

Physiological and fitness consequences of seasonal rainfall variation in
neotropical live oak seedlings (*Quercus oleoides*): implications for global change

A DISSERTATION
SUBMITTED TO THE FACULTY OF
UNIVERSITY OF MINNESOTA
BY

Alyson Center

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

Advisor: Jeannine Cavender-Bares

June 2015

© Alyson Center 2015

Acknowledgements

I would like to acknowledge the community of people that have supported this research and my work as a graduate student. I thank my advisor, Jeannine Cavender-Bares for her support and guidance through the years. I would like to thank all of the faculty, including my committee, Julie Etterson, Ruth Shaw, Rebecca Montgomery, and Eric Seabloom for their guidance and constructive feedback helping to refine my ideas, providing constructive feedback, and overall helping to improve my research.

This work would not have been possible without the help of collaborators Jed. P Sparks, Timothy Longwell and George Pilz. I am especially grateful for Esau Zuniga, field manager at the garden site at Zamorano University Honduras, and Marileth Briceño, manager for the gardens sites in the Guanacaste Conservation Area (ACG) in NW Costa Rica. This research would not have been possible without their tireless efforts and hardwork. I thank Roger Blanco for assistance with permits and equipment at the ACG, and María Marta for compiling weather data from Sector Santa Rosa. I would also like to thank the numerous student volunteers from Zamorano University that assisted in weeding, planting, and the collection of growth measurements. This work would not have been possible without the efforts of Johanny Hernandez-Brenes and Alonso Espinoza whom helped me prepare garden sites, plant seeds, install watering equipment, weed the gardens, collect growth measurements along with dozens of other tasks throughout the years. My time in Costa Rica would not have been the same without the friendship of fellow graduate students who worked around the ACG including Justin Becknell, Maga Gei, Moana McClellan, and Kristen Becklund and UMN faculty Dr. Jennifer Powers.

Numerous students from the University of Minnesota have assisted on the project including Rhea Smylaski, Derrick Ostlie, Tyler Carlson, Kelsey Thurow, and Anne Beulke. I would also like to thank the former Cavender-Bares lab manager Kari Koehler for her assistance early on in the project. I thank AJ Lange for wandering around Mexico in a rental car with me to collect acorns. I am grateful to all those that have provided feedback on previous versions of manuscripts. I thank the past and current members of

the Cavender-Bares lab, including Jessica Savage, Nicholas Deacon, Paul Gugger, Gina Quiram, Jake Grossman, Laura Williams, Beth Fallon, Xiaojing Wei, Jennifer Teshera-Levy, Matthew Kaproth, Will Pearse, and José Ramírez-Valiente. I am appreciative of all the guidance I have received in completing the statistical analyses. I especially thank Ruth Shaw and Charles Geyer for their assistance with Aster analyses and troubleshooting.

I would like to thank the Plant Biological Sciences Graduate Program for being supportive. I especially thank Gail Kalli for her assistance traversing the logistics of graduate school. PBS has generously provided summer stipend fellowships and travel grants throughout my graduate career. I thank the Department of Ecology and Evolution's Dayton Wilkie grant for support with equipment purchases. A substantial part of the funding for this research has come from the National Science Foundation: IOS-0843665.

Finally I would like to thank my family and friends for their support through the years. My parents have been unconditionally loving and patient with me. They have also provided months, if not years, of free dog and cat sitting while I was working in Central America. I especially acknowledge my long-time best friend Bobbie Kite who has supported me since our undergraduate days and we have been growing together since. Lastly I thank my partner, Andrea Carpentier, first for her help collecting physiology measurements in Honduras and second for her patience, love, laughter, and for our collective 'woodslife' dreams.

Abstract

Broadly distributed species often span a large range of environmental conditions, which pose contrasting physiological challenges. Such species are thought to persist across this heterogeneity, either by locally adapting or by evolving wide environmental tolerances via phenotypic plasticity or maintaining high genetic variation. The extent to which populations display local adaptation, phenotypic plasticity, and high within-population genetic variation will have large impacts on species responses to climate change. Large-scale habitat fragmentation impedes migration making plasticity and adaptation important mechanisms for *in situ* persistence. Using common gardens with reciprocal plantings we investigated the consequences of changes in water availability in the broadly distributed tropical live oak, *Quercus oleoides*. Chapter 1 examines the relationship among seed production timing, germination and seedling fitness at the local scale in dry forests of NW Costa Rica. In chapter 2, I investigate the extent to which four populations of *Q. oleoides* from regions with contrasting rainfall patterns exhibit local adaptation and the role of changes in water availability on seedlings fitness. In chapter 3, I examine the extent that populations exhibit differentiation in traits related to carbon and water use. Chapter 3 also investigates the role of trait plasticity in seedling responses to changes in seasonal water availability and the patterns of phenotypic selection on traits. Results from these studies show that local-scale differences in seed production timing have significant consequences for germination and seedling fitness. At a larger spatial scale, results of this work indicate that the broadly distributed *Q. oleoides* does not consist of a series of locally adapted populations, but rather, of populations with wide environmental tolerances. Seedlings from all populations show similar physiological and morphological responses to changes in water availability and differences among garden sites. Trait plasticity contributes more to phenotypic trait variation than within-population genetic differences. Overall, populations of *Q. oleoides* lineage represent a lineage well-adapted to drought. Populations are able to maintain fitness with changes in water availability in the short-term through plasticity but may be limited in their long-term adaptive capacity to future changes in rainfall patterns due to low within-population genetic variation for physiological traits.

Table of Contents

Acknowledgements	i
Abstract	iii
Table of Contents	iv
List of Tables	v
List of Figures	xi
Introduction	1
Chapter 1	5
Chapter 2	31
Chapter 3	61
References	102
Appendix 1:Supplemental material for Chapter 1	116
Appendix 2:Supplemental material for Chapter 2	125
Appendix 3:Supplemental material for Chapter 3	216

List of Tables

Table 1.1- Analysis of seed size, germination success, survival, and cumulative seedlings fitness measured on progeny from early-and late-cohort <i>Quercus oleoides</i> seeds.....	25
Table 1.2- Site-specific phenotypic selection analysis on traits (days to germination and seed size) from early- and late-cohort <i>Quercus oleoides</i> seeds.....	26
Table 2.1- Summary of nested model comparison of Aster models of seedling fitness across garden sites.....	51
Table 2.2- Summary of nested model comparisons of Aster models of seedling fitness within dry garden site.....	52
Table 2.3- Summary of nested model comparisons of Aster models of seedling fitness at intermediate and wet gardens.....	53
Table 2.4- Summary of nested model comparisons of Aster models of seedling fitness among maternal families.....	54
Table 3.1- Summary of nested mixed effects model comparisons of leaf predawn and midday water potentials in seedlings at dry garden.....	87
Table 3.2- Summary of nested mixed effects model comparisons for carbon and water use traits in 2010 transplant seedlings across gardens.....	88
Table 3.3- Summary of nested mixed effects model comparisons for carbon and water use traits in 2010 transplant seedlings in watering treatments at dry garden.....	89
Table 3.4- Summary of nested mixed effects model comparisons for carbon and water use traits in 2010 transplant seedlings at intermediate and wet gardens.....	90
Table 3.5- Site and season specific phenotypic selection analyses.....	91
Table 3.6- Analyses of phenotypic selection within the four watering treatments at the dry garden site.....	92
Table 3.7- Analyses of phenotypic selection within the two watering treatments at the intermediate garden site.....	93
Table S1.1- Summary of model effect estimates for germination, days to germination (DTG), survival, and fitness progeny from early-and late-cohort seeds.....	117-118
Table S1.2- Summary of nested model comparisons of growth traits.....	119

