

Relative performance of eelgrass genotypes shifts during extreme warming event: disentangling the roles of multiple traits

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SUPPLEMENT:

SUPPLEMENTAL TABLE:

Table S1. Physiological justifications for the relationships included in the Meta-SEM and additional paths added to the selected model (Fig 4).

	Path	Justification
Meta-Model	Photosynthetic efficiency (α) to productivity	In seagrass electron transport as measured with PAM fluorometry is positively correlated with photosynthesis as measured by oxygen evolution (Beer et al. 1998), thus it seems plausible that photosynthetic efficiency could be a limiting step in photosynthesis and plant growth.
	Photoinhibition (β) to productivity	In seagrass electron transport as measured with PAM fluorometry is positively correlated with photosynthesis as measured by oxygen evolution (Beer et al. 1998), thus it seems plausible that photoinhibition could be a limiting step in photosynthesis and plant growth.
	Relative maximum electron transport rate (rETR _{max}) to productivity	In seagrass electron transport as measured with PAM fluorometry is positively correlated with photosynthesis as measured by oxygen evolution (Beer et al. 1998), thus it seems plausible that relative maximum electron transport rate could be a limiting step in photosynthesis and plant growth.
	Shoot length to productivity	Increasing leaf area (i.e. leaf length) can lead to higher efficiency in carbon fixation per unit dry mass and is usually associated with faster relative growth rates (Lambers & Poorter 1992). Longer <i>Z. marina</i> sheath lengths are correlated to faster absolute growth rates (Ruesink et al. 2018).
	Shoot density to productivity	<i>Z. marina</i> shoot density in the field is thought to lower productivity through self-shading (Olesen B & Sand-Jensen K 1994), and might also increase respiratory burden of large clones during times of stress (Vermaat & Verhagen

		1996)
	Traits across both time points	<i>Z. marina</i> traits are distinct among genotypes (Tomas et al. 2011), if these trait differences are genetically based it is possible that relative trait values across genotypes would be maintain through time.
	Productivity across both time points	Based on Kendall Rank Correlation analysis (Fig 3) we were not expecting genotype productivity to be correlated through time. Relative performance (i.e. productivity) among genotypes could be uncorrelated across environments that allowed trait differences to be expressed (Gillespie & Turelli 1989)
Additional paths added to selected model (Model 7)	Summer photosynthetic efficiency (ζ) to summer photoinhibition (β)	More efficient light capture under stressful and high light conditions should reduce the amount of excess light capable of causing photodamage in the PSII and subsequent increase in photoinhibition (Lambers et al. 2008)
	Summer shoot length to summer photoinhibition (β)	Two possible mechanisms by which summer shoot length could result in an increase in photoinhibition include 1) greater self-shading by longer leaves, or 2) if longer leaves were older (Ralph et al. 2005, Alcoverro et al. 1998).
	Winter productivity to summer shoot length	It seems reasonable that greater growth in the winter could cause shoots to be longer in the following season.
	Winter shoot density to summer productivity	Shoot density and ramet size have been linked to stored carbohydrate levels within the rhizome (Vermaat & Verhagen 1996, Govers et al. 2015). In particular, overwintering in smaller ramets increases stored carbohydrates and survival by lowering winter respiratory demand (Vermaat & Verhagen 1996, Alcoverro et al. 2001). Therefore, genotypes maintaining higher shoot densities during the winter could incur a greater cost in terms of using carbohydrate stores. If the relative difference in carbohydrate stores is persistent, then during times of future stress these genotypes would be at a disadvantage.

