architecture and demographic processes found within different populations.**

* Need to consider both populations:
  + Physiological traits and underlying:
  + CVH hypothesis and other one

**Broad range species may not always have increased adaptive potential/Genetic architecture to overcome changes in selection pressures caused by climate change. Isolated populations across large ranges may all be affected, therefore entire species affected (see (Jump 2005)).**

* Thus, making it important to consider regional influences within species ranges…
* Long lived species can rapidly change allele frequencies within generation due to number of offspring produced

**Species regions (trailing/core/leading edge)**

**Apoly/Research objectives and aims**

Metapopulations that exist over large geographical distributions and thermal gradients contain locally adapted populations that can help species buffer against extinction (Conover et al. 2006, 2009; Munday et al. 2008a; Pereira et al. 2017). However, local adaptation and genetic subdivision within metapopulations can also produce populations with narrow thermal breadths; increasing susceptibility to warming temperatures (Atkins and Travis 2010; Kelly and Griffiths 2021).

However, to accurately predict potential species responses to warming temperatures, intraspecific variation between populations must be accounted for.

Locally adapted optimums and phenotypes can be identified via thermal performance curves (i.e., TPCs; physiological metrics measured across temperatures) (Eliason et al. 2011; Jayasundara and Somero 2013). When used to understand key mechanisms that affect organisms’ performance, such as aerobic capacity, TPCs can begin to identify physiological limits and how populations will respond to thermal changes (Pörtner and Knust 2007; Gardiner et al. 2010; Somero 2010; Eliason et al. 2011). However, caution is warranted when extrapolating results from TPC experiments. Life stage (e.g., hatchling, juvenile, adult), and physiological state (e.g., reproductively active, food deprived) can alter an individual’s thermal performance; additionally, different physiological traits and functions (e.g., oxygen uptake, reproduction, immunity) may possess different thermal optima (multiple performance – multiple optima hypothesis) (Clark et al. 2013).

~~Intraspecific variation within marine systems (outside of a few economically important species) have not received the same attention as terrestrial systems (Sanford and Kelly 2011). Marine systems have previously been viewed as demographically open networks with minimal dispersal barriers. However, a growing body of evidence suggests that oceanographic features, life history traits, and larval dispersal ability act as challenges to gene flow; including the inability for few successful migrants to overcome localized selection pressures (Sanford and Kelly 2011). Evidence of greater confinement to organismal thermal tolerance limits suggests that marine species and their populations are locally adapted to thermal conditions and can be more sensitive to warming temperatures than terrestrial species(Sunday et al. 2011; Pinsky et al. 2019; Lenoir et al. 2020).~~

Intraspecific variation with *A.* polyacanthus populations suggests the presence of varying thermal tolerances and adaptive potential across different populations. Previous research on low-latitude populations have demonstrated that projected end of century temperature projects of +2-3°C (Masson-Delmotte et al. 2021) have negative effects on sex ratios (Donelson and Munday 2015; Rodgers et al. 2017) , growth (Munday et al. 2008b; Zarco-Perello et al. 2012; Spinks et al. 2019), reproduction (Donelson et al. 2010; Pankhurst and Munday 2011), and aerobic capacity (Nilsson et al. 2009; Gardiner et al. 2010; Donelson et al. 2011; Donelson and Munday 2012) among low-latitude populations. While there is limited research on southern populations, evidence from Gardiner *et al.,* (2010) and Donelson and Munday (2012) suggest that models for this species that assume a constant thermal niche across populations, would risk inaccurately projecting geographical persistence, and potential for evolutionary change (Hampe and Petit 2005; Hoffmann and Sgró 2011; Sanford and Kelly 2011; Kelly et al. 2012; O’Brien et al. 2017; Moffett et al. 2018). However, intraspecific variation between northern and southern populations of *A. polyacanthus* remains underexplored, with Gardiner *et al.,* (2010) and Donelson and Munday (2012), both examining the same southern populations (Heron Island). The lack of diversity in explored locations suggests the intraspecific variation within the region remains underexamined.

--------------------------------------------------------------------------------------------------------------------------------------

When

~Fish are sensitive to temperature. Although they may not be living at their thermal maximums temperature shifts of a dew degrees can impact important fitness functions~.~The future distribution of marine fish species will be determined by the relationship between organisms’ biochemical and physiological constraints, and temperature (Munday et al. 2008a; McKenzie et al. 2020; Lefevre et al. 2021; Wu and Seebacher 2022). ~

~however, variation between fish populations has been largely ignored and restricted to few locations.~

~as temperatures warm it becomes increasingly more important to focus on marine species that are expected to witness +3c by the end of the century~

~~Irrespective of the evolutionary mechanisms at play, understanding thermal tolerance across populations is necessary for estimating species level response to warming temperatures~~ (Sorte et al. 2011; Bennett et al. 2019; McKenzie et al. 2020).

One of the leading hypotheses for predicting intraspecific spatial variation is the climatic variability hypothesis (CVH). Under the CVH, thermal conditions at low-latitudes, warmer temperatures and less variation, are hypothesized to favor genetic adaptation; whereas, high-latitudes conditions, cooler temperatures with more variation, are expected favor phenotypic plasticity. However, the evidence supporting the CVH is not ubiquitous(Overgaard et al. 2011; Chiono and Paul 2023).

Thermal tolerance of individuals can be used as a proxy to estimate a population’s ability to tolerate warmer temperatures (Sorte et al. 2011).