Table S1.3- Repeated measures analysis of traits measured for three seasons on progeny from early-and late-cohort <i>Quercus oleoides</i> seeds.....	120-121
Table S2.1- Summary of the number of seeds collected from four natural populations of <i>Q. oleoides</i>	126
Table S2.2- Summary nested model comparison of 2010 transplant seedling survivorship in common gardens in Honduras and NW Costa Rica.....	127
Table S2.3- GLMM summary of 2010 transplant seedling survivorship in common gardens in Honduras and NW Costa Rica.....	128
Table S2.4- Summary of nested LMM comparisons for growth traits of 2010 transplant cohort in common gardens in Honduras and NW Costa Rica.....	129
Table S2.5- Summary of LMM of growth traits of 2010 transplant cohort in common gardens in Honduras and NW Costa Rica.....	130-131
Table S2.6- Summary nested model comparison of 2011 transplant seedling survivorship in common gardens in Honduras and NW Costa Rica.....	134
Table S2.7- GLMM summary of 2011 transplant seedling survivorship in common gardens in Honduras and NW Costa Rica.....	135
Table S2.8- Summary nested model comparison of 2011 transplant seedling growth traits in common gardens in Honduras and NW Costa Rica.....	136
Table S2.9- Summary of LMM of growth traits of 2011 transplant cohort seedlings in common gardens in Honduras and NW Costa Rica.....	137-140
Table S2.10- Summary nested model comparison of 2010 direct planting seedling survivorship of seedlings in common gardens in Honduras and NW Costa Rica.....	143
Table S2.11- GLMM summary of 2010 direct planting seedling survivorship in common gardens in Honduras and NW Costa Rica.....	144
Table S2.12- Summary of nested LMM comparisons for growth traits of 2010 direct planting cohort in common gardens in Honduras and NW Costa Rica.....	145
Table S2.13- Summary of LMM of growth traits of 2010 direct planting cohort in common gardens in Honduras and NW Costa Rica.....	146
Table S2.14- Summary nested model comparison of 2011 direct planting seedling survivorship of seedlings in common gardens in Honduras and NW Costa Rica.....	149

Table S2.15- GLMM summary of 2010 direct planting seedling survivorship in common gardens in Honduras and NW Costa Rica.....	150
Table S2.16- Summary of nested LMM comparisons for growth traits of 2011 direct planting cohort in common gardens in Honduras and NW Costa Rica.....	151
Table S2.17- Summary of LMM of growth traits of 2011 direct planting cohort in common gardens in Honduras and NW Costa Rica.....	152-153
Table S2.18- Summary nested model comparison of 2010 transplant seedling survivorship in watering treatments at dry garden.....	156
Table S2.19- GLMM summary of 2010 transplant seedling survivorship in watering treatments at dry garden.....	157
Table S2.20- Summary of nested LMM comparisons for growth traits of 2010 transplant cohort in watering treatments at dry garden.....	158
Table S2.21- Summary of LMM of growth traits of 2010 transplant cohort in watering treatments at dry garden.....	159-160
Table S2.22- Summary nested model comparison of 2011 transplant seedling survivorship in watering treatments at dry garden.....	163
Table S2.23- GLMM summary of 2011 transplant seedling survivorship in watering treatments at dry garden.....	164
Table S2.24- Summary of nested LMM comparisons for growth traits of 2011 transplant cohort in watering treatments at dry garden.....	165-166
Table S2.25- Summary of LMM of growth traits of 2011 transplant cohort in watering treatments at dry garden.....	167-170
Table S2.26- Summary nested model comparison of 2010 direct planting seedling survivorship in watering treatments at dry garden.....	173
Table S2.27- GLMM summary of 2010 direct planting seedling survivorship in watering treatments at dry garden.....	174
Table S2.28- Summary of nested LMM comparisons for growth traits of 2010 direct planting cohort in watering treatments at dry garden.....	175
Table S2.29- Summary of LMM of growth traits of 2010 direct planting cohort in watering treatments at dry garden.....	176-177

Table S2.30- Summary nested model comparison of 2011 direct planting seedling survivorship in watering treatments at dry garden.....	180
Table S2.31- GLMM summary of 2011 direct planting seedling survivorship in watering treatments at dry garden.....	181
Table S2.32- Summary of nested LMM comparisons for growth traits of 2011 direct planting cohort in watering treatments at dry garden.....	182
Table S2.33- Summary of LMM of growth traits of 2011 direct planting cohort in watering treatments at dry garden.....	183-184
Table S2.34- Summary nested model comparison of 2010 transplant seedling survivorship in watering treatments at intermediate and wet gardens.....	187
Table S2.35- GLMM summary of 2010 transplant seedling survivorship in watering treatments at intermediate and wet gardens.....	188
Table S2.36- Summary of nested LMM comparisons for growth traits of 2010 transplant cohort in watering treatments at intermediate and wet gardens.....	189
Table S2.37- Summary of LMM of growth traits of 2010 transplant cohort in watering treatments at intermediate and wet gardens.....	190-191
Table S2.38- Summary nested model comparison of 2011 transplant seedling survivorship in watering treatments at intermediate and wet gardens.....	194
Table S2.39- GLMM summary of 2011 transplant seedling survivorship in watering treatments at intermediate and wet gardens.....	195
Table S2.40- Summary of nested LMM comparisons for growth traits of 2011 transplant cohort in watering treatments at intermediate and wet gardens.....	196
Table S2.41- Summary of LMM of growth traits of 2011 transplant cohort in watering treatments at intermediate and wet gardens.....	197-200
Table S2.42- Summary nested model comparison of 2010 direct planting seedling survivorship in watering treatments at intermediate and wet gardens.....	203
Table S2.43- GLMM summary of 2010 direct planting seedling survivorship in watering treatments at intermediate and wet gardens.....	204
Table S2.44- Summary of nested LMM comparisons for growth traits of 2010 direct planting cohort in watering treatments at intermediate and wet gardens.....	205

Table S2.45- Summary of LMM of growth traits of 2010 direct planting cohort in watering treatments at intermediate and wet gardens.....	206
Table S2.46- Summary nested model comparison of 2011 direct planting seedling survivorship in watering treatments at intermediate and wet gardens.....	209
Table S2.47- GLMM summary of 2011 direct planting seedling survivorship in watering treatments at intermediate and wet gardens.....	210
Table S2.48- Summary of nested LMM comparisons for growth traits of 2011 direct planting cohort in watering treatments at intermediate and wet gardens.....	211
Table S2.49- Summary of LMM of growth traits of 2011 direct planting cohort in watering treatments at intermediate and wet gardens.....	212-213
Table S3.1- Summary of LMM output for leaf predawn (PD) and midday (MD) water potentials in seedlings at the dry garden.....	217
Table S3.2- Summary of LMM output for $\delta^{13}\text{C}$, SLA, SD and SPI in 2010 transplant seedlings across gardens.....	218
Table S3.3- Summary of pairwise contrasts of garden x season interaction from LMM of $\delta^{13}\text{C}$ and SLA in 2010 transplant seedlings across gardens.....	219
Table S3.4- Summary of pairwise contrasts of population x season interaction from LMM for SLA in 2010 transplant seedlings across gardens.....	220
Table S3.5- Summary of nested LMM comparisons for stomatal pore length of 2010 transplant seedlings across gardens.....	221
Table S3.6- Summary of nested mixed effects model comparisons for $\delta^{13}\text{C}$, SLA, SD and SPI in 2010 direct planting cohort seedlings across gardens.....	223
Table S3.7- Summary of nested mixed effects model comparisons for $\delta^{13}\text{C}$, SLA, SD and SPI in 2010 direct planting cohort seedlings across gardens.....	224
Table S3.8- Summary of LMM output for gas exchange traits in 2010 transplant seedlings in watering treatments at dry garden.....	226
Table S3.9- Summary of post-hoc contrasts treatment x season interaction for A, g_s , A/ g_s , and $\delta^{13}\text{C}$ in transplant cohort seedlings in watering treatments at dry garden.....	227-228

Table S3.10- Summary of nested mixed effects model comparisons for A_{mass} and A_{area} in transplant cohort seedlings at the dry garden.....	229
Table S3.11- Summary of LMM output for A_{mass} and A_{area} in transplant cohort seedlings at the dry garden.....	230
Table S3.12- Summary of post-hoc contrasts population x season interaction LMM of A and g_s in transplant cohort seedlings in watering treatments at dry garden.....	232
Table S3.13- Summary of LMM output for $\delta^{13}\text{C}$, SLA, SD and SPI in 2010 transplant seedlings in watering treatments at dry garden.....	233-234
Table S3.14- Summary of nested model comparisons for A , g_s , A/g_s , $\delta^{13}\text{C}$, SLA, SD and SPI in 2010 direct planting cohort seedlings at the dry garden.....	235
Table S3.15- Summary of LMM output for A , g_s and A/g_s in 2010 direct planting cohort seedlings in watering treatments at dry garden.....	236
Table S3.16- Summary of LMM output for $\delta^{13}\text{C}$, SLA, SD and SPI in 2010 direct planting cohort seedlings in watering treatments at dry garden.....	237
Table S3.17- Summary of LMM output for $\delta^{13}\text{C}$, SLA, SD and SPI in 2010 transplant cohort seedlings at the intermediate and wet gardens.....	239
Table S3.18- Summary of pairwise contrasts of treatment x season interaction in LMM of $\delta^{13}\text{C}$ and SLA in transplant cohort seedlings intermediate and wet gardens.....	240
Table S3.19- Summary of nested model comparisons for $\delta^{13}\text{C}$, SLA, SD and SPI in 2010 direct planting cohort seedlings at intermediate and wet gardens.....	241
Table S3.20- Summary of LMM output for $\delta^{13}\text{C}$, SLA, SD and SPI in 2010 direct planting cohort seedlings in watering treatments at intermediate and wet gardens.....	242
Table S3.21- Summary of pairwise contrasts treatment x season for $\delta^{13}\text{C}$ in 2010 direct planting cohort seedlings in watering treatments at intermediate and wet gardens.....	244

