Received: 29 January 2021 | Revised: 24 May 2021 | Accepted: 13 August 2021

DOI: 10.1111/mec.16143

ORIGINAL ARTICLE

MOLECULAR ECOLOGY WILEY

Balanced polymorphism fuels rapid selection in an invasive crab despite high gene flow and low genetic diversity

Carolyn K. Tepolt[1] | Edwin D. Grosholz[2] | Catherine E. de Rivera[3] | Gregory M. Ruiz[4]

[1]Department of Biology, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA

[2]Department of Environmental Science and Policy, University of California, Davis, California, USA

[3]Department of Environmental Science and Management, Portland State University, Portland, Oregon, USA

[4]Smithsonian Environmental Research Center, Smithsonian Institution, Edgewater, Maryland, USA

Correspondence
Carolyn K. Tepolt, Department of Biology, Woods Hole Oceanographic Institution, 266 Woods Hole Road, MS #33, Woods Hole, MA, USA.
Email: ctepolt@whoi.edu

Funding information
National Science Foundation, Grant/Award Number: 1514893; Smithsonian Institution; The Penzance Endowed Fund

Abstract

Adaptation across environmental gradients has been demonstrated in numerous systems with extensive dispersal, despite high gene flow and consequently low genetic structure. The speed and mechanisms by which such adaptation occurs remain poorly resolved, but are critical to understanding species spread and persistence in a changing world. Here, we investigate these mechanisms in the European green crab *Carcinus maenas*, a globally distributed invader. We focus on a northwestern Pacific population that spread across >12 degrees of latitude in 10 years from a single source, following its introduction <35 years ago. Using six locations spanning >1500 km, we examine genetic structure using 9376 single nucleotide polymorphisms (SNPs). We find high connectivity among five locations, with significant structure between these locations and an enclosed lagoon with limited connectivity to the coast. Among the five highly connected locations, the only structure observed was a cline driven by a handful of SNPs strongly associated with latitude and winter temperature. These SNPs are almost exclusively found in a large cluster of genes in strong linkage disequilibrium that was previously identified as a candidate for cold tolerance adaptation in this species. This region may represent a balanced polymorphism that evolved to promote rapid adaptation in variable environments despite high gene flow, and which now contributes to successful invasion and spread in a novel environment. This research suggests an answer to the paradox of genetically depauperate yet successful invaders: populations may be able to adapt via a few variants of large effect despite low overall diversity.

KEYWORDS
balanced polymorphism, invasive species, island of divergence, rapid adaptation, seascape genomics

1 | INTRODUCTION

In the ocean, where many species are characterized by large population sizes, long-distance planktonic dispersal and broad ranges (Kinlan & Gaines, 2003; Palumbi & Pinsky, 2014), there has been a classical assumption of genetic homogeneity and little persistent differentiation (Hedgecock, 1986). Recently, however, both population genomics and comparative physiology have uncovered evidence of genetic selection and functional differences among widespread populations living across varied marine environments (Pespeni & Palumbi, 2013; Sanford & Kelly, 2011). Likewise, genetic studies and associated modelling have detected subtle genetic structure driven by oceanography in species that disperse widely (Galindo et al., 2006; White et al., 2010; Xuereb et al., 2018). This increasing

 © 2021 John Wiley & Sons Ltd

13652294x, 2021, 0, Downloaded from https://onlinelibrary.wiley.com. By MBL WHOI Library, Oceanographic Institution-MS#8- on [02/12/2021]. Re-use and distribution is strictly not permitted, except for Open Access articles

evidence for differentiation in the sea begs the question of how quickly, and through which mechanisms, marine species may cope with rapidly changing environmental conditions (Munday et al., 2013). Introduced species, which in many cases establish and thrive in novel habitats, offer the opportunity to examine these questions in the context of the natural environment (Blackburn, 2008; Lee et al., 2011).

Marine species exhibit a spectrum of evolutionary mechanisms based in part on their dispersal. Local adaptation in the classical sense is restricted to species with relatively limited dispersal, which facilitates the selection and retention of adaptive alleles within a population (Kawecki & Ebert, 2004). Relatively isolated populations are also likely to diverge due to neutral processes, as genetic drift changes allele frequencies across the genome (Ellingson & Krug, 2016; Prunier et al., 2017). On the other end of this evolutionary spectrum lie open marine systems, where alleles are continually exported from each location to a mixed pool of larvae that may settle in environments far different from their sources. In this dynamic, balanced polymorphism is favoured, and adaptive variation is maintained within the population as a whole (Sanford & Kelly, 2011). These adaptive alleles mix as larvae disperse, and the environmental conditions they encounter as they recruit can result in strong and rapid selection that culls less-fit alleles from the local population (Sotka, 2012). This phenomenon has been described largely in the context of maintaining differentiation across small-scale environmental differences year after year in systems where the scale of dispersal far exceeds the scale of selection. For example, strong selection to salinity appears to have maintained an enzymatic cline in mussels along Long Island Sound, USA (Koehn et al., 1980), and microhabitat differences across tidal heights maintain balanced polymorphism in limpet populations (Schmidt et al., 2000). Such examples may better reflect the realized capacity of highly dispersive marine species to adapt to stressors across complex oceanographic regimes than studies of strict local adaptation (Véliz et al., 2006).

As species expand into new environments, the process of adaptation may be mediated by the complex demographic effects that often occur at range edges (Bridle & Vines, 2007; Chuang & Peterson, 2016). Expanding populations are frequently characterized by sequential bottlenecks and losses of genetic diversity caused by small groups of colonizing organisms (Bors et al., 2019; Eckert et al., 2008; White et al., 2013). The success of some such populations, which multiply and spread despite low genetic diversity, has been coined the "genetic paradox of invasions" (Roman & Darling, 2007). These bottlenecks can also lead to increased stochasticity at range edges, causing allele surfing and other distinctive genetic patterns (Excoffier & Ray, 2008). Gene flow plays a substantial role in this process. In some cases, low-diversity edge populations may be evolutionarily limited by a lack of gene flow (Sexton et al., 2011; Takahashi et al., 2016), while in others, semi-isolation at range edges permits rapid evolution in organisms at the expansion front (Kilkenny & Galloway, 2012; Phillips et al., 2006; Szücs et al., 2017). High dispersal and large populations may also facilitate species persistence and expansion, if functional diversity can be maintained and quickly spread throughout the expanding range (Rius & Darling, 2014). The maintenance of such diversity can in theory provide the raw substrate for adaptation and permit extremely quick evolutionary response to shifting conditions (Llaurens et al., 2017; Tigano & Friesen, 2016). However, to date, the relative contributions of selection and drift as populations establish in novel environments have not been explored empirically in high gene flow systems.

The European green crab (*Carcinus maenas*) along the northeast Pacific coastline presents an ideal test case for untangling the dynamics of rapid marine adaptation and differentiation with high potential gene flow. In this region, the species established an initial population in San Francisco Bay by 1990 (Carlton & Cohen, 2003), and spread >1500 km to Vancouver Island in <10 years despite deriving from a single, significantly bottlenecked source (Tepolt et al., 2009). Green crabs advanced along the coast and primarily to the north, reaching northern California by 1995, southern Oregon by 1997 and Vancouver Island, British Columbia, by 1998 (Behrens Yamada & Gillespie, 2008; Figure 1). This rapid expansion was associated with extremely strong positive El Niño-Southern Oscillation (ENSO) indices in 1997–1998 that promoted high reproductive output, northward transport and coastal retention of larvae (Behrens Yamada et al., 2005; Behrens Yamada & Kosro, 2010; See & Feist, 2010). Importantly, in the northeast Pacific, *C. maenas* are found almost exclusively in shallow waters of protected embayments and not along the exposed outer coast between bays, resulting in a disjunct distribution of green crab populations. This habitat distribution is similar to its introduced range in South Africa, where the rocky coast is also subject to high-energy wave action (Hampton & Griffiths, 2007), but differs from its more continuous distribution in other global regions (Carlton & Cohen, 2003). The species also has a relatively wide environmental tolerance and diet breadth, along with a 30- to 75-day pelagic larval duration (Dawirs, 1985), which have contributed to its spread and establishment in six introduced regions across five continents (Carlton & Cohen, 2003; Hidalgo et al., 2005).

The importance of ENSO events in the spread and abundance of northeast Pacific *C. maenas* suggests that both temperature and local oceanography may play substantial roles in structuring the population. Decades of field surveys of abundance in both the northwest Atlantic and northeast Pacific support the importance of temperature during early development in driving recruitment strength: cold winters have been associated with weaker recruitment and smaller cohorts of crabs than milder years (Behrens Yamada & Kosro, 2010; Welch, 1968). A global physiological study demonstrated population-level differences in adult heat and cold tolerance consistent with local adaptation (Tepolt & Somero, 2014). Subsequently, transcriptomic work has identified genetic markers associated with temperature tolerance on a population level (Tepolt & Palumbi, 2020). Like many marine species, *C. maenas* larvae have shown narrower temperature tolerances than adults in laboratory trials, suggesting that thermal tolerance at early life stages may be particularly important in shaping crab

1365294x, 2021, 0, Downloaded from https://onlinelibrary.wiley.com. By MBL WHOI Library, Oceanographic Institution-MS#8- on [02/12/2021]. Re-use and distribution is strictly not permitted, except for Open Access articles

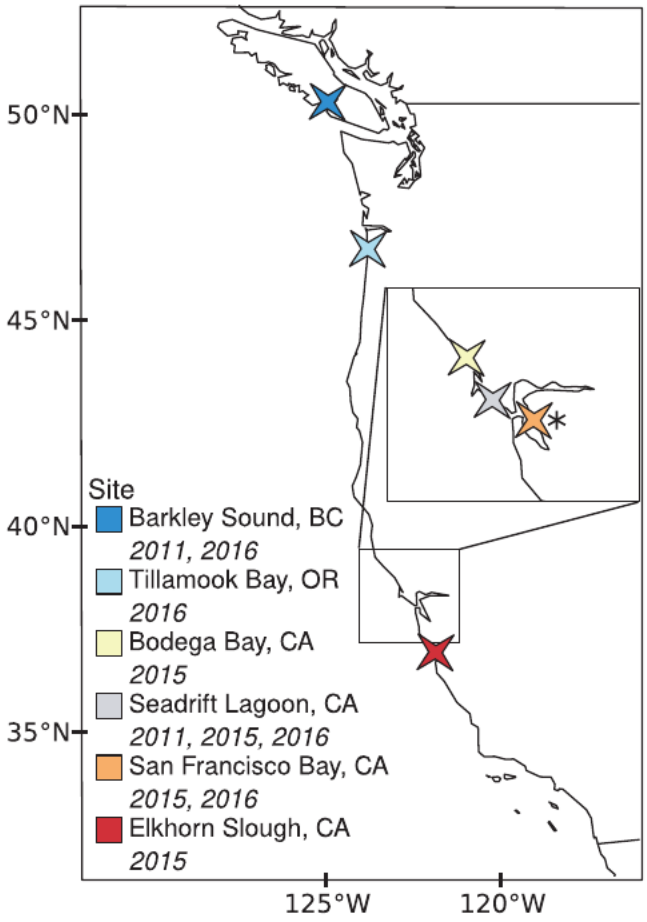

FIGURE 1 Map of sampling sites; year(s) of sampling given in italics under site names. From north to south: Barkley Sound, BC (2011, 2016); Tillamook Bay, OR (2016); Bodega Bay, CA (2015); Seadrift Lagoon, CA (2011, 2015, 2016); San Francisco Bay, CA (2015, 2016); and Elkhorn Slough, CA (2015). Asterisk indicates the location where the species was initially introduced (first detected in 1989)

populations across different years (Dawirs, 1985; de Rivera et al., 2007).