SUPPELEMENTAL FIGURES:

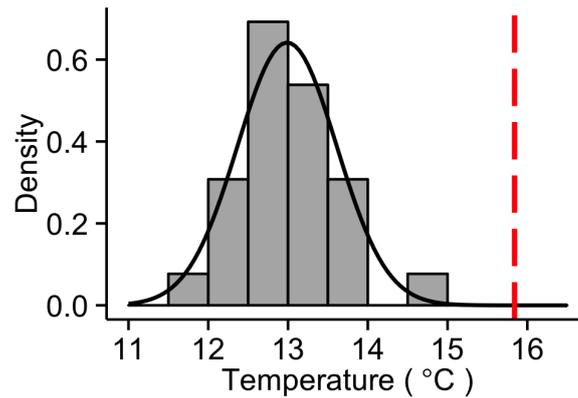


Figure S1. Average summer temperature during 2014 (vertical dashed line) was 3.35 standard deviations higher than the long-term summer average at the Bodega Marine Laboratory, Bodega Bay, CA. Data shown are summer averages (July-September) since 1988, calculated from the Bodega Ocean Observing Node (BOON) dataset (www.boon.ucdavis.edu).

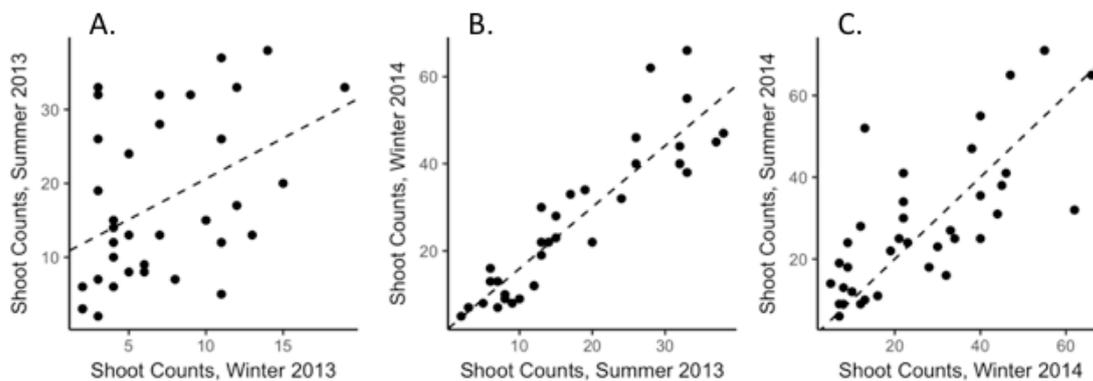


Figure S2. Shoot counts (i.e. number of shoots within a pot, effectively shoot density) stabilize after the first year in common garden. Six months after the common garden was planted counts range from 1-15, then 1 year after planting counts range from 1-30 (A & B). Shoot counts reach a range of 5-60 during Winter 2014 (B). Shoot counts remain stable for all of 2014 (C).

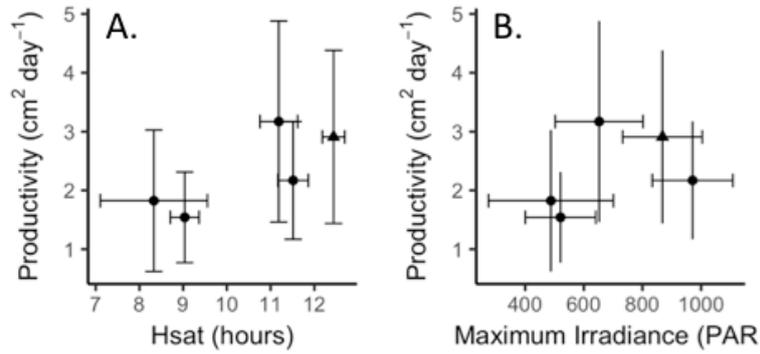


Figure S3. There is potentially an effect of hours of saturating irradiance (H_{sat}) on average productivity of the 36 genotypes ($p = 0.12$, $R^2 = 0.61$), driven by seasonal differences in daylight hours (A). There is no relationship between maximum irradiance (I_{max}) and productivity (B). Circles are data take from genotypes in common garden. Triangles are data taken on 36 genotypes in separate experiment (Abbott et al. 2018) during July 2014.