List of Figures

Figure 1.1- Site characteristics where early-and late-cohort <i>Quercus oleoides</i> seeds were harvested and reciprocally planted in gardens in NW Costa Rica.....	.27
Figure 1.2- Seed production timing of monitored adult <i>Quercus oleoides</i> trees from low- and high-elevation populations in Guanacaste Conservation Area of NW Costa Rica....	28
Figure 1.3- Predicted means (SE) for a) germination proportion, b) days to germination, c) survivorship, and d) Aster model estimates of seedling fitness measured on progeny from early-and late-cohort seeds.....	29
Figure 1.4- Bivariate fitness surfaces showing joint selection on days to germination and seed size.....	30
Figure 2.1- Hypothetical distribution of populations of <i>Q. oleoides</i> along environmental axis showing a) populations adapted to local conditions or b) spanning broad environmental niches.	55
Figure 2.2- Range of <i>Q. oleoides</i> , seed collection sites, and mean monthly rainfall and minimum and maximum temperatures across the species range.....	56
Figure 2.3- Aster predicted mean fitness of seedlings at gardens in Honduras and NW Costa Rica.....	57
Figure 2.4- Aster predicted mean fitness of seedlings in watering treatments at dry garden site.....	58
Figure 2.5- Aster predicted mean fitness of seedlings in watering treatments at intermediate and wet gardens	59
Figure 2.6- Aster predicted fitness of seedlings across maternal families in watering treatments at dry garden site.....	60
Figure 3.1- Mean monthly rainfall and mean monthly minimum and maximum temperatures from meteorological stations from 2000-2014 at dry and intermediate gardens.....	94
Figure 3.2- Volumetric soil water content from May 2012 to April 2014 of the watering treatments at the a) intermediate and wet gardens and b) dry garden	95

Figure 3.3- Leaf predawn and midday water potential of seedlings in watering treatments at dry garden.....	96
Figure 3.4- LMM predicted means for leaf-level carbon at water use traits in transplant cohort seedlings across garden sites.....	97
Figure 3.5- LMM predicted means for leaf-level carbon at water use traits in transplant cohort seedlings in watering treatments at dry garden.....	98
Figure 3.6- LMM predicted means for leaf-level carbon at water use traits in transplant cohort seedlings in watering treatments at intermediate and wet gardens.....	99
Figure 3.7- Site and season specific bivariate fitness surfaces of joint selection on carbon isotope discrimination and specific leaf area at the three garden site.....	100
Figure 3.9- Treatment and season specific bivariate fitness surfaces of joint selection on carbon isotope discrimination and specific leaf area at intermediate garden.....	101
Figure S1.1- Histogram of null model.....	122
Figure S1.2- Predicted mean (SE) of growth traits.....	123
Figure S1.3- LS mean (SE) of seed mass high and low-elevation populations.....	124
Figure S2.1- GLMM predicted survival of 2010 transplant cohort seedlings across gardens.....	132
Figure S2.2- LMM predicted growth trait means of 2010 transplant cohort seedlings across gardens.....	133
Figure S2.3- GLMM predicted survival of 2011 transplant cohort seedlings across gardens.....	141
Figure S2.4- LMM predicted growth trait means of 2011 transplant cohort seedlings across gardens.....	142
Figure S2.5- GLMM predicted survival of 2010 direct planting cohort seedlings across gardens.....	147
Figure S2.6- LMM predicted growth trait means of 2010 direct planting cohort seedlings across gardens.....	148
Figure S2.7- GLMM predicted survival of 2011 direct planting cohort seedlings across gardens.....	154
Figure S2.8- LMM predicted growth trait means of 2011 direct planting cohort seedlings	

across gardens.....	155
Figure S2.9- GLMM predicted survival of 2010 transplant cohort seedlings in watering treatments at dry garden.....	161
Figure S2.10- LMM predicted growth trait means of 2010 transplant cohort seedlings in watering treatments at dry garden.....	162
Figure S2.11- GLMM predicted survival of 2011 transplant cohort seedlings in watering treatments at dry garden.....	171
Figure S2.12- LMM predicted growth trait means of 2011 transplant cohort seedlings in watering treatments at dry garden.....	172
Figure S2.13- GLMM predicted survival of 2010 direct planting cohort seedlings in watering treatments at dry garden.....	178
Figure S2.14- LMM predicted growth trait means of 2010 direct planting cohort seedlings in watering treatments at dry garden.....	179
Figure S2.15- GLMM predicted survival of 2011 direct planting cohort seedlings in watering treatments at dry garden.....	185
Figure S2.16- LMM predicted growth trait means of 2011 direct planting cohort seedlings in watering treatments at dry garden.....	186
Figure S2.17- GLMM predicted survival of 2010 transplant cohort seedlings in watering treatments at intermediate and wet gardens.....	192
Figure S2.18- LMM predicted growth trait means of 2010 transplant cohort seedlings in watering treatments at intermediate and wet gardens.....	193
Figure S2.19- GLMM predicted survival of 2011 transplant cohort seedlings in watering treatments at intermediate and wet gardens.....	201
Figure S2.20- LMM predicted growth trait means of 2011 transplant cohort seedlings in watering treatments at intermediate and wet gardens.....	202
Figure S2.21- GLMM predicted survival of 2010 direct planting cohort seedlings in watering treatments at intermediate and wet gardens.....	207
Figure S2.22- LMM predicted growth trait means of 2010 direct planting cohort seedlings in watering treatments at intermediate and wet gardens.....	208
Figure S2.23- GLMM predicted survival of 2011 direct planting cohort seedlings in	

watering treatments at intermediate and wet gardens.....	214
Figure S2.24- LMM predicted growth trait means of 2011 direct planting cohort seedlings in watering treatments at intermediate and wet gardens.....	215
Figure S3.1- LMM predicted mean of stomate length measured on leaves in transplant cohort seedlings across garden sites.....	222
Figure S3.2- LMM predicted mean for leaf-level traits related to carbon and water-use on direct planting cohort seedlings across garden sites.....	225
Figure S3.3- LMM predicted mean (SE) for A_{mass} and A_{area} transplant cohort seedlings in watering treatments at dry garden.....	231
Figure S3.4- LMM predicted means for leaf-level carbon at water use traits in direct planting cohort seedlings in watering treatments at dry garden.....	238
Figure S3.5- LMM predicted means for leaf-level carbon at water use traits in direct planting cohort seedlings in watering treatments at intermediate and wet gardens.....	243

Introduction

Broadly distributed tree species often span large environmental gradients and are rich testing grounds to examine the evolutionary mechanisms underlying population responses to environmental pressures. Contrasting selection pressures on fitness-related traits have been shown to result in adaptive differentiation among populations in broadly distributed species (Endler 1986, Linhart and Grant 1996, Dudley 1996a, Heschel et al. 2002, Kawecki and Ebert 2004). Genetic divergence among populations is not necessarily adaptive and may be the result of genetic drift among relatively isolated populations (Lande 1976, Travisano et al. 1995, Lammi et al. 2001, Gandon and Nuismer 2009). Additionally, asymmetrical gene flow from central to peripheral populations can impede adaptive responses at range margins (Moeller et al. 2011). The extent that differentiation in traits is adaptive among spatially structured populations depends on the relative strengths of selection and gene flow (Slatkin 1987, Rehfeldt 1999, Storz 2002, Baines et al. 2004, Lopez et al. 2008). If the homogenizing influence of gene flow is weak, the likelihood of populations being locally adapted is expected to increase with the extent of environmental divergence between populations (Lande 1976, Endler 1977, Slatkin 1985, Hereford 2009).