Here, we use transcriptome-derived single nucleotide polymorphisms (SNPs) from *C. maenas* populations in the northeast Pacific to test the roles of connectivity and selection in shaping the population structure of this highly dispersive and recently introduced species. Using six sites spanning >1500 km of coastline, we examine population structure and relative migration to elucidate connectivity among embayments across the species' northeast Pacific range. For a few sites, we have temporal samples spanning 2–5 years, which we use to examine the stability of population structure over time. Finally, we test for candidate genes for selection across a thermal latitudinal gradient, comparing these candidates to genes identified in a prior global study of the genetic basis of thermal tolerance differences in the species. As this population was founded <35 years ago from a single source, our data represent patterns of divergence and selection that have arisen in under 20 generations.

2 | MATERIALS AND METHODS

2.1 | Sample collection

Twelve crabs were sampled from each of six sites along the northeast Pacific range of *C. maenas* in 2015–2016 (Figure 1). Two of these sites (Seadrift Lagoon and San Francisco Bay, CA, USA) were sampled in both years, while the remaining sites were sampled once. We also re-analysed raw sequence data from a prior study of crabs collected in 2011 from two sites (Seadrift Lagoon and Barkley Sound, BC, Canada; Tepolt & Palumbi, 2015). Crabs were collected by hand or trap, and hearts were dissected and stored in RNALater at −80°C.

2.2 | Extraction and sequencing

Total RNA was extracted from cardiac tissue using TRIzol (Invitrogen) with 1-bromo-3-chloropropane (Simms et al., 1993). RNA was quantified using the broad-range RNA assay on a Qubit 3.0 fluorometer (Invitrogen), and up to 4 μg of RNA was used to prepare individually barcoded cDNA libraries with Illumina's TruSeq Stranded mRNA Library Prep Kit (Illumina). Libraries were sent to the University of California Berkeley's Genomics Sequencing Laboratory, where they were quantified and pooled into groups of 16 multiplexed samples run on five lanes of an Illumina HiSeq 4000 in 50-bp single-end reads.

2.3 | Sequence processing and SNP identification

Raw sequences were cleaned and trimmed using TRIM GALORE! version 0.6.4 (http://www.bioinformatics.babraham.ac.uk/projects/trim_galore/), a wrapper for CUTADAPT version 2.6 (Martin, 2011). A nucleotide call quality cutoff of Phred ≥20 was used, and reads ≤20 bp after adapter removal and quality trimming were discarded. A published *C. maenas* cardiac transcriptome was used as a reference (Tepolt & Palumbi, 2015), after an expression-based screening to remove poorly supported contigs and reduce computational load. Briefly, we mapped trimmed and clipped reads from Tepolt and Palumbi (2015) back to the reference transcriptome using SALMON version 1.2.1 (Patro et al., 2017). We retained only contigs with TPM > 1, and re-annotated these contigs using ENTAP version 0.9.1 (Hart et al., 2020), comparing all six reading frames against the Swissprot, TrEMBL and nr protein databases (downloaded March 2020). Annotations to Decapoda were prioritized with the program's "--taxon" flag. Contigs with a clear taxonomic mismatch to decapods (bacteria, green plants, fungi, etc.), as well as all probable mitochondrial and ribosomal contigs, were identified and removed from the project after alignment to minimize nontarget mapping. This resulted in a clean reference transcriptome of 25,552 nuclear contigs.

Cleaned reads were mapped back to the *C. maenas* cardiac transcriptome using BOWTIE2 version 2.4.1 with default settings (Langmead & Salzberg, 2013). PICARD version 2.22.0 was used to sort reads,

1365294x, 2021, 0, Downloaded from https://onlinelibrary.wiley.com. By MBL WHOI Library, Oceanographic Institution-MS#8- on [02/12/2021]. Re-use and distribution is strictly not permitted, except for Open Access articles

identify and mark duplicate read sequences, and index the resulting bam files (http://broadinstitute.github.io/picard). The Genome Analysis Toolkit (GATK) version 4.1.7.0 was used to identify and genotype biallelic SNPs (DePristo et al., 2011; McKenna et al., 2010).

Across all 120 samples (24 from 2011 and 96 from 2015–2016), GATK identified 163,261 biallelic SNPs with Phred quality scores ≥20. We identified high-quality, well-supported SNPs for downstream analyses using a custom python script that retained only individual genotypes with Phred ≥20 and supported by five or more reads. We excluded SNPs missing high-quality genotypes at four or more individuals for any site-by-year samples of 12 individuals, SNPs with heterozygosity ≥0.7 (to screen out obvious paralogs), and SNPs where the alternate allele was observed only once across all individuals (to minimize bias by potential sequencing errors). In total, 9376 SNPs had high-quality genotypes for eight or more individuals per group and were retained for downstream processing. All 120 individuals had high-quality genotypes at >80% of these SNPs.

2.4 | Identification of putative inversion polymorphisms

We explored the relationship of the 9376 high-quality SNPs to identify potential inversion polymorphisms and other disproportionately large groups of SNPs in linkage disequilibirum (LD). Pairwise R^2 was calculated across all SNPs using the --geno-r2 and --interchrom-geno-r2 options in VCFTOOLS version 0.1.16 (Danecek et al., 2011). We then used the R package LDNA version 0.64 to identify networks of SNPs in large, compact clusters, setting minimum edges to 45 (expected for 10 closely linked SNPs) and Φ to 15 (Kemppainen et al., 2015).

We identified one large outlier LD cluster, which contained 168 SNPs from 56 different contigs. To further investigate this cluster, we explored the relationship between member SNPs using principal components analysis (PCA) in SMARTPCA, implemented in EIGENSOFT version 7.2.1 (Price et al., 2006). We used the 116 individuals that had <20% missing genotypes across the 168 SNPs in this cluster. This PCA separated individuals into three clear groups along PC1, and we calculated F_{IS} within each of these groups to determine relative heterozygosity (Kemppainen et al., 2015). These analyses strongly suggested an inversion polymorphism (see Section 3 below), so for clarity we refer to this group of 168 SNPs as an "inferred inversion" throughout the rest of the paper. To compare the impact this putative inversion had on overall population structure, we also ran a PCA on the same 116 individuals using the full SNP set both with and without the 168 SNPs in the inferred inversion (N = 9376 and 9208 SNPs, respectively).

2.5 | Genetic structure and diversity

The 9376 high-quality SNPs were separately screened to identify all sets of markers in LD and generate a set of independent SNPs for population genomics. Pairwise R^2 values (calculated above) were used to identify groups of two or more SNPs in LD at $R^2 \geq 0.8$ using the R package IGRAPH version 1.2.4.2 (Csardi & Nepusz, 2006), and then all but one SNP in each group was removed, leaving a set of 6848 independent SNPs. The one SNP retained from each group had the highest number of high-quality genotypes, with lower coverage SNPs within an LD group preferentially removed. We use the term "independent" to indicate that these SNPs have been screened to remove those in strong LD, but note that these SNPs may be in LD at lower levels so are not all truly independent. Similarly, this set of 6848 independent SNPs retained 54 of the 168 SNPs in the inferred inversion which were in lower levels of LD with each other (R^2 = .29 to .79).

Basic descriptive statistics were calculated for each site-by-year sample using the set of 6848 independent SNPs (Table 1). Allelic richness (Ar) and private allelic richness (pAr) were determined using ADZE version 1.0 (Szpiech et al., 2008). The R package GENEPOP version 1.1.7 was used to calculate observed and expected heterozygosity (H_O and H_E), and to calculate the inbreeding coefficient (F_{IS}) and test for heterozygote excess or deficiency using Hardy–Weinberg tests (Rousset, 2008). The number of polymorphic SNPs in each sample was determined using ARLEQUIN version 3.5.2.2 (linux core implementation; Excoffier & Lischer, 2010).

To identify a subset of putatively neutral SNPs with which to examine population structure unconfounded by selection, we used BAYPASS version 2.2 in the core model (Gautier, 2015), with each site-by-year sample treated as its own group. We assessed potential outliers using a simulated pseudo-observed data set of 6848 SNPs with the parameters of the real data to set a 10% false discovery rate (FDR) threshold for SNP XtX. This conservative threshold was chosen to avoid retaining SNPs under weak selection, thus yielding a set of SNPs more likely to be truly neutral. This frequency-based approach removed all but one of the SNPs later identified as a candidate for environmental association (see below).

Genetic structure for both the independent (N = 6848) and putatively neutral (N = 6311) SNP sets was assessed with SMARTPCA. Pairwise F_{ST} was calculated between all site-by-year groups according to Weir and Cockerham's (1984) approach using the R package STAMPP version 1.6.1 with both the independent and putatively neutral SNP sets (Pembleton et al., 2013). Significance was assessed using 10,000 permutations, and resulting p-values were adjusted for multiple tests using a Benjamini–Hochberg FDR correction (Benjamini & Hochberg, 1995).

We included only one of the 2015-2016 temporal samples from each site for an analysis of relative migration using the putatively neutral SNP set (Table 1). Symmetry and relative magnitude of migration between sites was assessed using the"divMigrate" function in the R package DIVERSITY version 1.9.90, with the Nm method and 1000 bootstraps (Sundqvist et al., 2016). This approach, which calculates relative directional migration, was chosen because it is more robust if populations do not perfectly satisfy some of the assumptions underlying approaches to quantify an effective migration rate (e.g., island model, mutation–drift equilibrium).

13652294x, 2021, 0, Downloaded from https://onlinelibrary.wiley.com. By MBL WHOI Library, Oceanographic Institution-MS#8- on [02/12/2021]. Re-use and distribution is strictly not permitted, except for Open Access articles

TABLE 1 Sampling information and summary statistics for each site × year sample

Code	Site	Coordinates	Year	Age	N	N_{poly}	Ar	pAr	H_O	H_E	F_{IS}
ES_15[a]	Elkhorn Slough, CA	36.820, −121.745	2015	Adult	12	5546	1.708	0.00697	0.2612	0.2510	−0.0409
SF_15[a]	San Francisco Bay, CA	37.997, −122.370	2015	Adult	12	5549	1.702	0.00621	0.2510	0.2491	−0.0078
SF_16	San Francisco Bay, CA	37.997, −122.370	2016	YOY	12	5560	1.705	0.00666	0.2593	0.2501	−0.0365
SL_11	Seadrift Lagoon, CA	37.907, −122.662	2011	Adult	12	5233	1.669	0.00494	0.2461	0.2414	−0.0196
SL_15[a]	Seadrift Lagoon, CA	37.907, −122.662	2015	YOY	12	5234	1.675	0.00584	0.2609	0.2424	−0.0761
SL_16	Seadrift Lagoon, CA	37.907, −122.662	2016	YOY	12	5264	1.677	0.00434	0.2498	0.2442	−0.0228
BB_15[a]	Bodega Bay, CA	38.324, −123.054	2015	Adult	12	5538	1.706	0.00645	0.2681	0.2511	−0.0674
OR_16[a]	Tillamook Bay, OR	45.542, −123.904	2016	YOY	12	5548	1.711	0.00762	0.2618	0.2539	−0.0311
BC_11	Barkley Sound, BC	49.026, −125.346	2011	Adult	12	5562	1.711	0.00771	0.2600	0.2520	−0.0316
BC_16[a]	Barkley Sound, BC	49.026, −125.346	2016	Adult	12	5517	1.705	0.00676	0.2630	0.2512	−0.0471

Note: Adult = 1+ year old animal; YOY = young of the year or <1 year old animal. N_{poly} = number of polymorphic SNPs; Ar = allelic richness; pAr = private allelic richness; H_O = observed heterozygosity; H_E = expected heterozygosity; F_{IS} = Wright's inbreeding coefficient. All samples showed a significant heterozyote excess ($p < .05$).