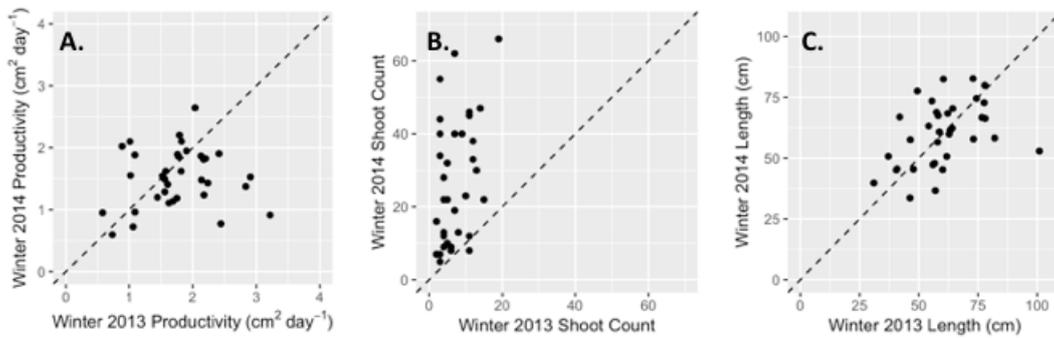


Figure S4. Raw productivity (A), shoot count (B), and length (C) trait data for all 36 genotypes comparing winter 2013 with winter 2014. Trait variation among the 36 genotypes is maintained or increases through time. Dashed line is the 1:1 correspondence line.

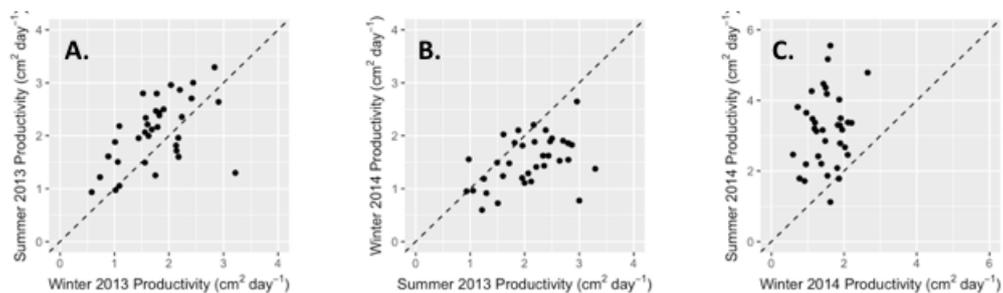


Figure S5. Raw productivity estimates for all 36 genotypes comparing adjacent time points (A) Winter 2013-Summer 2013, (B) Summer 2013-Winter 2014, (C) Winter 2014-Summer 2013. Dashed line is the 1:1 correspondence line.

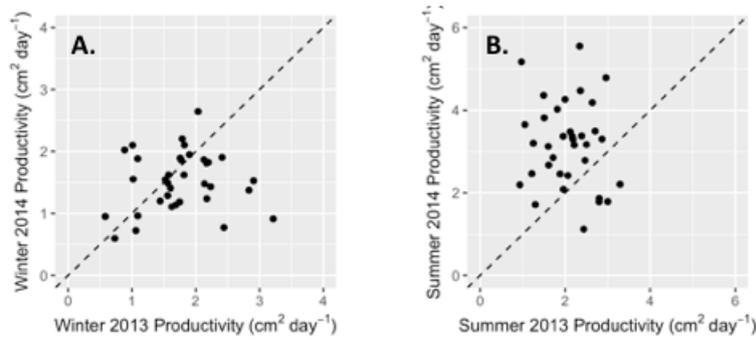


Figure S6. Raw productivity estimates for all 36 genotypes comparing the same seasons across years including a (A) winter comparison, and a (B) summer comparison. Dashed line is the 1:1 correspondence line.