Long-lived trees have been shown to be well-adapted to local conditions (Rehfeldt et al. 1999, Rehfeldt et al. 2002, Ramírez-Valiente et al. 2009). However, given their long generation times, trees, particularly those that span broad geographic ranges, are often associated with high environmental tolerances and plastic responses to environmental variability (Delagrange et al. 2004, Rozendaal et al. 2006, Valladares et al. 2007, Ramírez-Valiente et al. 2010). Theory predicts that plasticity, the ability of a single genotype to produce various phenotypes for a trait, should be greater in populations that inhabit more heterogeneous environments (Bradshaw and Hardwick 1989, Alpert and Simms 2002). For example, theoretical models in plants have shown that predictable variation, such as seasonal environmental stress, select for plastic changes in underground carbohydrate storage, while unpredictable environmental fluctuations favor a constant level of storage (Iwasa and Kubo 1997). The roles of specialization and plasticity in population responses to environmental variability have been extensively

studied in both Mediterranean (Balaguer et al. 2001, Gimeno et al. 2009, Ramírez-Valiente et al. 2010, Peguero-Pina et al. 2014) and temperate (Schlichting and Levin 1990, Dudley 1996, Rehfeldt et al. 2001, Etterson 2004a, Zhang and Cregg 2005, Donovan et al. 2007) systems, few studies have examined these mechanisms in broadly distributed and long-lived tree species of highly seasonal tropical systems. The extent to which populations of such species display adaptation to local conditions, high within-population genetic diversity, and/or phenotypic plasticity has important implications for their likely responses to future environmental changes (Davis et al. 2005, Jump and Peñuelas 2005).

Current models estimate that much of the tropics, including Central America, will be drier by 2100 (IPCC 2013b). Dry season drought in seasonal tropical forests has shown to significantly influence seedling survival and growth of many species (Gentry 1988, Veenendaal et al. 1998, Hawkins et al. 2003). Additionally, short dry spells during the wet season have been found to influence seedling survival of pioneer species in seasonally dry forests (Pearson et al. 2003, Engelbrecht et al. 2006). However, it remains unclear whether seedlings are more limited by total annual rainfall or severity of dry season drought. Compounding the effects of climate change, extensive land-use change and habitat fragmentation in tropical systems (Malhi and Phillips 2004, Portillo-Quintero and Sanchez-Azofeifa 2010) limit migration and dispersal of many species. Limitations in species' ability to spatially shift ranges make *in situ* adaptation and phenotypic plasticity important mechanisms for persistence given the progression of climate change.

The tropical live oak, *Quercus oleoides*, of seasonal dry forests of Latin America spans a range from the Gulf Coast regions of northern Mexico to northwestern Costa Rica. Populations from northern Mexico to Honduras represent a disjoint patchy network of partially isolated populations and do not show large divergence at neutral loci (Cavender-Bares et al. 2011). Populations throughout the range experience similar temperature regimes, with a mean maximum temperature between 30-34°C, but experience differing local rainfall patterns. Dry forests regions of Belize are characterized by wet season rainfall levels similar to that in Honduras, but have a less severe dry season than dry forests of Honduras regions. At the southern edge of the species range,

populations in Costa Rica are both geographically and genetically distinct from the rest of the range (Cavender-Bares et al. 2011). Dry forest regions in Costa Rica differ in wet and dry season rainfall depending on elevation; lowland areas (<300m above sea level) are characterized by a severe dry season and high rainfall during the wet season. Upland dry forest regions (~900 m above sea level) have a mild dry season comparable to Belize and high rainfall during the wet season.

Quercus oleoides is an atypical tree species for seasonally dry forests because it is evergreen in a system dominated by deciduous or semi-deciduous species. It is wind pollinated and produces nondormant and desiccation intolerant seeds in a system where the majority of trees are insect pollinated and produce dormant seeds that are desiccation tolerant (Klemens et al. 2010). While seemingly mismatched for seasonally dry forests, *Q. oleoides* is found at high densities where it occurs and may represent up to 80% or more of individuals in a stand (Boucher 1983). Ecologically, this species plays an important role in terms of biomass and the ecosystem services it provides (Boucher 1983, Powers et al. 2009, Klemens et al. 2010, Cavender-Bares et al. 2011). It has been shown to influence local water balance, carbon storage, temperature mitigation, and seasonal productivity (Boucher 1983, Powers and Veldkamp 2005, Powers et al. 2009, Kissing and Powers 2010). Given its importance in Latin American dry forests, in the subsequent three studies we investigate the physiological and fitness consequences of seasonal rainfall variation in seedlings from populations with contrasting rainfall regimes.

Quercus oleoides trees generally flower at the beginning of the wet season and set seed just before the onset of the dry season (Deacon and Cavender-Bares *accepted*). Some populations in NW Costa Rica have been found to flower up to seven months of the year and produce seeds both early- and late- in the wet season, (Boucher 1983, Deacon 2010) a pattern atypical for this genus. Given high sensitivity of the seeds to drying (Klemens et al. 2010), in chapter 1 we investigated the consequences of seed production timing on germination, seedling survival and growth, and fitness (cumulative measure of survival and growth). We found that the early- and late- produced seeds differ in their germination success such that early-produced seeds had high seed mortality and delayed germination. Late- produced seeds germinated quicker on average and exhibited

high germination success and estimates of seedlings fitness. Post-germination, seedlings were limited by dry season drought through its effects on growth. However, high seedling survivorship suggests that *Q. oleoides* seedlings are well adapted to cope with drought at early life stages.

At a larger spatial scale, in chapter 2 we investigated whether populations that are geographically disparate and genetically differentiated exhibit local adaptation. We also examined the consequences of variation in water availability on seedlings fitness from populations that experience contrasting rainfall regimes. We found that the broadly distributed tropical live oak does not appear to consist of a series of locally adapted populations, but rather, of populations with wide tolerances of changes in water availability. Specifically, we found that both within-population genetic variation and plasticity contribute to fitness.

In chapter 3 we investigated the physiological and morphological consequences of seasonal rainfall variation in seedlings from populations with contrasting rainfall regimes. Phenotypic selection analyses were used to examine the relationship between seedling fitness (chapter 2) and phenotypic traits related to carbon and water use. We found that seedlings from contrasting rainfall regimes did not show differentiation in traits related to carbon and water use according to their population of origin. We found that dry season drought limits seedling physiological function of gas exchange traits but this was not reflected in integrated measures of water use efficiency (carbon isotope discrimination). Additionally, plasticity contributed more to phenotypic trait variation than genetically-based differences among maternal families within-population. Selection generally favored increased water use efficiency and lower SLA regardless of season, watering treatment, or garden site. Overall populations of *Q. oleoides* represent a lineage well adapted to drought and exhibit large tolerances for changes in water availability through plasticity. There was little evidence of significant within-population genetic variation for traits (except carbon isotope discrimination) related to carbon and water use. All R code for chapter analyses is available at github (<https://github.com/cente016/Dissertation-Analyses>)

Chapter 1: Seed production timing influences seedling fitness in the tropical live oaks, *Quercus oleoides*, of Costa Rican dry forests

Seed production timing is expected to be especially critical for tree species in highly seasonal habitats that have non-dormant and desiccation intolerant seeds. Species in seasonally dry systems with these seed characteristics depend on seed dispersal, germination, and seedling establishment during the wet season prior to the onset of drought. We tested whether previously observed peaks of seed production in the evergreen tropical live oak, *Quercus oleoides*, represent distinct strategies to contend with seasonality in dry forests of NW Costa Rica. We collected seeds from early- and late- wet season cohorts from two populations with contrasting rainfall regimes and reciprocally planted them into common gardens. At the low-elevation garden, the site with a more severe dry season, two watering treatments were established: ambient rainfall, and added water during the dry season that increased water availability to levels found at the high-elevation site. Only one treatment was established at the high-elevation garden since it represents the site with higher annual rainfall and has a milder dry season. Supplemental watering at the low-elevation garden allowed us to isolate the role of dry season drought severity on germination, seedlings survival, growth and fitness (cumulative measure of seedling survival and growth). We conducted selection analyses in the contrasting conditions to examine selective pressures on germination and seed size. Collectively, we found that seeds produced early in the wet season had delayed and reduced germination success compared to seeds produced late in the wet season. Post-germination, water limitation during the dry season only had a small effect on survivorship. Germination appears to be a critical stage in seedling fitness. Phenotypic selection on days to germination and seed size differed both temporally between seed cohorts and spatially between sites. Overall, the delayed and reduced germination of early produced seeds suggests that wet season conditions may be inhospitable to juvenile establishment.