[a]Samples used in tests of selection and relative migration.

All analyses showed strong separation of a single site, Seadrift Lagoon, from all other sites (see Section 3 below). Because of this genetic distinctiveness, isolation-by-distance (IBD) analysis excluded pairwise comparisons with Seadrift Lagoon, focusing only on the remaining five "open" sites. Pairwise F_{ST} values were used to plot IBD between sites, using along-shore distance calculated at 50-km resolution with the USA map from GADM supplemented with Google Maps for distances <50 km (https://gadm.org). When comparisons spanned San Francisco Bay and the Strait of Juan de Fuca, distances were calculated across the mouths of these features. IBD was plotted using five different SNP sets, to explore different potential drivers of latitudinal structure along the coast: (i) 6848 independent SNPs, (ii) 6794 independent SNPs excluding the 54 independent SNPs in the inferred inversion, (iii) 6311 putatively neutral SNPs, (iv) 144 outlier SNPs identified among the five open sites with BAYPASS (see Section 3) and (v) 54 "independent" SNPs in the inferred inversion. The significance of these relationships was assessed using linear regression in R.

2.6 | Markers under selection

We identified SNPs potentially under environmental selection using BAYPASS and redundancy analysis (RDA). We ran these tests using only the five open sites, excluding Seadrift Lagoon, to identify markers potentially driving the observed signal of IBD and latitudinal structuring along the coast. For this testing we used a single sample, collected in 2015–2016, from each site: 6662 SNPs of the full 6848 SNP set were polymorphic in these five samples and were used for tests of selection. Tested covariates included site latitude (as Cartesian Y-values) and winter and summer sea surface temperature (SST). Temperature data were derived from NOAA's OI SST V2 High Resolution Dataset provided by the NOAA/OAR/ESRL PSD, Boulder, CO, USA, from their website at https://www.esrl.noaa.gov/psd/ (Reynolds et al., 2007). Daily temperatures were averaged over the 2 years prior to sampling, and were determined for the nearest 0.25° grid location to each study site for January (winter) and July (summer).

In BAYPASS, we first ran a core model analysis to identify frequency outlier SNPs, then used the auxiliary covariate model to test for associations between allele frequencies and latitude and winter and summer SST (Gautier, 2015). Covariates were scaled, and we used an Ising prior of 0 since the physical order of contigs is unknown. We considered any SNP with Bayes factor (BF) ≥15 dB to be a candidate for selection with respect to a given covariate.

We ran an RDA on individual genotypes using the R package VEGAN version 2.5–6 (Oksanen et al., 2019), with missing genotypes imputed to be the most commonly observed. Few individual genotypes were missing in our data set: genotyping was ≥90% complete for 97.1% of SNPs, and no single sampling site was missing more than four individual genotypes at any SNP. We used latitude and summer temperature as covariates (RDA formula = individual genotypes ~Y + July SST); winter temperature was excluded as it was strongly

1365294x, 2021, 0, Downloaded from https://onlinelibrary.wiley.com. By MBL WHOI Library, Oceanographic Institution-MS#8- on [02/12/2021]. Re-use and distribution is strictly not permitted, except for Open Access articles

correlated with latitude (R^2 = .79; p =.03). We considered any SNP >3 *SD* outside the mean loading for its RDA axis to be a candidate for selection (Forester et al., 2018).

SNPs were considered strong candidates for selection if they were identified by both BAYPASS and RDA. Latitude is largely correlated with SST in this data set, due both to the strongly linear north–south arrangement of sites along the coast and to the relative coarseness of the satellite-derived temperature data. Because of this confounding, we treated all SNPs identified as candidates for association with either latitude or temperature interchangeably. To visualize these relationships, candidate SNPs were tested for linear correlation between minor allele frequency and latitude or temperature.

2.7 | Potential function of candidate SNPs

Candidate SNPs were examined for their potential impact on protein structure, to provide an initial idea of SNPs that were particularly likely to affect organismal function. Open reading frames (ORFs) and corresponding coding sequences for all contigs were predicted using ORFPREDICTOR version 3.0 (Min et al., 2005); as many contigs could not be annotated, sequence data alone were used to predict ORFs. Predicted sequences were then used to class the impact of a given SNP on the resulting protein sequence (untranslated, synonymous, or nonsynonymous) using a custom python script. Of the 9376 high-quality SNPs, we predicted that 4339 were in the untranslated regions of the mRNA and two were in contigs for which an ORF could not be predicted. Of the putatively coding SNPs, 3843 were predicted to be synonymous and 1192 to be nonsynonymous. We examined SNP substitution patterns for all 9376 candidate SNPs prior to LD screening. While putatively linked SNPs were removed from the data set prior to selection analysis, they could potentially be driving any relationships we detected in SNPs with which they are in strong LD.

Data manipulation and plotting were done using the DATA.TABLE and GGPLOT2 packages in R (Dowle & Srinivasan, 2019; R Core Team, 2016; Wickham, 2016).

3 | RESULTS

3.1 | Inferred inversion polymorphism

Linkage disequilibrium network analysis identified one single outlier LD cluster nested in one compound outlier LD cluster (Figure 2a,b). The compound outlier LD cluster, which we refer to as an "inferred inversion," contained 168 SNPs at an LD of $R^2 \geq .29$. PCA of these 168 SNPs split individuals into three discrete groups along the first principal component, explaining 73.08% of variance (p = .001; Figure 2c). While individuals from most sites appeared in all three groups, the left-most group contained predominantly British Columbia and Seadrift Lagoon while the right-most group contained predominantly Elkhorn Slough and San Francisco Bay. This pattern of three distinct groups explaining the majority of structure, with no discrete partitioning of sites, is diagnostic of a region of the genome where recombination is reduced (Kemppainen et al., 2015). In that case, each group represents a karyotype: homozygotes on the left and right sides of PC1, and heterozygotes midway between. Analysis of F_{IS} within each of these groups supports this conclusion, with values near zero in the putative homozygotes (indicating Hardy–Weinberg equilibrium) and strongly negative in the putative heterozygotes (indicating an excess of heterozygous individuals; Figure 2d). Overall F_{IS} is lower in the middle than in the left or right groups ($p < .0001$ for both comparisons), while the left and right groups are not significantly different from each other ($p = .1$).

Genetic structure over all SNPs showed a significant divide between Seadrift Lagoon and the other five sites, both with and without the 168 SNPs in the inferred inversion ($p < .0001$; Figure 2e,f). With the full set of 9376 SNPs, individuals in both Seadrift Lagoon and the remaining five open sites were further subdivided into three clusters according to their inferred inversion genotype ($p < .0001$; Figure 2c,e). When the 168 SNPs in the inferred inversion were removed, this three-part structure disappeared and the second principal component was no longer significant ($p = .09$; Figure 2f).

3.2 | SNP selection and genetic diversity

Of the full 9376 high-quality SNP set, 3962 SNPs comprised 1434 groups in LD with $R^2 \geq .8$; all but one SNP was removed from each group to create a set of 6848 "independent" SNPs. This screening differs from the earlier LDna analysis, which sought to identify large clusters of LD; by contrast, this approach intends simply to remove bias to population structure measurements from including any sets of SNPs in strong LD. The majority of these groups (N = 839) comprised small numbers of SNPs in the same contig. The largest of these groups by far included 77 SNPs from the inferred inversion; no other groups contained >13 SNPs. We note that this analysis did not identify all 168 SNPs in the inferred inversion as being in the same group, since some of those SNPs are in LD with others at $R^2 < .8$; consequently, the set of 6848 independent SNPs includes 54 SNPs in the inferred inversion.

After removing SNPs in strong LD, we had a final working panel of 6848 high-quality, independent SNPs. BAYPASS identified 537 of these SNPs as potentially under selection at FDR ≤ 0.1 across all site-by-year samples; these SNPs were removed to construct a panel of 6311 putatively neutral SNPs for selected downstream analyses.

Allelic richness ranged from 1.669 to 1.711 (Table 1); it was significantly lower in Seadrift Lagoon than in all other sites in all years ($p \leq .005$; Table 1). Private allelic richness was low, ranging from 0.00438 to 0.00771; seven pairwise comparisons were significant, all comparing Seadrift Lagoon in 2011 or 2016 with non-Seadrift Lagoon sites ($p < .05$ for all comparisons). Lower allelic richness in Seadrift Lagoon reflects a lower number of polymorphic SNPs there than in all other sites (Table 1). All samples showed a significant heterozygote excess.

1365294x, 2021, 0, Downloaded from https://onlinelibrary.wiley.com. By MBL WHOI Library, Oceanographic Institution-MS#8- on [02/12/2021]. Re-use and distribution is strictly not permitted, except for Open Access articles