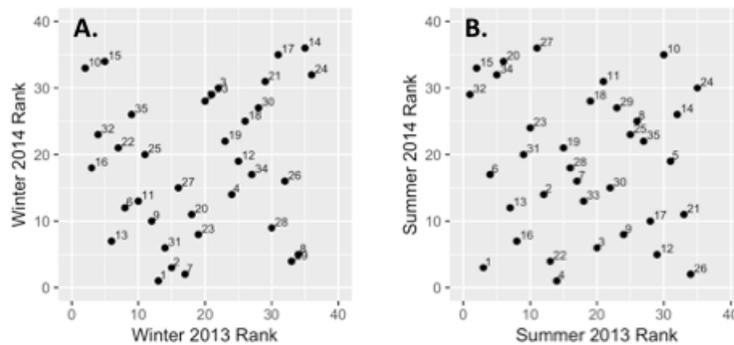


Figure S7. There is no correlation in productivity between the same seasons across years for (A) winter, and (B) summer. If temperature shifts genotype rank during summer 2014, we would not expect there to be a correlation across summers when temperature varied. The lack of correlation across the two winters (which had similar temperature and light conditions) could be because genotypes had only been in common garden for four month by winter 2013 and were acclimating to garden conditions at different rates.

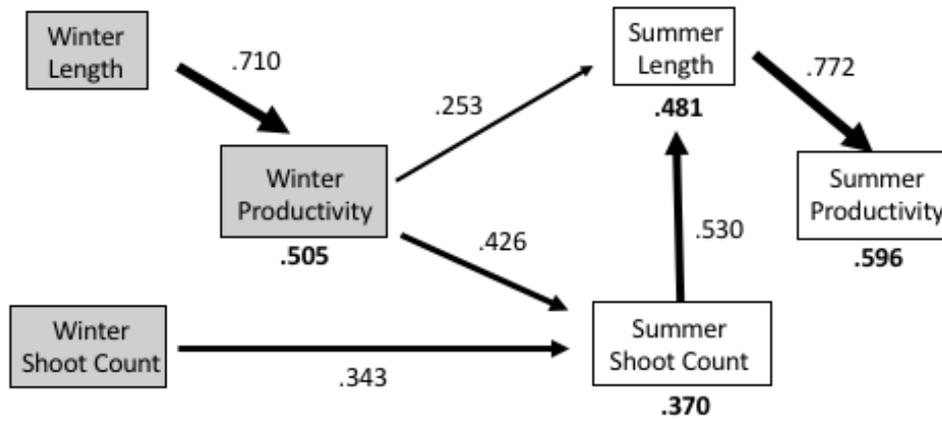


Figure S8. Measured variable SEM for all 36 genotypes during 2013. As demonstrated in the 2014 SEM, there is a robust positive feedback between shoot length and productivity. Contrary to the 2014 SEM, winter shoot count (i.e. shoot density) does not have a delayed negative effect on summer productivity, rather summer shoot count has an indirect positive effect on summer productivity. Because all relationships are positive, the positive correlation seen in Kendall’s rank correlation analysis between winter productivity and summer productivity in 2013 would be expected. Gray shaded variables are winter 2014 measurements, unshaded variables are summer 2014 measurements. In the selected model (B.) all paths are significant. Coefficients of determination are shown in bold by the endogenous variables: winter productivity, summer productivity, summer shoot count, summer shoot length. Path regression coefficients are standardized. Arrow widths are proportional to the size of the coefficient of determination. Model was run with global estimation using the R Package “Lavaan”. MF = 6.551, DF = 8, Fit(P) = 0.586, N = 70.