Introduction

Germination is a critical transitional stage in the plant lifecycle that has been shown to affect lifetime fitness, especially in short-lived species (Kalisz 1986, Donohue 2002). Abiotic and biotic conditions at the time of germination can have profound consequences for survival of young seedlings (Kalisz 1986, Shimono and Kudo 2003, Leger et al. 2009, Mercer et al. 2011), early growth (Gross and Smith 1991, Stratton 1992, Verdú and Traveset 2005), timing of subsequent life history stages (Donohue 2002, Galloway 2002), and establishment (Stratton 1992, Seiwa 2000, Castro 2006, Gómez-Aparicio et al. 2008). Not surprisingly, plants have evolved diverse endogenous and exogenous mechanisms that influence germination phenology (Baskin and Baskin 2001, Willis et al. 2014), including responsiveness to environmental cues such as fluctuations in light quality (Vázquez-Yanes and Smith 1982, ten Brink et al. 2013), temperature (Hardegree and Van Vactor 1999), water availability (Zohar et al. 1975, Bradford and Haigh 1994, Köchy and Tielbörger 2007, Footitt et al. 2013), and fire (Daskalidou and Thanos 1996). The relationship between fitness and germination phenology has been studied extensively in temperate species in seasonal environments (Stratton 1992, Seiwa 2000, Simons and Johnston 2000, Donohue 2002, Shimono and Kudo 2003, Castro 2006, Benard and Toft 2007, Mercer et al. 2011) and selection frequently favors early germination over late germination (reviewed by Donohue et al. 2010). However, in some systems, seedlings that germinate early in the growing season have been found to be at a disadvantage like that of *Potentilla marschuriana* of the alpine regions of Japan, where late germination was found to increase seedling survivorship (Shimono and Kudo 2003).

Seed dormancy, desiccation tolerance, and mode of dispersal are mechanisms that allow many plant species to escape adverse environments. Species with dormant and desiccation tolerant seeds may persist through unfavorable temporal and spatial conditions (Evans and Cabin 1995, Donohue 2002, Galloway 2002, Pearson et al. 2002). Desiccation intolerant and non-dormant seeds have a moisture content between 30-70% at maturity are metabolically active (Baskin and Baskin 2001) and, consequently, establishment depends upon germination prior to seed mortality through desiccation, reserve depletion, and/or predation (Donohue et al. 2010). Typically, desiccation intolerant seeded species germinate readily and are thought to have less opportunity to

alter germination timing in response to external cues compared to dormant seeds (Berjak et al. 1989). Although it is reasonable to hypothesize that species with desiccation intolerant and nondormant seeds are capable of delaying germination within a season, few studies to date have documented this phenomenon in a natural system (but see Garwood 1983, Pierce and King 2007).

Reproductive phenology for species with desiccation intolerant and nondormant seeds is expected to be especially important for fitness in seasonal and drought-prone environments. In tropical dry forests, seedling germination and establishment is restricted to the months of high rainfall during the wet season (Khurana and Singh 2001). During this mesic period, seedlings must establish before the onset of drought. It follows that tropical dry forests are dominated by species with dormant orthodox seeds that break dormancy during the wet season. Despite the odds, almost one quarter of species (24%) in these environments produce desiccation intolerant and nondormant seeds (Khurana and Singh 2001). The timing of seed production is critically important for these species given the high reductions in seed viability past a minimum water content threshold (Pammenter et al. 1998, Finch-Savage 1992).

Recruitment in desiccation intolerant seeded species requires seed dispersal, germination, and seedling establishment within a single wet season because these seeds do not survive through drought (Klemens et al. 2010). Thus, it is reasonable to expect that these species would be under strong selection to set seeds early in the wet season and germinate rapidly thereafter. However, if the wet season consists of periods of very high rainfall and prolonged soil saturation, waterlogging may stress seeds (Pierce and King 2007) and young seedlings, reducing survival and growth (Parolin 2001, Ferreira et al. 2007). Under these conditions, there may be a much narrower window at the end of the wet season and before the onset of the dry season that is truly favorable for germination and establishment.

Here we examine the fitness consequences of seed production and germination phenology in the desiccation intolerant-seeded species, *Quercus oleoides*, in the seasonal dry forests of NW Costa Rica. Seasonal dry forests of this region are characterized by extreme rainfall during the wet season at all elevations but the dry season differs in

drought intensity (Klemens et al. 2010) and is less severe at high-elevation compared to low-elevations (Fig. 1.1). *Quercus oleoides* initiates flowering at the end of the dry season (April-May) and continues to flower throughout the wet season (until October) for up to seven months in some populations, a pattern that is atypical for species in the *Quercus* genus because of its extended duration. Semi-episodic peaks in seed production also occur early in the wet season (July/August) and late in the wet season (November/December, Deacon 2010). This unusual reproductive phenology and the desiccation intolerant and nondormant nature of *Q. oleoides* seeds coupled with variation in rainfall patterns across the elevation gradient in NW Costa Rica provides a rich testing ground to examine adaptive patterns in germination phenology in a desiccation intolerant and nondormant seeded species relative to water availability in this highly seasonally environment.

It is difficult to assess the ultimate fitness consequences of reproduction and germination phenology for long-lived tree species because of delayed sexual maturity and decades of seed production. In the absence of fecundity data, survival and growth have been found to be good surrogates of fitness (Rehfeldt et al. 2001). However, because these fitness components have distinct underlying statistical distributions (i.e. survival, binomial; growth, Poisson) their joint analysis is fraught with statistical difficulties. We use Aster statistical models (Geyer et al. 2007, Shaw et al. 2008) to estimate cumulative seedling fitness, an approach that simultaneously and appropriately accounts for components of fitness with different statistical distributions and also allows the inclusion of covariates that are known to affect the timing of germination, such as seed size (Lafond and Baker 1986, Seiwa 2000, Pearson et al. 2002).

We use field observations and experimental gardens with water-manipulation treatments to evaluate the relationship between reproductive phenology, seasonal rainfall, and seedling fitness of a high-elevation (~900m) and low-elevation population (~300m) of *Quercus oleoides* sampled from the dry forests of NW Costa Rica. First, we hypothesized that trees from high-elevation populations would set seed more often and earlier in the wet season than trees from low-elevation population because trees require less time to recover from the milder dry season at this site. Second, in contrast to

temperate systems, we hypothesized that later germination would be favored by selection at both elevations because water conditions are excessive during the peak of the wet season. Finally, we hypothesized that seeds produced early- and late- in the wet season would differ with respect to days from dispersal to germination such that seedling establishment would occur synchronously during a narrow window of favorable conditions after soil saturation diminishes but before excessive drying. Support for these hypotheses would suggest that selection on the timing of germination differs qualitatively between temperate and tropical systems and that even species with desiccation intolerant and nondormant seeds can evolve delayed germination that enhances seedling fitness.

Methods

Study Species

Quercus oleoides, the evergreen live oak of the tropical dry forests, a close relative of to the live oak, *Q. virginiana*, found in the southern United States (Cavender-Bares et al. 2011), is among the minority of dry forest species that produce desiccation intolerant and nondormant seeds (Klemens et al. 2010). *Q. oleoides* grows on nutrient poor, rocky soil and commonly forms monodominant stands (Boucher 1983). Oaks are monoecious, producing both male and female flowers asynchronously on the same individual. Flowers are wind pollinated and assumed to be highly out-crossing as in other oak species (Muir et al. 2004).

Study Site and Experimental Design

This study was conducted in the Guanacaste Conservation Area in NW Costa Rica across elevation extremes of the *Q. oleoides* range from dry coastal habitats to higher elevation forests with higher rainfall levels (Fig. 1.1a, b). Climate variables, especially rainfall, differ across an elevation gradient from the high-elevation site at Sector Pailas (~900 m, 10°46'23''N, 85°21'03''W), which receives ~2900mm of rainfall annually, and ~11% of it within the three to five month dry season. The low-elevation site at Sector Santa Rosa (~270 m, 10°55 '12''N, 85°36'39''W) receives ~1800mm of rainfall annually with less than 4% of that occurring during the five- month dry season

(Hijmans et al. 2005). Additionally these sites differ in mean temperature during the warmest and coldest quarter of the year. Sector Santa Rosa, the low-elevation site, has mean temperatures of 26°C and 24°C during the warmest and coldest quarters respectively. The high-elevation site, Sector Pailas, has lower mean warmest and coldest quarters, with 22.9 and 21.2°C respectively. Meteorological data from 2000 to 2014 were obtained from the Santa Rosa park weather station (low-elevation site) but data were not collected from the high-elevation site (Sector Pailas) due to technological limitations. Mean monthly rainfall and average minimum and maximum temperatures at the low-elevation site during the duration of the experiment (2010-2012) appear to be within range of decadal variation (Fig. 1.1c).

Previous work by Deacon (2010) indicated that flowering phenology differs between high and low-elevation populations. We also characterized the phenology of seed production in maternal trees, by checking trees (14 high-elevation; 14 low-elevation) for presence of seeds early in the wet season (early August) and late in the wet season (late November) in 2010 and 2011. To test for differences between the two focal populations, we calculated a production-difference index for each sampled individual by subtracting the early production score (0 for no seeds, 1 for seeds) from the late production score and generated a null distribution by permuting 999 times the production-difference index scores for individuals in both high- and low-elevation populations. A p-value was calculated based on a two-tailed test from the null model (Cavender-Bares et al. 2006).