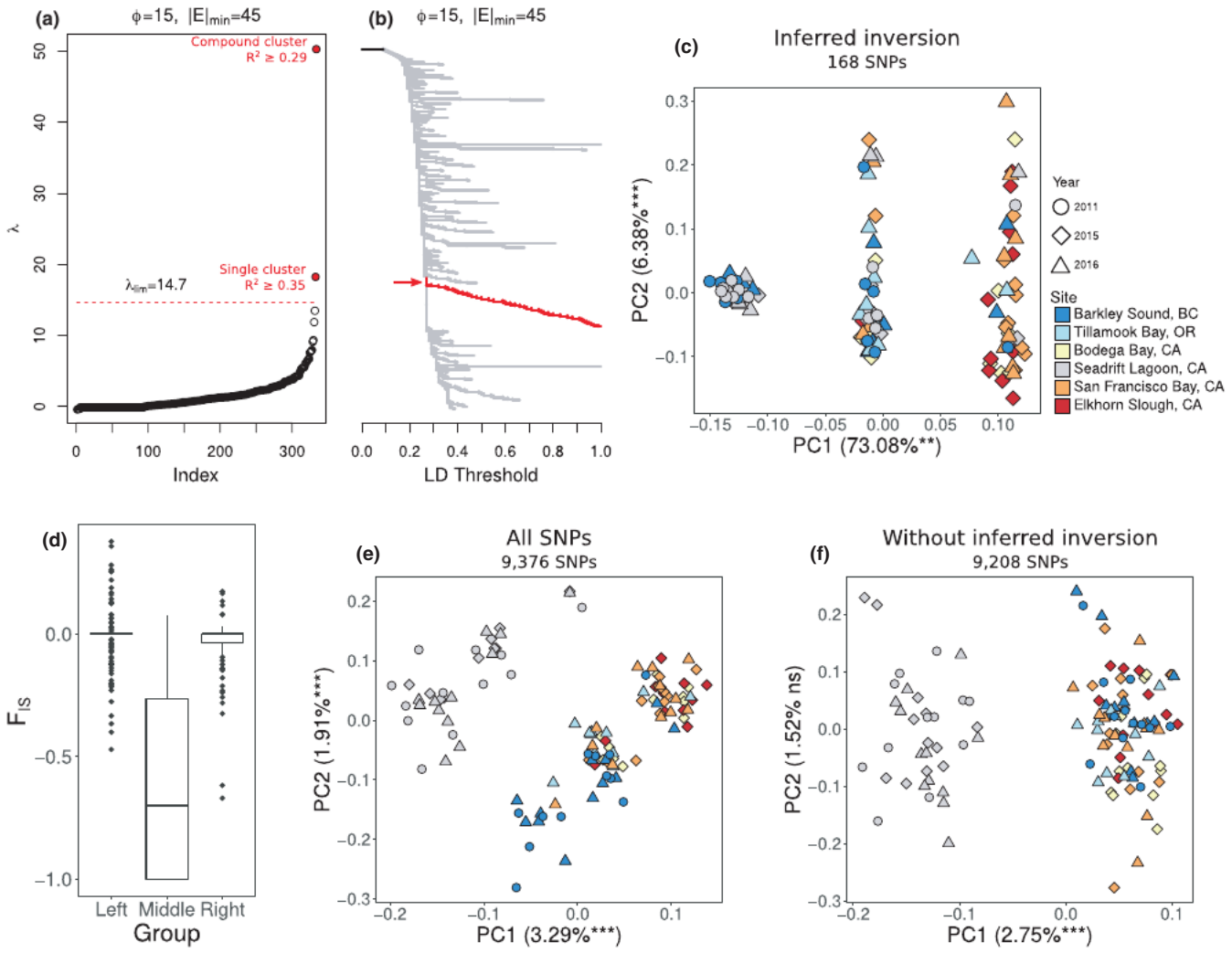

FIGURE 2 Linkage disequilibrium analysis of the full 9376 SNP set, showing evidence for an inferred inversion. (a, b) Clustering in LDna network analysis showing nested single and compound outlier LD clusters. In b, the inferred inversion (compound cluster in a) is indicated by an arrow and highlighted in red. (c) PCA of 168 SNPs in inferred inversion. (d) F_{IS} of 168 SNPs in inferred inversion, grouped by PC1 position in c. (e) PCA of the full 9376 SNP set. (f) PCA of the full 9376 SNP set excluding the 168 SNPs in the inferred inversion. For c–f, four individuals were excluded because they were missing high-quality genotypes at >20% of SNPs in the inferred inversion

3.3 | Population structure and migration

F_{ST} was significant between most sample pairs when using the 6848 independent SNP set (pairwise F_{ST} excluding temporal comparisons: 0.00058–0.027; Table S1). By contrast, when using the 6311 putatively neutral SNPs nearly all significant comparisons were between Seadrift Lagoon samples and all other sites (pairwise F_{ST} including Seadrift: 0.0081–0.016; pairwise F_{ST} excluding Seadrift: −0.0021 to 0.0044; Table S2). There was no evidence for differentiation within any temporal comparison across years with the putatively neutral SNP set (pairwise F_{ST}: −0.0020 to 0.0014; Table S2). PCA reinforced these patterns, with the first component separating Seadrift Lagoon from all other sites with both the independent and neutral SNP sets (6848 independent SNPs: loading = 2.75%, p <.0001; 6311 neutral SNPs: loading = 2.07%, $p < .0001$; Figure 3a,b). The second component was significant only with the independent SNP set (loading = 1.53%, $p < .0001$), and spread non-Seadrift Lagoon sites along a rough north–south axis (Figure 3a). With the neutral SNP set, this pattern collapsed ($p > .05$), with near-complete overlap among all non-Seadrift Lagoon samples (Figure 3b). While Seadrift Lagoon had significantly lower allelic richness than all other sites, there were no significant differences among the remaining open sites (Figure 3c).

To test a realistic migration scenario, we estimated relative migration using only one recent sample from each site. Estimates of relative migration between sites (using 6311 neutral SNPs only) demonstrated similar and symmetrical migration among all sites except Seadrift Lagoon (Figure 3d). Consistent with Seadrift Lagoon's distinctiveness, we found evidence for reduced migration both into and out of this site relative to the rest of our study sites (Figure 3d). The approach we used sets the maximum observed migration to 1 and scales the rest of the migration estimates accordingly. Between all five open sites, we observed values of 88%–100% of maximum observed migration, while estimated migration between Seadrift Lagoon and all other sites ranged from 68% to 78% of the maximum.

1365294x, 2021, 0, Downloaded from https://onlinelibrary.wiley.com. By MBL WHOI Library, Oceanographic Institution-MS#8- on [02/12/2021]. Re-use and distribution is strictly not permitted, except for Open Access articles

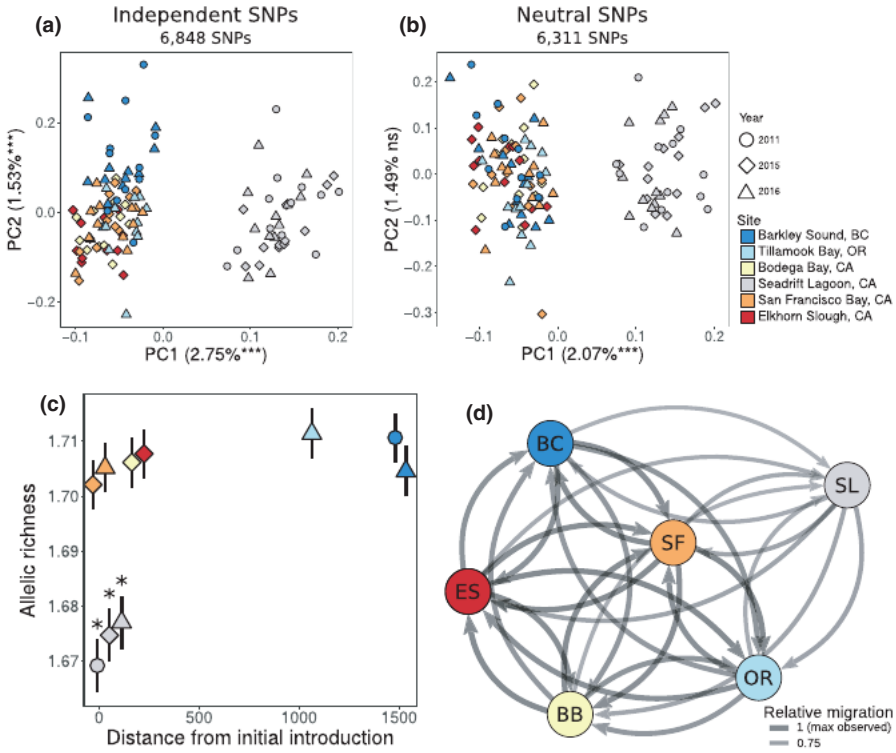

FIGURE 3 Genetic structure, diversity, and migration across all sites, showing high gene flow among all sites except Seadrift Lagoon. (a) PCA of the independent 6848 SNPs. (b) PCA of the putatively neutral 6311 SNPs. (c) Allelic richness by population and collection year across the 6848 independent SNPs, plotted against distance from the initial point of introduction in San Francisco Bay, CA. Points from the same site have been jittered horizontally for clarity. Vertical bars indicate standard error. Starred samples have significantly lower allelic richness than non-starred samples. (d) Relative migration between sites, calculated with the Nm method, across the 6662 independent SNPs in the five open sites. The highest observed rate is set to 1, and all other rates are scaled to that maximum; estimated migration both into and out of Seadrift was lower than migration between all other sites

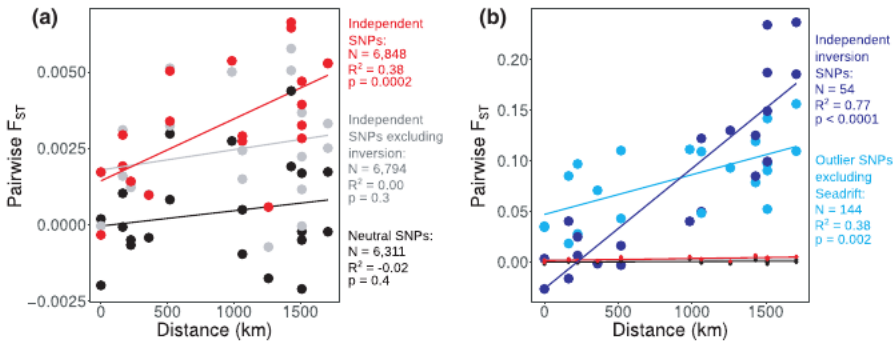

FIGURE 4 Comparison of isolation-by-distance (IBD) patterns across all open populations (excluding Seadrift Lagoon), showing IBD driven by SNPs in the inferred inversion. (a) For all 6848 independent SNPs (red); 6794 independent SNPs excluding the inferred inversion (gray); and 6311 putatively neutral independent SNPs (black). (b) For all 144 frequency outlier SNPs across the open populations (aqua); and all 54 SNPs from the inferred inversion in the independent SNP set (blue). The relationships in a are shown in b with smaller points; note the difference in *Y*-axis magnitude between the two panels

We note, however, that it is impossible to fully differentiate between ongoing low-level migration and recent divergence (with no ongoing migration) given the recent history of green crabs in the northeast Pacific.

A test of IBD along the five open sites (excluding Seadrift Lagoon) recapitulated the north–south pattern observed for these sites in the PCA, but only when putatively selected SNPs were included. The 6848 independent SNP set showed a significant pattern of IBD (R^2 = .38; p = .0002), which collapsed completely with the 6311 neutral SNP set (R^2 = −.02; p = .4) or when removing only the 54 SNPs in the inferred inversion (R^2 = .00; p = .3; Figure 4a). However, we note that overall differentiation for all of these SNP sets was very low, with a maximum pairwise F_{ST} of 0.0066. IBD was much stronger in the 144 outlier SNPs (frequency outliers across the five open sites),

13652294x, 2021, 0, Downloaded from https://onlinelibrary.wiley.com. By MBL WHOI Library, Oceanographic Institution-MS#8- on [02/12/2021]. Re-use and distribution is strictly not permitted, except for Open Access articles

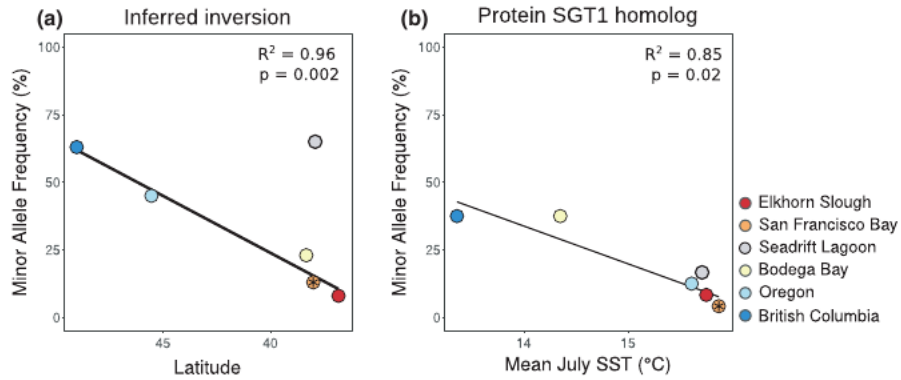

FIGURE 5 Correlation between Minor Allele Frequency (MAF) and latitude or July SST at candidate genomic regions, showing putative selection to temperature or latitude across the five "open" sites at environmental outlier SNPs. Asterisks indicate the location where the species was initially introduced (first detected in 1989). In both cases, Seadrift Lagoon (gray point) is shown for comparison but was not used in the regression lines or equations. (a) The inferred inversion; samples were classed into overall "inversion genotypes" based on their group membership in Figure 2c. (b) Outlier SNP in the protein SGT homolog transcript

and stronger still in the 54 "independent" SNPs in the inferred inversion. The 144 frequency outliers had significant IBD with a maximum pairwise F_{ST} of 0.16 ($R^2 = .38$; $p = .002$), while the SNPs in the inferred inversion showed a strong IBD pattern ($R^2 = .77$; $p < .0001$) with a maximum pairwise F_{ST} of 0.24 between the most distant two sites (Figure 4b).