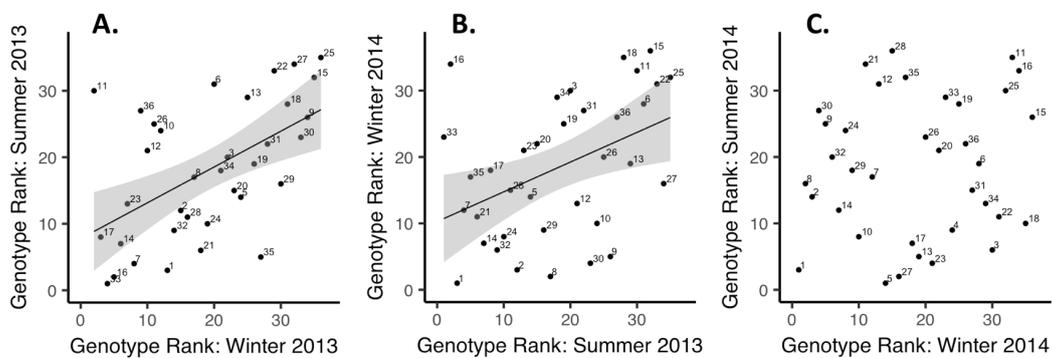


Figure S9. Kendall’s Rank Correlations for 36 genotypes ranked by average productivity between four consecutive time points, Winter 2013-Summer 2013 (A. $p < 0.001$, $\tau = 0.41$), Summer 2013-Winter 2014 (B. $p = 0.011$, $\tau = 0.30$), and Winter 2014-Summer 2014 (C. $p = 0.525$, $\tau = 0.07$). Shaded regions denote 95% confidence interval. Labels are genotype ID numbers. Data shown in C. are the same productivity data used in SEM (See Fig 4). N = 36

SUPPLEMENTAL REFERENCES

- Abbott JM, DuBois K, Grosberg RK, Williams SL, Stachowicz JJ (2018) Genetic distance predicts trait differentiation at the subpopulation but not the individual level in eelgrass, *Zostera marina*. *Evol and Ecol* (*in press*)
- Alcoverro T, Manzanera M, Romero J (2001) Annual metabolic carbon balance of the seagrass *Posidonia oceanica*: The importance of carbohydrate reserves. *Mar Ecol Prog Ser* 211:105–116
- Alcoverro T, Manzanera M, Romero J (1998) Seasonal and age-dependent variability of *Posidonia oceanica* (L.) Delile photosynthetic parameters. *Mar Bio and Eco* 230:1-13
- Beer S, Vilenkin B, Weil A, Veste M, Susel L, Eshel A (1998) Measuring photosynthetic rates in seagrasses by pulse amplitude modulated (PAM) fluorometry. *Mar Ecol Prog Ser* 174:293-300
- Gillespie JH, Michael T (1989) Genotype-environment interactions and the maintenance of polygenic variation. *Genetics* 121:129-138
- Govers LL, Suykerbuyk W, Hoppenreijts JHT, Giesen K, Bouma TJ, Katwijk MM van (2015) Rhizome starch as indicator for temperate seagrass winter survival. *Ecol Indic* 49:53–60
- Lambers H, Chapin FSC III, Pons TL (2008) *Plant physiological ecology*, second edition. Springer, New York.
- Lambers H, Poorter H (1992) Inherent variation in growth rate between higher plants: a search for physiological causes and ecological consequences. *Advan Ecol Res* 23:187-261
- Olesen B, Sand-Jensen K (1994) Demograph of shallow eelgrass (*Zostera marina*) populations – Shoot dynamics and biomass development. *J Ecol* 82:379-390
- Ralph PJ, Macinnis-Ng CMO, Frankart C (2005) Fluorescence imaging application: effect of leaf age on seagrass photokinetics. *Aquat Bot* 81:69-84
- Ruesink JL, Stachowicz JJ, Reynolds PL, Brostrom C, Cusson M, Douglass J, Eklof J, Engelen AH, Hori M, Hovel K, Iken K, Moksnes P, Nakaoka M, O'Connor MI, Olsen JL, Sotka EE, Whalen MA, Duffy JE (2018) Form-function relationships in a marine foundations species depend on scale: a shoot to global perspective from a distributed ecological experiment. *Oikos* 127:364-374
- Tomas AF, Abbott JM, Steinberg C, Balk M, Williams SL, Stachowicz JJ (2011) Plant genotype and nitrogen loading influence seagrass productivity, biochemistry, and plant–herbivore interactions. *Ecology* 92:1807–1817
- Vermaat JE, Verhagen FCA (1996) Seasonal variation in the intertidal seagrass *Zostera noltii* Hornem.: coupling demographic and physiological patterns. *Aquat Bot* 52:259–281