Experimental gardens were established at a high-elevation site (hereafter referred to as the ambient wet treatment) and at a low-elevation site with an experimental watering treatment (ambient dry and supplemental wet treatments) in open pastures at the edge of the forest canopy where *Q. oleoides* seeds naturally germinate (Klemens et al. 2010). Gardens were established within 2km from collected seeds from each natural population. Early- and late-cohort seeds were collected from trees monitored for phenology and were also augmented with nearby trees (within 500m) because some observed trees failed to reproduce (high-elevation $N_{\text{early}} = 360$, $N_{\text{late}} = 241$; low-elevation $N_{\text{early}} = 246$, $N_{\text{late}} = 409$). Seeds were visually inspected upon collection and only those

with no visible insect or pathogen damage were used for the experiment. Seeds were planted reciprocally into each garden in a randomized complete block design with maternal families represented evenly across treatments and blocks and seeds were randomized within blocks. Seeds collected in both August and November 2010 were planted within one week of collection (between August 12-18 and between November 23-26) and are hereafter referred to as the “early-” and “late-” cohorts respectively. Seeds were planted 1cm beneath the soil surface and 15cm apart. To prevent herbivory and photoinhibition, blocks were covered with wire mesh cages (0.6m x 0.6m x 0.6m) and 70% shade cloth. Blocks were weeded biweekly to reduce competition effects; cages were removed when plants were ~0.5m tall, after a year of growth. Germination was monitored weekly for the first five months. Survival and growth (height, basal diameter, length of longest leaf, and total leaf number) were measured in April 2011, October 2011, and April 2012.

Watering Treatment

To determine whether water limitation inhibits seedling fitness, three treatments were established, each of which were replicated with six blocks: 1) the “Ambient Dry Treatment” (ADT) in which plants experienced the natural rainfall at the drier low-elevation site, 2) the “Supplemental Wet Treatment” (SWT) in which plants at the low-elevation site were supplemented with 18mm of water per week during the dry season to mimic the average dry season water availability at the high-elevation site, and 3) the “Ambient Wet Treatment” (AWT) in which plants at high-elevation site received ambient rainfall. Due to strong winds and logistical constraints, it was not feasible to construct rainout shelters to reduce water availability at the high-elevation site and produce a factorial design.

Seed Size, Germination, Survival and Growth

Mass of these ellipsoid seeds was approximated based on seed volume (V) calculated as $V=4/3\pi(d/2)^2+(h/2)$, where d is diameter, and h is height. Volume was converted to seed mass based on an empirical relationship with fresh mass without the

seed coat, $M=0.636V-0.1213$ ($R^2=0.97$, (Cavender-Bares et al. 2004). Germination was considered to be successful if a shoot was visible above ground and this categorical measure was used to examine germination probabilities with a generalized linear mixed model. Block and maternal family were treated as random effects, with block nested in treatment and maternal family nested in population. Population, treatment and cohort were treated as fixed effects. Survivorship to the end of the experiment was analysed using a generalized linear mixed model with the logit link function and survival counts following a binomial distribution. Only plants that survived to the end of the experiment were included in the analyses for growth traits (stem height, leaf number, basal diameter, and length of longest leaf) using linear mixed models, treating block as random effect and all other effects as fixed and included covariates of seed mass and germination date. Maternal family could not be included in these analyses but was included as a random effect in the germination, survival and fitness analyses. Mixed effects models were analyzed in R (version 3.0.2) using 'lme4' package. To account for multiple testing of effects without correction in model P-values, likelihood ratio tests, using nested model comparison, were employed to test for significance of effects.

Seedling Fitness and Phenotypic Selection

Fitness was modeled with Aster based on final leaf count conditional upon germination and survival survival to the end of the experiment as follows:

(1) Planted → Germination → Survival → Leaf number

with germination and survival modelled as Bernoulli, and leaf number conditional on survival, modelled as Poisson distribution. Leaf count was chosen as a fitness surrogate measure because it reflects plant growth and photosynthetic capacity while accounting for multiple stems and compensatory growth after herbivory. The Aster model was used to estimate cumulative seedling fitness, estimated fitness (leaf count conditional on survival and germination) was modelled with block and maternal family as random effects and all other factors as fixed: treatment (ADT, SWT, AWT), seed cohort (early or

late), and population (high- or low-elevation). Seed size was included as a covariate since it often associated with maternal effects (Benard and Toft 2007, Donohue 2009, Ramírez-Valiente et al. 2009). Germination date was also included as a covariate in estimating seedling fitness and seeds that did not germinate were assigned a value of zero. Fitness analyses were conducted using the ‘aster’ package in R.

Aster models were used to assess phenotypic selection on traits in April 2012 at the end of the experiment. The Aster graphical model for estimating seedling fitness was reduced to only including seeds that germinated. We quantified phenotypic selection on seed size and days to germination. Data were analysed by combining the two populations (due to limitations in sample size) on a per treatment basis in order to examine differences in seasonal cohorts. To reduce complexity, only the ambient treatments were included in the selection analyses (ambient dry and ambient wet treatments). All phenotypic traits were standardized to have a mean of zero and a standard deviation of one. Relative fitness was calculated by dividing individual Aster predicted fitness by the overall mean fitness for each treatment. Partial selection coefficients (β_i) were estimated as the slope of regressing predicted fitness on trait values (Lande and Arnold 1983, Brodie et al. 1995) using linear mixed models with block and maternal family (nested in population) as random effects. Separate multiple regressions were used to estimate the curvature of selection surfaces and relative fitness regressed on the quadratic (γ_{ii}) and the cross-product terms between the traits (γ_{ij}). Partial regression coefficients from the quadratic selection analyses were separate from those estimating β because of correlations between linear and nonlinear variables (Brodie et al. 1995). Given that assumptions of parametric models of phenotypic selection are frequently violated (Brodie et al. 1995), we used Aster models to test significance of selection gradients without violating assumptions of parametric tests. Aster models appropriately integrate multiple components of fitness and accommodate non-normal underlying distributions of fitness components (Shaw et al. 2008, Shaw and Geyer 2010). We also used nested model comparison to determine if selection differed between cohorts within a treatment by fitting models with and without interaction terms between the traits and cohort. The same type of nested model comparison was used to test for differences between

treatments (within a cohort) by testing models with and without interaction terms between treatment and traits.

Three-dimensional plots were used to visualize the nonlinear selection gradients using the ‘persp’ function in R. Selection surfaces were plotted as a mesh surface (interval=15) using the ‘loess’ function for local regression to estimate the surface from standardized trait values (days to germination and seed size) and predicted relative fitness. Data were also plotted onto the projection surface using ‘trans3d’ function to increase clarity of how well the selection surface represents the relationship between relative fitness and traits.

Results

Early and Late Seed Cohorts

Spatial and temporal differences in seed production timing were observed among adult maternal trees adjacent to the experimental gardens. The majority of selected trees produced seeds only once during the wet season, either early or late (86% in 2010; 81.8% in 2011). However, the number of trees producing seeds differed between source elevations and years (Fig. 1.2). As hypothesized, 71% of high-elevation trees produced acorns early in the wet season whereas only 29% of the low-elevation trees produced an acorn crop at this time (including trees that produced seeds only early and those that produced seeds during both times). Approximately 15% of selected low-elevation trees set seeds both early and late in the wet season in both 2010 and 2011, whereas only 7% of high-elevation trees set seeds both early and late in 2010. No trees set seeds at both time points in 2011. In general, the proportion of trees producing seeds was lower for both populations in 2011, but especially for the high-elevation population where only 35% of the trees reproduced. Between-population differences in the timing of seed production were significant in 2010 ($P < 0.01$) and marginally significant in 2011 ($P = 0.06$) based on randomization tests (Appendix 1- Fig. S1.1). Overall, these results suggest that trees at the low-elevation site more often produced seeds late in the wet season, whereas high-elevation trees more frequently produced seeds early in the wet season.

Seed Size and Germination

Seeds from the high-elevation population had significantly larger seeds than that of the low-elevation population on average (Table 1.1) and did not differ in mean seed size between seasons (Appendix 1- Fig. S1.2). For the low-elevation population, where trees experience a more extreme dry season, early-cohort seeds were significantly smaller on average than late-cohort seeds. However, these size differences did not significantly influence the likelihood or timing of germination (Table 1.1).