3.4 | Selection in the northeast Pacific

All tests for selection were run with only one recent temporal sample from the five open sites, using the 6662 SNPs of the 6848 independent SNP set that were variable in these five samples. Using the BAYPASS core model, 144 unlinked SNPs were frequency outliers at FDR ≤0.05 among these five samples. The BAYPASS covariate test identified 26 SNPs related to latitude, 26 SNPs associated with January SST and six SNPs associated with July SST (Figure S1). Seventeen of these SNPs were associated with two or more traits, for a total of 40 unique environmentally associated SNPs. Some associations were quite strong, with seven SNPs associated with latitude and/or winter temperature at BF ≥25 dB. No SNPs were strongly associated with July SST (Figure S1).

RDA showed that latitude fell almost perfectly along the first axis, while July SST fell between the first and second axes (Figure S2). In this test, association with latitude also represents association with January SST, which was not included as the two measures were strongly correlated. The full RDA was significant ($F = 1.10$, $p = .001$), as were both resulting RDA axes (RDA1: $F = 1.12$, $p = .001$; RDA2: $F = 1.09$, $p = .003$). Variance inflation factors were less than 2 for both axes, indicating no potential confounding from multicollinearity in the environmental variables. In total, 23 SNPs were identified as outliers on one of the two RDA axes: of these, 15 were most strongly associated with latitude while eight were most strongly associated with July SST (Figure S2).

We took as our most likely candidate markers for selection those associated with latitude or temperature in both the BAYPASS and RDA analyses. In total, 13 SNPs overlapped between the 40 identified with BAYPASS and the 23 identified with RDA. Of these, two were excluded because of rarity (maximum per-population minor allele frequency [MAF] ≤ 0.3). Ten of the remaining 11 candidate SNPs were in the inferred inversion; these were retained in the independent SNP set because they were not in strong enough LD with each other to have been removed (threshold for strong LD: $R^2 \geq .8$). For visualization purposes, we generated "extended genotypes" for the inferred inversion by classing individuals based on group membership in a PCA of all 168 SNPs (Figure 2c). As noted earlier, individuals belonging to the left-most group were classed as homozygotes for the minor allele, those in the middle group as heterozygotes and those in the right-most group as homozygotes for the major allele. For the open sites (minus Seadrift Lagoon), both the inferred inversion and the independent candidate SNP had MAFs that were significantly correlated with latitude (Figure 5). Interestingly, for the inferred inversion, MAF in Seadrift Lagoon fell outside the predicted line, instead having an MAF closer to that of British Columbia and predicted to belong to a more northern and/or colder site (Figure 5a). By contrast, Seadrift MAF fell along the line predicted by MAF in the open sites for the one candidate SNP outside this inferred inversion (Figure 5b).

The 10 candidate SNPs in the inferred inversion were in strong LD with a number of SNPs removed from the unlinked data set, for a total of 97 SNPs in 39 different contigs (Table S3). Because we ran selection analyses on a set of SNPs that had been pruned to remove those in strong LD, any of these 97 SNPs (or other linked variation we did not retain after SNP quality control) could be driving the observed pattern of selection. Of the 97 candidate SNPs in the inferred inversion, 18.6% (18/97) were predicted to change the amino acid sequence of the resulting protein compared to 12.7% (1192/9374) in the full 9376 SNP set (before linkage filtering). The 18 predicted nonsynonymous SNPs in the inferred inversion were in contigs annotated as: hypoxia inducible factor 1 alpha (two SNPs), NAD-dependent protein deacylase, fibrillin-2-like isoform X4, ubiquinol-cytochrome-c reductase complex assembly factor 1,

1365294x, 2021, 0, Downloaded from https://onlinelibrary.wiley.com. By MBL WHOI Library, Oceanographic Institution-MS#8- on [02/12/2021]. Re-use and distribution is strictly not permitted, except for Open Access articles

SMB domain-containing protein (three SNPs), protein lingerer-like, prosaposin-like, cartilage oligomeric matrix protein, ATP-dependent RNA helicase DDX56, one uncharacterized protein and four unannotated contigs (five SNPs). The one candidate SNPs not in the inferred inversion was predicted to be a synonymous substitution in protein SGT1 homologue (Table S3).

4 | DISCUSSION

The expansion of *C. maenas* along the northeast Pacific coast is a canonical example of the genetic paradox of invasions. The population has been demonstrably successful, rapidly expanding along >1500 km of coastline despite deriving from a single genetically depauperate source. Here, we have shown that variation in a specific region of the genome—an inferred chromosomal inversion previously associated with cold tolerance in the species—appears to be under strong latitudinal selection in this system. Population genomics shows that this putative selection is occurring against a backdrop of high oceanographic connectivity. Our sampling comprises five discrete bays connected by high larval gene flow, and a single oceanographically isolated population that has diverged genetically in <20 generations, demonstrating the importance of larval connectivity in mediating population dynamics in range expansion. Comparison with older data shows that genetic structure and diversity have remained stable across at least one generation, suggesting large population sizes and consistent recruitment pools over time. We propose that this high connectivity, a hallmark of the species, may have promoted the initial evolution of this inferred inversion as a balanced polymorphism in Europe and may be critical to its persistence and spread in introduced populations. In turn, the variation protected by this inversion may play a key role in the success of *C. maenas* across wide environmental gradients in its introduced range despite significant reductions in overall genetic diversity.

4.1 | Chromosomal inversions and adaptation

The importance of chromosomal architecture, particularly chromosomal inversions, has been increasingly recognized in selection with gene flow in natural systems (Tigano & Friesen, 2016). Inversion polymorphisms can be extensive, and can maintain extended genotypes at hundreds to thousands of genes by suppressing recombination in heterozygotes (Kirkpatrick, 2010). While inversion is not the only mechanism by which recombination can be reduced, it is generally believed to be most effective in maintaining large blocks of co-adapted genes over time (Lamichhaney & Andersson, 2019). This recombination suppression, in turn, permits suites of gene variants to evolve and be inherited together, capturing complex multigene interactions in a single "supergene" (Thompson & Jiggins, 2014).

Inversions have been directly associated with important differences in ecotype across small spatial scales in interbreeding populations, suggesting that this type of chromosomal architecture can promote highly localized selection (Huang et al., 2020; Westram et al., 2018). In some systems, including monkeyflowers and Atlantic cod, important differences in life history have been linked to just one or two inversions (Kirubakaran et al., 2016; Twyford & Friedman, 2015). Pioneering work on *Drosophila* identified a number of inversions showing clinal associations with latitude and temperature; such relationships have been shown to develop rapidly in introduced populations (Balanyà et al., 2006), and to predictably cycle in frequency with changing seasonal temperatures within a population (Kapun et al., 2016). Together, this growing body of work suggests that inversions can act as targets of spatial balancing selection in systems where the scale of gene flow exceeds the scale of environmental heterogeneity, providing an effective mechanism by which such species can respond to their environments on very fast time scales (Sanford & Kelly, 2011; Tigano & Friesen, 2016).

We have previously proposed that a chromosomal inversion or another genomic region of reduced recombination is probably under selection to temperature in *C. maenas* (Tepolt & Palumbi, 2020). Many of the same SNPs identified in the inferred inversion in this study were independently found to be part of the putative inversion in that prior global study, indicating that the same probable inversion is associated with cold tolerance globally and with latitudinal divergence along the northeast Pacific. In the earlier study, candidate SNPs were variable in the European native range and showed similar evidence of strong LD and reduced recombination there (Tepolt & Palumbi, 2020). This demonstrates that rapid selection in the northeast Pacific is acting primarily on standing variation that arose in the original source population, ruling out post-invasion dynamics as a driver for this LD (Slatkin, 2008).

4.2 | Population structure and temporal dynamics

In the northeast Pacific, *C. maenas* has lost significant overall genetic diversity compared to its East Coast source or the species' native range in Europe (Tepolt & Palumbi, 2015). However, diversity is largely consistent across its northeast Pacific range, with no losses at the range edges relative to the San Francisco source (Figure 3c). While diversity loss in expanding range edges has been widely noted and is a common expectation (Eckert et al., 2008; Vucetich et al., 1997), it may be mediated by large population sizes and high gene flow (Excoffier et al., 2009). Green crabs spread rapidly but episodically up the coast from the initial point of introduction in San Francisco Bay, with the largest expansion in conjunction with the strong 1997–1998 ENSO event (Behrens Yamada et al., 2005). Further research has shown that strong crab cohorts have corresponded with warmer waters and enhanced northward nearshore currents (Behrens Yamada et al., 2015). Modelling has shown that larval dispersal trajectories probably vary considerably both within and between years depending on hydrography, with larvae potentially travelling both north and south (Brasseale et al., 2019). Together with this prior work, our data suggest that periodic transport events are sufficient to maintain consistent genetic diversity

1365294x, 2021, 0, Downloaded from https://onlinelibrary.wiley.com. By MBL WHOI Library, Oceanographic Institution-MS#8- on [02/12/2021]. Re-use and distribution is strictly not permitted, except for Open Access articles

and structure across time and space in these open bays despite the variable nature of recruitment in the system.

All of our data point to ongoing high gene flow across the range of the recent and rapid *C. maenas* expansion in the northeast Pacific, with one exception (Figure 3). This exception is Seadrift Lagoon, which is small, isolated from the adjacent Bolinas Lagoon, and now oceanographically separated from the larger coastal circulation (Ritter, 1970). Green crabs were first reported in Seadrift Lagoon in 1993 (Tepolt et al., 2009), and by 2011, our first year of sampling, they had lost significant genetic diversity relative to the rest of our study sites (Tepolt & Palumbi, 2015; Figure 3c). Our current sampling does not include Bolinas Lagoon, the larger lagoon to which Seadrift Lagoon was historically connected but to which it is now linked only by culverts with managed water flow. However, a prior study of the temporal dynamics of *C. maenas* using microsatellites found no evidence for diversity loss in Bolinas Lagoon relative to any other sites, including San Francisco Bay and Bodega Bay (Tepolt et al., 2009). Data from experimental removal work in Seadrift Lagoon suggest that population dynamics in the lagoon are highly localized (Grosholz et al., 2021). Given the observed openness of the other bays, we would expect structure and diversity to homogenize quickly if Seadrift Lagoon were receiving substantial larval inputs from surrounding, higher diversity populations.

Genetic structure and diversity appear to be stable over time at least for the 5–6 years covered by our sampling, with no significant changes in F_{ST} or allelic richness across years within a site. The lifespan of *C. maenas* is no more than 4–6 years (Behrens Yamada et al., 2005), and we did not sample the largest and oldest individuals, so the 2011 and 2016 samples represent nonoverlapping generations. Structure and diversity were stable in both sites we sampled across generations, including one of the well-mixed open sites (Barkley Sound), and the putatively isolated Seadrift Lagoon.

4.3 | High gene flow and rapid selection

Against a background of high gene flow and negligible neutral genetic structure among most sites along the northeast Pacific, we observed a north–south gradient in the system driven by an inferred inversion polymorphism (Figures 3a and 4). While it is very difficult to disentangle selection from allele surfing at range expansion (Excoffier et al., 2009; Lotterhos & Whitlock, 2014), and we cannot say conclusively that allele surfing does not play a role in this pattern of IBD, several lines of evidence suggest that we are detecting a genuine signal of selection. Green crabs along the northeastern Pacific coast comprise large populations with high dispersal and gene flow, traits that limit the potential for successful allele surfing (Excoffier et al., 2009; Goodsman et al., 2014). These traits are reflected in similar levels of genetic diversity across all of the populations in the more highly connected "open" bays (Figure 3c). In addition, while *C. maenas* has spread primarily northward from its site of first introduction, the sole area of southern spread with an established population (Elkhorn Slough) shows MAF consistent with increases of "southern" alleles. This is contrary to the expectations of allele surfing, in which a species expanding along multiple range edges is expected to demonstrate different "favoured" alleles in each direction by chance (Demastes et al., 2019).

Finally, many of the same SNPs found in the inferred inversion driving latitudinal divergence were previously identified as belonging to a putative supergene strongly associated with thermal physiology in a data set spanning six native- and invasive-range *C. maenas* populations (Tepolt & Palumbi, 2020). While winter SST and latitude cannot be disentangled in our current data set, this previous study provided stronger evidence for temperature in driving selection. Together with the minimal neutral structure across the open sites, we suggest that the inferred inversion in our study is very probably maintained as a balanced polymorphism under strong selection to temperature.

Recent research using fine-scale sampling covering multiple years, life stages and sampling sites has shown that targets of selection can vary across all of these scales in high-dispersal systems, contributing to patterns that may appear chaotic with less thorough sampling (Thia et al., 2021). While chaotic genetic patchiness is often a hallmark of such systems (Eldon et al., 2016), we did not observe that in our sampling (Figures 3a,b and 5). This may be due in part to the domination of the selective signal in our system by a single large genomic region with what is probably a high selection coefficient, in concert with our sampling of adults. If selection at this region is acting primarily on the dispersive larval stage, our sampling will reflect the aftermath of this selection rather than the initial pool of recruits (Sanford & Kelly, 2011). Similar patterns of balanced polymorphism have been shown in two classic examples of selection on large-effect alleles in early life stages in barnacles and mussels (Koehn et al., 1980; Schmidt & Rand, 2001).

For SNPs in the inferred inversion, MAF at Seadrift Lagoon did not follow the predicted relationship based on the open sites and was instead characteristic of higher latitudes (Figure 5a). While speculative, we suggest that Seadrift Lagoon's isolation means that crabs at this site are responding to the environment on an extremely local scale as opposed to those in other bays, whose larvae may travel hundreds of kilometres through coastal currents (Behrens Yamada et al., 2005; Brasseale et al., 2019). Seadrift Lagoon is shallow and small, and may experience more extreme (and especially lower) temperatures than nearby open bays. Finer-scale temperature data from within Seadrift Lagoon, rather than larger-scale satellite-derived SST data, would help to test this hypothesis.

While prior work uncovered a robust link between this inferred inversion and physiological cold tolerance, its ability to identify rapid selection after invasion was limited by a complex invasion history and differences in genetic background across the six studied populations on three coastlines. Here, we demonstrate that this inferred inversion recapitulates predicted allele frequency correlation with temperature in an otherwise homogenous, highly bottlenecked introduced population over a period of 10–20 generations. This study provides evidence for very rapid adaptive change in an introduced species with extremely limited genetic diversity, and proposes this

1365294x, 2021, 0, Downloaded from https://onlinelibrary.wiley.com. By MBL WHOI Library, Oceanographic Institution-MS#8- on [02/12/2021]. Re-use and distribution is strictly not permitted, except for Open Access articles

adaptation was facilitated by variation at a single inversion polymorphism that evolved and is probably maintained as a balanced polymorphism in the native range.

5 | CONCLUSIONS

We have long known that diversity is important to population resilience in the face of changing conditions (Reed & Frankham, 2003). The genetic paradox of invasions is that we do occasionally find incredibly successful, nonclonal populations that have passed through severe bottlenecks, dramatically decreasing their genetic diversity relative to their sources (Kohn et al., 2006). Perhaps we can partially resolve this paradox by considering that diversity at specific parts of the genome (rather than genome-wide diversity) may play a critical role in resilience (Estoup et al., 2016). Simulations have shown that expanding populations can adapt via a few variants of large effect even in the face of low overall diversity (Gilbert & Whitlock, 2017). High dispersal, which characterizes many marine systems, may promote the evolution of a few alleles of large effect via genomic mechanisms such as inversion polymorphisms (Tigano & Friesen, 2016). While balanced polymorphisms at large-effect alleles may permit these populations to respond extremely quickly to their local environments, they may also be a huge benefit to the survival and success of introduced populations.

Introduced marine species often exhibit an extensive dispersal ability, resulting from close association with human-built marine infrastructure or a high capacity for larval transport (Carlton & Geller, 1993; Wilson et al., 2009). For the latter, high dispersal and gene flow may have a twofold effect wherein the same traits that allow a species to reach and spread in a new range may also promote the evolution of genomic mechanisms (i.e., balanced polymorphisms) that facilitate rapid adaptation to a range of environmental conditions (Tigano & Friesen, 2016). This is similar to the idea that periodic disturbance promotes the evolution of traits that enhance invasiveness and increase the likelihood of success in novel environments (Ketola et al., 2013; Lee & Gelembiuk, 2008). We propose that an analogous process may be at work in highly dispersive marine invaders. Such species may be able to evolve and maintain balanced polymorphisms across broad environmental gradients in their native ranges, giving them the substrate for rapid adaptive change as they expand in new environments.

ACKNOWLEDGMENTS

We thank S. Yamada, J. Gonzalez, R. Jeppeson, I. McGaw and E. Clelland for their assistance in obtaining genetic samples. We thank the editor and three anonymous reviewers for their thoughtful comments that greatly improved this manuscript. We also thank the National Science Foundation (OCE-RAPID #1514893 to E.D.G., C.D. and G.M.), Smithsonian Institution (Hunterdon Fund to G.M.R.), and The Penzance Endowed Fund for Assistant Scientists (to C.K.T.) for their support of this project.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

AUTHOR CONTRIBUTIONS

All authors designed the research. C.T. performed research, analysed data and wrote the paper. All authors edited multiple drafts.

DATA AVAILABILITY STATEMENT

Raw transcriptome reads from new sequencing for this project have been deposited in GenBank's Sequence Read Archive (SRA) under BioProject ID PRJNA690934 and BioSample IDs SAMN17267686–SAMN17267781. Raw sequence reads from 2011, re-analysed in this project, are available in the SRA under BioProject ID PRJNA283611 and BioSample IDs SAMN03653390–SAMN03653413. The cleaned transcriptome, high-quality individual SNP genotypes, and custom scripts used in this bioinformatics pipeline from this paper have been archived in Dryad at https://doi.org/10.5061/dryad.4b8gthtdd.

ORCID

Carolyn K. Tepolt https://orcid.org/0000-0002-7062-3452

REFERENCES

Balanyà, J., Oller, J. M., Huey, R. B., Gilchrist, G. W., & Serra, L. (2006). Global genetic change tracks global climate warming in *Drosophila subobscura*. *Science*, *313*, 1773–1775. https://doi.org/10.5061/dryad.4b8gthtdd

Behrens Yamada, S., Dumbauld, B. R., Kalin, A., Hunt, C. E., Figlar-Barnes, R., & Randall, A. (2005). Growth and persistence of a recent invader *Carcinus maenas* in estuaries of the northeastern Pacific. *Biological Invasions*, *7*, 309–321. https://doi.org/10.1007/s10530-004-0877-2

Behrens Yamada, S., & Gillespie, G. (2008). Will the European green crab (*Carcinus maenas*) persist in the Pacific Northwest? *ICES Journal of Marine Science*, *65*, 725–729. https://doi.org/10.1093/Icesjms/Fsm191

Behrens Yamada, S., & Kosro, P. (2010). Linking ocean conditions to year class strength of the invasive European green crab, *Carcinus maenas*. *Biological Invasions*, *12*, 1791–1804. https://doi.org/10.1007/s10530-009-9589-y

Behrens Yamada, S., Peterson, W., & Kosro, P. (2015). Biological and physical ocean indicators predict the success of an invasive crab, *Carcinus maenas*, in the northern California current. *Marine Ecology Progress Series*, *537*, 175–189. https://doi.org/10.3354/meps11431

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society B*, *57*, 289–300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

Blackburn, T. (2008). Using aliens to explore how our planet works. *Proceedings of the National Academy of Sciences*, *105*(1), 9–10. https://doi.org/10.1073/pnas.0711228105

Bors, E., Herrera, S., Morris, J., & Shank, T. (2019). Population genomics of rapidly invading lionfish in the Caribbean reveals signals of range expansion in the absence of spatial population structure. *Ecology and Evolution*, *9*, 3306–3320. https://doi.org/10.1002/ece3.4952

Brasseale, E., Grason, E., McDonald, P. S., Adams, J., & MacCready, P. (2019). Larval transport modeling support for identifying population sources of European green crab in the Salish Sea. *Estuaries and Coasts*, *42*, 1586–1599. https://doi.org/10.1007/s12237-019-00586-2

1365294x, 2021, 0, Downloaded from https://onlinelibrary.wiley.com. By MBL WHOI Library, Oceanographic Institution-MS#8- on [02/12/2021]. Re-use and distribution is strictly not permitted, except for Open Access articles

Bridle, J., & Vines, T. (2007). Limits to evolution at range margins: When and why does adaptation fail? *Trends in Ecology and Evolution*, *22*, 140–147. https://doi.org/10.1016/j.tree.2006.11.002

Carlton, J., & Cohen, A. (2003). Episodic global dispersal in shallow water marine organisms: The case history of the European shore crabs *Carcinus maenas* and *C. aestuarii*. *Journal of Biogeography*, *30*, 1809–1820. https://doi.org/10.1111/j.1365-2699.2003.00962.x

Carlton, J., & Geller, J. (1993). Ecological roulette: The global transport of nonindigenous marine organisms. *Science*, *261*, 78–82. https://doi.org/10.1126/science.261.5117.78

Chuang, A., & Peterson, C. (2016). Expanding population edges: Theories, traits, and trade-offs. *Global Change Biology*, *22*, 494–512. https://doi.org/10.1111/gcb.13107

Csardi, G., & Nepusz, T. (2006). The igraph software package for complex network research, *InterJournal*, *Complex Systems*, 1695. http://igraph.org

Danecek, P., Auton, A., Abecasis, G., Albers, C. A., Banks, E., DePristo, M. A., Handsaker, R. E., Lunter, G., Marth, G. T., Sherry, S. T., McVean, G., & Durbin, R., & 1000 Genome Project Analysis Group. (2011). The variant call format and VCFtools. *Bioinformatics*, *27*, 2156–2158. https://doi.org/10.1093/bioinformatics/btr330

Dawirs, R. (1985). Temperature and larval development of *Carcinus maenas* (Decapoda) in the laboratory; predictions of larval dynamics in the sea. *Marine Ecology-Progress Series*, *24*, 297–302. https://doi.org/10.3354/meps024297

de Rivera, C., Hitchcock, N. G., Teck, S. J., Steves, B. P., Hines, A. H., & Ruiz, G. M. (2007). Larval development rate predicts range expansion of an introduced crab. *Marine Biology*, *150*, 1275–1288. https://doi.org/10.1007/s00227-006-0451-9

Demastes, J., Hafner, D., Hafner, M., Light, J., & Spradling, T. (2019). Loss of genetic diversity, recovery and allele surfing in a colonizing parasite, *Geomydoecus aurei*. *Molecular Ecology*, *28*, 703–720. https://doi.org/10.1093/oxfordjournals.jhered.a111627