Germination success of seeds from the two populations was highly variable and ranged from 4.7% to 77%, differing across seasonal cohorts, treatments and among maternal families (Table 1.1, Fig. 1.3a). On average, early-cohort seeds germinated at the lowest rates regardless of population compared to late-cohort seeds. There was a significant cohort by population interaction with late-cohort seeds from the low-elevation population having higher germination success than late-cohort seeds from the high-elevation population ($X^2 = 23.78$, $P < 0.01$). Treatment significantly enhanced germination; a post hoc contrast showed that germination was higher in the ambient wet and supplemental wet treatments relative to the ambient dry treatment ($Z = 3.00$, $P < 0.01$). Days from planting to germination did not differ between the populations but did differ between seasonal cohorts (Fig. 1.3b, Appendix 1- Table S1.1). On average, early-cohort seeds germinated after 105 days (± 7.23), whereas late-cohort seeds germinated relatively rapidly after only 64 days (± 1.78). Despite the delayed germination of early-cohort seeds, they did not germinate at precisely the same time as the late-cohort seeds but, on average, 57 days earlier.

Survival and Cumulative Seedling Fitness

Survivorship was generally high during the experiment and was nearly 100% in April 2011 and October 2011. Consequently, survivorship was only explicitly analysed at one time point at the end of the experiment in April 2012 where there was sufficient variation. Although neither population nor seasonal cohort influenced likelihood of survival, seedlings at the high-elevation site had 34% lower survival than at the low-elevation site (Table 1.1, Fig. 1.3c). At the low-elevation site, a post-hoc contrast

between the two treatments showed that supplemental water during the dry season significantly increased likelihood of survival ($Z_j = 2.40$, $P = 0.02$). There was no difference in seedling survival between the early- and late-cohort seeds (Appendix 1- Table S1.1). Neither germination date nor seed size influenced likelihood of survival.

An Aster model that combined three components (germination, survival, and terminal leaf count) into a single analysis revealed seedling fitness did not differ between populations (Table 1.1, Fig. 1.3d) but did differ between cohorts; late-cohort seeds had a significant fitness advantage over early-cohort seeds (Appendix 1- Table S1.1). Water supplementation at the low-elevation site during the dry season resulted in a modest increase of mean fitness for the late cohort seeds but not the early cohort. Analysis of growth traits (leaf number, stem height, basal diameter and length of longest leaf) revealed that leaf number showed consistent trends with other components of growth and was a good surrogate for fitness (Appendix 1- Tables S1.2&1.3, Fig. S1.2). Additionally, supplemental water during the dry season did not have a significant impact on growth at the low-elevation site. Seedlings at the high-elevation garden had the lowest estimates of fitness (and lowest estimates in growth, Tables S1.1-S1.3, Fig. S1.2), likely due to herbivory by leaf-cutter ants (personal observation). Both seed size and days to germination had strong positive impacts seedling fitness.

Phenotypic Selection

Phenotypic selection on days to germination and seed size of germinated seeds differed among seasonal cohorts and treatments (Table 1.2, Fig. 1.4). At the low-elevation site (ADT), seeds with fewer days to emergence were favored in the early-cohort ($\beta = -0.334 \pm 0.114$) but no selection on days to germination was detected for the late-cohort ($\beta = -0.021 \pm 0.021$). Additionally, larger seeds ($\beta = -0.941 \pm 0.142$) were favored for the early-cohort in ADT but smaller seeds ($\beta = -0.078 \pm 0.025$) were favored in the late-cohort (Aster nested model comparison, $Dev = 47147$, $P < 0.001$). At the high-elevation site (AWT), selection on days to germination also differed between cohorts ($Dev = 7.56$, $P = 0.006$) with selection favoring fewer days to germination in the early-cohort ($\beta = -0.475 \pm 0.150$) and delayed emergence in the late-cohort ($\beta = 0.195 \pm 0.023$).

Unlike the early-cohort in ADT, at the high-elevation site (AWT), selection favored smaller seeds for the early-cohort (nested model comparison, $Dev= 34.62$, $P<0.001$) and no direct selection was detected on seed size for the late cohort in AWT. Quadratic selection analyses indicated that the shapes of selection surfaces differed somewhat between seasonal cohorts and treatments. γ_{ii} for seed size was negative ($\gamma_{ii} = -0.126 \pm 0.010$) for the late cohort in the ADT (Table 1.2, Fig. 1.4). Visualization of the selection surface is consistent with stabilizing selection since the fitness maximum is at intermediate phenotypes. γ_{ii} for germination timing was positive ($\gamma_{ii} = 0.209 \pm 0.129$) for the early-cohort in AWT but visualization of the selection surface does not support the interpretation of disruptive selection. We detected significant joint selection on germination timing and seed size in only the early-cohort in the AWT ($\gamma_{ij} = 0.715 \pm 0.170$).

Discussion

This study yielded results that challenge our current understanding of the role of germination timing on seedling fitness, which is largely based on studies conducted on dormant seeds in temperate habitats. In these temperate environments, natural selection typically favors early germination because it enhances post-germination survival (Jones et al. 1997, Benard and Toft 2007, Leger et al. 2009), or increases growth or fecundity (Kalisz 1986, Seiwa 2000, Donohue et al. 2005). Here we show that juvenile *Q. oleoides* trees in the dry forests of NW Costa Rica have higher fitness if they originate from seeds that disperse and germinate late in the wet season. Additionally, we show that selection on days to germination is temporally and spatially heterogeneous, with selection favoring either rapid or delayed germination depending on seed cohort and habitat.

Germination

Seeds produced early- and late- in the wet season differed in their germination success and average number of days to germination. Late-cohort seeds showed higher germination success and more rapid germination (64 days ± 1.78) compared to early-cohort seeds that exhibited high seed mortality and delayed germination (105 days ± 7.23 after planting). Late-cohort seeds may have had greater germination success because they dispersed at the end of the wet season when extreme rainfall events are less frequent

and conditions are more amenable to germination. It is reasonable to expect that early dispersal during the wet season followed by rapid germination would be favored in seasonally dry forests, if it permitted juvenile establishment and growth when water is abundant. However, the extremely high rainfall in the wet season can lead to high seed mortality due to flooding, fungal infection, predation and/or resource depletion (Garwood and Lighton 1990, Bustamante et al. 1993, Wagner and Mitschunas 2008). Flooding has been shown to have both positive and negative impacts on germination in different species. For example, Pierce and King (2007) found that two common floodplain oak species in the southeastern United States responded differently to flooding. *Quercus michauxii*, as a species with dormant seeds, showed significantly higher germination success in a flooding treatment compared to the non-flooded control. However, *Q. lyrata*, a species with nondormant seeds, showed significantly lower germination success and high seed mortality in the flooding treatment. Given that the early-cohort seeds of *Q. oleoides* suffered from significantly higher seed mortality (lower germination success) and delayed germination of survivors suggests that periods of high rainfall are inhospitable for seeds. Additionally, we find that both seed cohorts germinated in the transition period between the wet and dry seasons suggesting that excessive rainfall is not conducive to germination. Although we did not explicitly test for the effects of flooding on seed viability in a controlled environment, our results are consistent with the finding that flooding events (or periods of high rainfall and excessive soil saturation in this case) are detrimental to viability of non-dormant *Q. oleoides* seeds.

Delayed germination is surprising in this species since nondormant and desiccation intolerant seeds are widely thought to germinate rapidly (Berjak et al. 1989). To the best of our knowledge, this is one of only a few studies to report nondormant and desiccation intolerant seeds that are capable of delaying germination, albeit still restricted to a single season (Garwood 1983, Vazquez-Yanes and Orozco-Segovia 1993, Piña-Rodrigues and Figliolia 2005). In a community-level study of germination across a range of both seed dormancy types and seed desiccation sensitivities, Garwood (1983) found that seed dispersal timing (early or late in the wet season) did not correlate with germination timing in the desiccation intolerant species. Of the species that dispersed

and germinated seeds within the same wet season, half germinated in less than two weeks whereas the other half germinated anywhere from two to sixteen weeks after planting. Although differences in the timing of germination have been found among species with desiccation intolerant seeds at the community level seeds, there are no previous studies that we are aware of that have found this type of variation within a species. An alternative explanation for the observed differences in germination patterns is that germination is largely mediated by environmental factors, especially genotype by environment interactions. For example, seeds from particular mothers may germinate in response to environmental cues following a hydro-thermal time model, which predicts rapid germination when conditions are closer to optimal water potential and temperature levels (Alvarado and Bradford 2002). In this case, soil saturation during wet season would act to inhibit germination consistent with the delayed germination of early-cohort seeds.