DePristo, M. A., Banks, E., Poplin, R., Garimella, K. V., Maguire, J. R., Hartl, C., Philippakis, A. A., del Angel, G., Rivas, M. A., Hanna, M., McKenna, A., Fennell, T. J., Kernytsky, A. M., Sivachenko, A. Y., Cibulskis, K., Gabriel, S. B., Altshuler, D., & Daly, M. J. (2011). A framework for variation discovery and genotyping using next-generation DNA sequencing data. *Nature Genetics*, *43*, 491–498. https://doi.org/10.1038/ng.806

Dowle, M., & Srinivasan, A. (2019). data.table: Extension of 'data.frame'. R package version 1.12.8. https://CRAN.R-project.org/package=data.table

Eckert, C., Samis, K., & Lougheed, S. (2008). Genetic variation across species' geographical ranges: The central-marginal hypothesis and beyond. *Molecular Ecology*, *17*, 1170–1188. https://doi.org/10.1111/j.1365-294X.2007.03659.x

Eldon, B., Riquet, F., Yearsley, J., Jollivet, D., & Broquet, T. (2016). Current hypotheses to explain genetic chaos under the sea. *Current Zoology*, *62*, 551–566. https://doi.org/10.1093/cz/zow094

Ellingson, R., & Krug, P. (2016). Reduced genetic diversity and increased reproductive isolation follow population-level loss of larval dispersal in a marine gastropod. *Evolution*, *70*, 18–37. https://doi.org/10.1111/evo.12830

Estoup, A., Ravigné, V., Hufbauer, R., Vitalis, R., Gautier, M., & Facon, B. (2016). Is there a genetic paradox of biological invasion? *Annual Review of Ecology, Evolution, and Systematics*, *47*, 51–72. https://doi.org/10.1146/annurev-ecolsys-121415-032116

Excoffier, L., Foll, M., & Petit, R. (2009). Genetic consequences of range expansions. *Annual Review of Ecology, Evolution, and Systematics*, *40*, 481–501. https://doi.org/10.1146/annurev.ecolsys.39.110707.173414

Excoffier, L., & Lischer, H. E. L. (2010). Arlequin suite ver 3.5: A new series of programs to perform population genetics analyses under Linux and Windows. *Molecular Ecology Resources*, *10*, 564–567. https://doi.org/10.1111/j.1755-0998.2010.02847.x

Excoffier, L., & Ray, N. (2008). Surfing during population expansions promotes genetic revolutions and structuration. *Trends in Ecology and Evolution*, *23*, 347–351. https://doi.org/10.1016/j.tree.2008.04.004

Forester, B., Lasky, J., Wagner, H., & Urban, D. (2018). Comparing methods for detecting multilocus adaptation with multivariate genotype–environment associations. *Molecular Ecology*, *27*, 2215–2233. https://doi.org/10.1111/mec.14584

Galindo, H., Olson, D., & Palumbi, S. (2006). Seascape genetics: A coupled oceanographic-genetic model predicts population structure of Caribbean corals. *Current Biology*, *16*, 1622–1626. https://doi.org/10.1016/j.cub.2006.06.052

Gautier, M. (2015). Genome-wide scan for adaptive divergence and association with population-specific covariates. *Genetics*, *201*, 1555–1579. https://doi.org/10.1534/genetics.115.181453

Gilbert, K., & Whitlock, M. (2017). The genetics of adaptation to discrete heterogeneous environments: Frequent mutation or large-effect alleles can allow range expansion. *Journal of Evolutionary Biology*, *30*, 591–602. https://doi.org/10.1111/jeb.13029

Goodsman, D., Cooke, B., Coltman, D., & Lewis, M. (2014). The genetic signature of rapid range expansions: How dispersal, growth and invasion speed impact heterozygosity and allele surfing. *Theoretical Population Biology*, *98*, 1–10. https://doi.org/10.1016/j.tpb.2014.08.005

Grosholz, E., Ashton, G., Bradley, M., Brown, C., Ceballos-Osuna, L., Chang, A., Tepolt, C. (2021). Stage-specific overcompensation, the hydra effect, and the failure to eradicate an invasive predator. *Proceedings of the National Academy of Sciences*, *118*(12), e2003955118. https://doi.org/10.1073/pnas.2003955118

Hampton, S., & Griffiths, C. (2007). Why *Carcinus maenas* cannot get a grip on South Africa's wave-exposed coastline. *African Journal of Marine Science*, *29*, 123–126. https://doi.org/10.2989/AJMS.2007.29.1.11.76

Hart, A., Ginzburg, S., Xu, M., Fisher, C. R., Rahmatpour, N., Mitton, J. B., & Wegrzyn, J. L. (2020). EnTAP: Bringing faster and smarter functional annotation to non-model eukaryotic transcriptomes. *Molecular Ecology Resources*, *20*, 591–604.

Hedgecock, D. (1986). Is gene flow from pelagic larval dispersal important in the adaptation and evolution of marine invertebrates? *Bulletin of Marine Science*, *39*, 550–564.

Hidalgo, F., Barón, P., & Orensanz, J. (2005). A prediction come true: The green crab invades the Patagonian coast. *Biolical Invasions*, *7*, 547–552. https://doi.org/10.1007/s10530-004-5452-3

Huang, K., Andrew, R. L., Owens, G. L., Ostevik, K. L., & Rieseberg, L. H. (2020). Multiple chromosomal inversions contribute to adaptive divergence of a dune sunflower ecotype. *Molecular Ecology*, *29*, 2535–2549. https://doi.org/10.1111/mec.15428

Kapun, M., Fabian, D., Goudet, J., & Flatt, T. (2016). Genomic evidence for adaptive inversion clines in *Drosophila melanogaster*. *Molecular Biology & Evolution*, *33*, 1317–1336. https://doi.org/10.1093/molbev/msw016

Kawecki, T., & Ebert, D. (2004). Conceptual issues in local adaptation. *Ecology Letters*, *7*, 1225–1241. https://doi.org/10.1111/j.1461-0248.2004.00684.x

Kemppainen, P., Knight, C. G., Sarma, D. K., Hlaing, T., Prakash, A., Maung Maung, Y. N., Somboon, P., Mahanta, J., & Walton, C. (2015). Linkage disequilibrium network analysis (LDna) gives a global view of chromosomal inversions, local adaptation and geographic structure. *Molecular Ecology Resources*, *15*, 1031–1045. https://doi.org/10.1111/1755-0998.12369

Ketola, T., Mikonranta, L., Zhang, J. I., Saarinen, K., Örmälä, A.-M., Friman, V.-P., Mappes, J., & Laakso, J. (2013). Fluctuating temperature leads to evolution of thermal generalism and preadaptation to novel environments. *Evolution*, *67*, 2936–2944. https://doi.org/10.1111/evo.12148

Kilkenny, F., & Galloway, L. (2012). Adaptive divergence at the margin of an invaded range. *Evolution*, *67*, 722–731. https://doi.org/10.5061/dryad.6b2t6

1365294x, 2021, 0, Downloaded from https://onlinelibrary.wiley.com. By MBL WHOI Library, Oceanographic Institution-MS#8- on [02/12/2021]. Re-use and distribution is strictly not permitted, except for Open Access articles

Kinlan, B., & Gaines, S. (2003). Propagule dispersal in marine and terrestrial environments: A community perspective. *Ecology*, *84*, 2007–2020. https://doi.org/10.1890/01-0622

Kirkpatrick, M. (2010). How and why chromosome inversions evolve. *PLoS Biology*, *8*, e1000501. https://doi.org/10.1371/journal.pbio.1000501

Kirubakaran, T. G., Grove, H., Kent, M. P., Sandve, S. R., Baranski, M., Nome, T., De Rosa, M. C., Righino, B., Johansen, T., Otterå, H., Sonesson, A., Lien, S., & Andersen, Ø. (2016). Two adjacent inversions maintain genomic differentiation between migratory and stationary ecotypes of Atlantic cod. *Molecular Ecology*, *25*, 2130–2143. https://doi.org/10.1111/mec.13592

Koehn, R. K., Newell, R. I., & Immermann, F. (1980). Maintenance of an aminopeptidase allele frequency cline by natural selection. *Proceedings of the National Academy of Sciences*, *77*(9), 5385–5389. https://doi.org/10.1073/pnas.77.9.5385

Kohn, M., Murphy, W., Ostrander, E., & Wayne, R. (2006). Genomics and conservation genetics. *Trends in Ecology and Evolution*, *21*, 629–637. https://doi.org/10.1016/j.tree.2006.08.001

Lamichhaney, S., & Andersson, L. (2019). A comparison of the association between large haplotype blocks under selection and the presence/absence of inversions. *Ecology and Evolution*, *9*, 4888–4896. https://doi.org/10.1002/ece3.5094

Langmead, B., & Salzberg, S. (2013). Fast gapped-read alignment with Bowtie 2. *Nature Methods*, *9*, 357–359. https://doi.org/10.1038/nmeth.1923

Lee, C., & Gelembiuk, G. (2008). Evolutionary origins of invasive populations. *Evolutionary Applications*, *1*, 427–448. https://doi.org/10.1111/j.1752-4571.2008.00039.x

Lee, C., Kiergaard, M., Gelembiuk, G., Eads, B., & Posavi, M. (2011). Pumping ions: Rapid parallel evolution of ionic regulation following habitat invasions. *Evolution*, *65*, 2229–2244. https://doi.org/10.1111/j.1558-5646.2011.01308.x

Llaurens, V., Whibley, A., & Joron, M. (2017). Genetic architecture and balancing selection: The life and death of differentiated variants. *Molecular Ecology*, *26*, 2430–2448. https://doi.org/10.1111/mec.14051

Lotterhos, K. E., & Whitlock, M. C. (2014). Evaluation of demographic history and neutral parameterization on the performance of F_{ST} outlier tests. *Molecular Ecology*, *23*, 2178–2192. https://doi.org/10.1111/mec.12725

Martin, M. (2011). Cutadapt removes adapter sequences from high-throughput sequencing reads. *Embnet Journal*, *17*, 10–12. https://doi.org/10.14806/ej.17.1.200

McKenna, A., Hanna, M., Banks, E., Sivachenko, A., Cibulskis, K., Kernytsky, A., Garimella, K., Altshuler, D., Gabriel, S., Daly, M., & DePristo, M. A. (2010). The Genome Analysis Toolkit: A MapReduce framework for analyzing next-generation DNA sequencing data. *Genome Resources*, *20*, 1297–1303. https://doi.org/10.1101/gr.107524.110

Min, X. J., Butler, G., Storms, R., & Tsang, A. (2005). OrfPredictor: predicting protein-coding regions in EST-derived sequences. *Nucleic Acids Research*, *33*, W677–W680. https://doi.org/10.1093/nar/gki394

Munday, P., Warner, R., Monro, K., Pandolfi, J., & Marshall, D. (2013). Predicting evolutionary responses to climate change in the sea. *Ecology Letters*, *16*, 1488–1500. https://doi.org/10.1111/ele.12185

Oksanen, J., Blanchet, F. G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Wagner, H. (2019). *vegan: Community Ecology Package* (R package version 2.4-3). https://CRAN.R-project.org

Palumbi, S., & Pinsky, M. (2014). Marine dispersal, ecology, and conservation. In M. Bertness, J. Bruno, B. Silliman, & J. Stachowicz (Eds.), *Marine community ecology and conservation* (1st ed., pp. 57–84). Sinauer Associates.

Patro, R., Duggal, G., Love, M. I., Irizarry, R. A., & Kingsford, C. (2017). Salmon provides fast and bias-aware quantification of transcript expression. *Nature Methods*, *14*, 417–419. https://doi.org/10.1038/nmeth.4197

Pembleton, L. W., Cogan, N. O. I., & Forster, J. W. (2013). StAMPP: An R package for calculation of genetic differentiation and structure of mixed-ploidy level populations. *Molecular Ecology Resources*, *13*, 946–952.

Pespeni, M., & Palumbi, S. (2013). Signals of selection in outlier loci in a widely dispersing species across an environmental mosaic. *Molecular Ecology*, *22*, 3580–3597. https://doi.org/10.1111/mec.12337

Phillips, B., Brown, G., Webb, J., & Shine, R. (2006). Invasion and the evolution of speed in toads. *Nature*, *439*, 803. https://doi.org/10.1038/439803a

Price, A., Patterson, N. J., Plenge, R. M., Weinblatt, M. E., Shadick, N. A., & Reich, D. (2006). Principal components analysis corrects for stratification in genome-wide association studies. *Nature Genetics*, *38*, 904–909. https://doi.org/10.1038/ng1847

Prunier, J., Dubut, V., Chikhi, L., & Blanchet, S. (2017). Contribution of spatial heterogeneity in effective population sizes to the variance in pairwise measures of genetic differentiation. *Methods in Ecology and Evolution*, *8*, 1866–1877. https://doi.org/10.1111/2041-210X.12820

R Core Team. (2016). R: A Language and Environment for Statistical Computing. https://www.r-project.org

Reed, D., & Frankham, R. (2003). Correlation between fitness and genetic diversity. *Conservation Biology*, *17*, 230–237. https://doi.org/10.1046/j.1523-1739.2003.01236.x

Reynolds, R. W., Smith, T. M., Liu, C., Chelton, D. B., Casey, K. S., & Schlax, M. G. (2007). Daily high-resolution-blended analyses for sea surface temperature. *Journal of Climate*, *20*, 5473–5496. https://doi.org/10.1175/2007JCLI1824.1

Ritter, J. (1970). A summary of preliminary studies of sedimentation and hydrology in Bolinas Lagoon, Marin County, California. U.S. Geological Survey, Circular 627.

Rius, M., & Darling, J. (2014). How important is intraspecific genetic admixture to the success of colonising populations? *Trends in Ecology and Evolution*, *29*, 233–242. https://doi.org/10.1016/j.tree.2014.02.003

Roman, J., & Darling, J. (2007). Paradox lost: genetic diversity and the success of aquatic invasions. *Trends in Ecology and Evolution*, *22*, 454–464. https://doi.org/10.1016/j.tree.2007.07.002

Rousset, F. (2008). genepop'007: A complete re-implementation of the genepop software for Windows and Linux. *Molecular Ecology Resources*, *8*, 103–106. https://doi.org/10.1111/j.1471-8286.2007.01931.x

Sanford, E., & Kelly, M. (2011). Local adaptation in marine invertebrates. *Annual Review of Marine Science*, *3*, 509–535. https://doi.org/10.1146/annurev-marine-120709-142756

Schmidt, P., Bertness, M., & Rand, D. (2000). Environmental heterogeneity and balancing selection in the acorn barnacle, *Semibalanus balanoides*. *Philosophical Transactions of the Royal Society B*, *267*, 379–384. https://doi.org/10.1111/j.0014-3820.2001.tb00656.x

Schmidt, P. S., & Rand, D. M. (2001). Adaptive maintenance of genetic polymorphism in an intertidal barnacle: Habitat- and life-stage-specific survivorship of Mpi genotypes. *Evolution*, *55*, 1336–1344. https://doi.org/10.1111/j.0014-3820.2001.tb00656.x

See, K., & Feist, B. (2010). Reconstructing the range expansion and subsequent invasion of introduced European green crab along the west coast of the United States. *Biological Invasions*, *12*, 1305–1318. https://doi.org/10.1007/s10530-009-9548-7

Sexton, J. P., Strauss, S. Y., & Rice, K. J. (2011). Gene flow increases fitness at the warm edge of a species' range. *Proceedings of the National Academy of Sciences*, *108*(28), 11704–11709. https://doi.org/10.1073/pnas.1100404108

Simms, D., Cizdziel, P., & Chomczynski, P. (1993). TRIzol: A new reagent for optimal single-step isolation of RNA. *Focus*, 99–102. https://doi.org/10.1016/0003-2670(61)80041-X

1365294x, 2021, 0, Downloaded from https://onlinelibrary.wiley.com. By MBL WHOI Library, Oceanographic Institution-MS#8- on [02/12/2021]. Re-use and distribution is strictly not permitted, except for Open Access articles

Slatkin, M. (2008). Linkage disequilibrium–understanding the evolutionary past and mapping the medical future. *Nature Reviews Genetics*, *9*, 477–485. https://doi.org/10.1038/nrg2361

Sotka, E. (2012). Natural selection, larval dispersal, and the geography of phenotype in the sea. *Integrative and Comparative Biology*, *52*, 538–545. https://doi.org/10.1093/icb/ics084

Sundqvist, L., Keenan, K., Zackrisson, M., Prodöhl, P., & Kleinhans, D. (2016). Directional genetic differentiation and asymmetric migration. *Ecology & Evolution*, *6*, 3461–3475.

Szpiech, Z. A., Jakobsson, M., & Rosenberg, N. A. (2008). ADZE: A rarefaction approach for counting alleles private to combinations of populations. *Bioinformatics*, *24*, 2498–2504. https://doi.org/10.1093/bioinformatics/btn478

Szücs, M., Vahsen, M. L., Melbourne, B. A., Hoover, C., Weiss-Lehman, C., & Hufbauer, R. A. (2017). Rapid adaptive evolution in novel environments acts as an architect of population range expansion. *Proceedings of the National Academy of Sciences*, *114*(51), 13501–13506. https://doi.org/10.1073/pnas.1712934114

Takahashi, Y., Suyama, Y., Matsuki, Y., Funayama, R., Nakayama, K., & Kawata, M. (2016). Lack of genetic variation prevents adaptation at the geographic range margin in a damselfly. *Molecular Ecology*, *25*, 4450–4460. https://doi.org/10.1111/mec.13782

Tepolt, C., Darling, J. A., Bagley, M. J., Geller, J. B., Blum, M. J., & Grosholz, E. D. (2009). European green crabs (*Carcinus maenas*) in the Northeastern Pacific: genetic evidence for high population connectivity and current-mediated expansion from a single introduced source population. *Diversity and Distributions*, *15*, 997–1009. https://doi.org/10.1111/j.1472-4642.2009.00605.x

Tepolt, C., & Palumbi, S. (2015). Transcriptome sequencing reveals both neutral and adaptive genome dynamics in a marine invader. *Molecular Ecology*, *24*, 4145–4158. https://doi.org/10.1111/mec.13294

Tepolt, C., & Palumbi, S. (2020). Rapid adaptation to temperature via a potential genomic island of divergence in the invasive green crab, *Carcinus maenas*. *Frontiers in Ecology and Evolution*, *8*, 580701. https://doi.org/10.3389/fevo.2020.580701

Tepolt, C., & Somero, G. (2014). Master of all trades: thermal acclimation and adaptation of cardiac function in a broadly distributed marine invasive species, the European green crab, *Carcinus maenas*. *Journal of Experimental Biology*, *217*, 1129–1138. https://doi.org/10.1242/jeb.093849

Thia, J. A., McGuigan, K., Liggins, L., Figueira, W. F., Bird, C. E., Mather, A., Evans, J. L., & Riginos, C. (2021). Genetic and phenotypic variation exhibit both predictable and stochastic patterns across an intertidal fish metapopulation. *Molecular Ecology*, in press. https://doi.org/10.1111/mec.15829

Thompson, M. J., & Jiggins, C. D. (2014). Supergenes and their role in evolution. *Heredity*, *113*, 1–8. https://doi.org/10.1038/hdy.2014.20

Tigano, A., & Friesen, V. (2016). Genomics of local adaptation with gene flow. *Molecular Ecology*, *25*, 2144–2164. https://doi.org/10.1111/mec.13606

Twyford, A. D., & Friedman, J. (2015). Adaptive divergence in the monkey flower *Mimulus guttatus* is maintained by a chromosomal inversion. *Evolution*, *69*, 1476–1486. https://doi.org/10.5061/dryad.5h032

Véliz, D., Duchesne, P., Bourget, E., & Bernatchez, L. (2006). Stable genetic polymorphism in heterogeneous environments: Balance between asymmetrical dispersal and selection in the acorn barnacle. *Journal of Evolutionary Biology*, *19*, 589–599. https://doi.org/10.1111/j.1420-9101.2005.01000.x

Vucetich, J., Waite, T., & Nunney, L. (1997). Fluctuating population size and the ratio of effective to census population size. *Evolution*, *51*, 2017–2021. https://doi.org/10.1111/j.1558-5646.1997.tb05123.x

Weir, B. S., & Cockerham, C. C. (1984). Estimating *F*-statistics for the analysis of population structure. *Evolution*, *38*, 1358–1370.

Welch, W. (1968). Changes in abundance of the green crab, *Carcinus maenas* (L.), in relation to recent temperature changes. *Fishery Bulletin*, *67*, 337–345.

Westram, A. M., Rafajlović, M., Chaube, P., Faria, R., Larsson, T., Panova, M., Ravinet, M., Blomberg, A., Mehlig, B., Johannesson, K., & Butlin, R. (2018). Clines on the seashore: The genomic architecture underlying rapid divergence in the face of gene flow. *Evolution Letters*, *2–4*, 297–309. https://doi.org/10.1002/evl3.74

White, C., Selkoe, K. A., Watson, J., Siegel, D. A., Zacherl, D. C., & Toonen, R. J. (2010). Ocean currents help explain population genetic structure. *Proceedings of the Royal Society B*, *277*, 1685–1694. https://doi.org/10.1098/rspb.2009.2214

White, T., Perkins, S., Heckel, G., & Searle, J. (2013). Adaptive evolution during an ongoing range expansion: The invasive bank vole (*Myodes glareolus*) in Ireland. *Molecular Ecology*, *22*, 2971–2985. https://doi.org/10.1111/mec.12343

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. http://ggplot2.org

Wilson, J., Dormontt, E., Prentis, P., Lowe, A., & Richardson, D. (2009). Something in the way you move: Dispersal pathways affect invasion success. *Trends in Ecology and Evolution*, *24*, 136–144. https://doi.org/10.1016/j.tree.2008.10.007

Xuereb, A., Benestan, L., Normandeau, É., Daigle, R. M., Curtis, J. M. R., Bernatchez, L., & Fortin, M. J. (2018). Asymmetric oceanographic processes mediate connectivity and population genetic structure, as revealed by RADseq, in a highly dispersive marine invertebrate (*Parastichopus californicus*). *Molecular Ecology*, *27*, 2347–2364. https://doi.org/10.1111/mec.14589

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Tepolt, C. K., Grosholz, E. D., de Rivera, C. E., & Ruiz, G. M. (2021). Balanced polymorphism fuels rapid selection in an invasive crab despite high gene flow and low genetic diversity. *Molecular Ecology*, 00, 1–15. https://doi.org/10.1111/mec.16143

1365294x, 2021, 0, Downloaded from https://onlinelibrary.wiley.com. By MBL WHOI Library, Oceanographic Institution-MS#8- on [02/12/2021]. Re-use and distribution is strictly not permitted, except for Open Access articles