Selection on days to germination varied both between seed cohorts and environments. Timing of germination is a heritable trait within these populations as indicated by significant differences among maternal families. Thus, the differences that we observed could be a function of adaptive evolution in response to natural selection. Interestingly, we found that phenotypic selection favored distinct patterns of germination counter to the observed differences in days to emergence between the cohorts. Of the seeds that germinated, more rapid germination was favored in the early-cohort regardless of environment but delayed germination was favored in the late-cohort in the AWT (high-elevation site). Studies of selection in temperate systems have demonstrated that selection pressures can vary both temporally and on relatively small spatial scales (Kalisz 1986, Gilbert et al. 1996, Etterson 2004a). Additionally, large differences in days to germination between early-and late-cohort seeds suggests that early wet season conditions are inhospitable to germination but once rainfall decreases, seeds that germinate quicker from the early cohort have a fitness advantage over those that took longer to germinate. The fitness advantage is likely due to influences on growth components as indicated by significant negative influence of days to germination covariate in growth analyses.

Maternal Seed Production Timing and Seed Provisioning

Patterns of maternal seed production timing differed between the high- and low-elevation populations in a manner consistent with the findings of Deacon (2010). These differences in timing of when trees produced seeds could be due to genetic differentiation or due to contrasting environmental conditions. This genetic versus environment issue is difficult to resolve because reciprocally transplanted trees would need to be monitored until sexual maturity. Differences in elevation could be attributed to contrasting intensity of the drought during the dry season, which is less severe at high-elevation site (Klemens et al 2010) and may permit early flowering and seed production. Flowering phenology of a deciduous tree, *Tabebuia neochrysantha* (Bignoniaceae), in dry forests of NW Costa Rica, was contingent upon recovery and stem rehydration after initial drought stress and the amount of recovery time needed differed with manipulated drought severity (Reich 1995). Likewise, in evergreen trees in Mediterranean climates, flowering initiation has been shown to be dependent on drought recovery after a rain event (de Lillis and Fontanella 1992). Our findings of differences in seed production timing between the sites (regardless of mechanism) suggest that shifts in maternal flowering and seed production and/or rainfall patterns may have large impacts on germination and subsequent seedling fitness.

Maternal provisioning may play an important and extended role in fitness of *Quercus oleoides* seedlings. During the first year of growth, lipids and carbohydrates stored in the cotyledons of the acorn are shunted belowground into a tuber that swells around the root just below the root collar (Muller 1961, Nixon 1985). Although *Q. oleoides* and the other six species within the live oaks (*Quercus* section Virentes) are the only oaks to form underground tubers, they are not the only oaks with the capability of nutrient remobilization. *Quercus ilex* in Mediterranean climates has been found to use nitrogen in root reserves during resprouting after disturbance (El Omari et al. 2003). Given the tuber formation from seed reserves, maternal effects may have a prolonged influence on seedling fitness. Seed mass was incorporated into the models as a means of accounting for such maternal effects. However, we cannot rule out a contribution of

maternal provisioning to differences in fitness between the seasonal cohorts and populations. Seed mass did not significantly influence likelihood of germination but had a positive effect on seedling fitness. The positive effect of seed mass on fitness is consistent with previous studies showing that larger seeds are advantageous over smaller seeds, especially in unfavorable conditions (Stanton 1984, Wulff 1986, Walters and Reich 2000, Moles and Westoby 2004).

Our ability to test the hypothesis that abiotic factors associated with dry-season severity have contrasting fitness consequences at high- and low-elevation sites was complicated by herbivory at the high-elevation site. However, the differences in herbivore pressures between the sites demonstrate that biotic factors may have greater impact on seedling fitness than abiotic factors (Crawley and Long 1995, Asquith et al. 1997). Regardless of treatment, we did find a consistent significant difference between seed cohorts and seedling fitness even with herbivore pressure (AWT). Seedlings from early-cohort seeds had consistently lower estimates of fitness than the late-cohort across treatments suggesting early seed production may be a maladaptive consequence of environmentally induced maternal flowering phenology. If trees initiate flowering in response to water availability (Deacon 2010) and rehydration (Reich and Borchert 1982), then trees that experience a less severe dry season should flower earlier. We find evidence that seed production timing differs between sites that vary in dry season severity. Additionally, for both the 2010 and 2011 census we found that trees rarely produced seeds at both production peaks but either produce seeds early or late in the wet season indicating genetic based differences in production phenology. A higher proportion of trees from the high-elevation population, which experiences a mild dry season, set seed earlier in the wet season but this did not correlate with an advantage at the seedling stage.

Climate in tropical regions is influenced by many phenomena, including the Intertropical Convergence (ITC), North American Monsoon Systems (NAMS) and El Niño Southern Oscillation (ENSO). These phenomena result in tropical regions showing high decadal variations in both temperature and precipitation patterns. These dramatic fluctuations in seasonal and annual rainfall levels may impede adaptation by favoring

different genotypes depending on ENSO cycles. Alternating patterns of selection within generations may act to maintain within-population genetic diversity by favoring different genotypes in alternating years (Etterson and Shaw 2001). Early cohort seeds could have a fitness advantage during dry years, and studies examining the role temporally heterogeneous selective pressures are needed to elucidate how ENSO cycles may influence within-population diversity. Furthermore, the extent to which maternal flowering phenology and seed production are genetically based vs. plastic is not yet known. Further research is necessary to disentangle the genetic and environmental factors that drive seed production timing to examine the adaptive potential of populations to synchronize maternal seed production timing with optimal germination and post-germination seedling survival and growth conditions. Regardless of the mechanism, we have shown a functional association between maternal seed production timing, germination asynchrony, and seedling fitness.

Implications for Climate Adaptation

Current climate change is expected to affect both temperature and rainfall patterns over much of Central America with the greatest warming and reduction in rainfall projected to occur during the middle of the wet season in dry forest regions in June-August (IPCC 2013a). Declines in rainfall levels mid-wet season would potentially be beneficial for early-cohort seeds by reducing water levels and creating conditions more amenable to germination but could be detrimental for seeds produced late in the wet season if reductions in rainfall cause excessive drying below the viable threshold of nondormant and desiccation intolerant seeds (Finch-Savage and Clay 1994). The effects of climate change on El Niño Southern Oscillation (ENSO) events remains uncertain, but changes in the pattern and frequency of dry and wet years may impede species ability to synchronize seed production timing with optimal germination conditions through variability in the intensity of selection on germination timing.

Conclusion

We provide evidence that seed production timing, germination timing, and germination success are critical factors in seedling fitness and recruitment of the nondormant and desiccation intolerant seeded *Quercus oleoides* in the seasonal dry forests of Costa Rica. Following germination, water limitation during the dry season results in a significant but modest decline in seedling survival. Timing of seed production influenced both time-to-germination after seed fall and seedling fitness with late-cohort seeds showing low seed mortality, rapid germination, and high relative fitness. Phenotypic selection varied both spatially between sites and temporally between seed cohorts. These results highlight the consequences of phenological variation in seed production for seedling fitness in the seasonal and interannually variable environments.

Effect	DF	Seed Size		Germination		Days to Germination		Survival		Fitness	
		χ^2		χ^2		χ^2		χ^2		χ^2	
Population (P)	1	551.6	***	0.11		2.00		0.01		2.18	
Cohort (C)	1	9.13	**	108.83	***	83.71	***	1.72		197.34	***
Treatment (T)	2	--		6.13	+	4.97	+	14.74	***	23.44	***
P x C	1	6.35	*	23.78	***	0.90		1.95		0.07	
T x C	2	--		0.39		8.09	*	0.38		14.85	***
P x T	2	--		2.38		3.10		0.22		3.18	
P x T x C	2	--		1.46		2.15		--		16.88	***
Seed Size	1	--		0.03		0.19		0.43		33.42	***
Germination date	1	--		--		--		3.03	+	843.54	***
Block (Treat)	1	--		48.39	***	5.52	***	12.60	***	192.42	***
MF (Pop)	1	--		24.16	***	18.85	***	0		2.05	+

Table 1.1-Analysis of seed size, germination success, survival, and cumulative seedlings fitness measured on progeny from early- and late-cohort *Quercus oleoides* seeds sampled from a high-elevation and low-elevation population in NW Costa Rica and reciprocally planted into three watering treatments: ambient dry treatment (ADT) and supplemental water treatment (SWT) at the low-elevation site, and ambient wet treatment (AWT) at high-elevation site. Block and maternal family (MF) treated as random effects. Degrees of freedom shown are for the difference in nested models. +0.10 \geq P>0.05; * P \leq 0.05, ** P \leq 0.01; ***<0.001

Trait		ADT			AWT			
		Early		Late	Early		Late	
Days	β	-0.334 (0.114)	**	-0.021 (0.021)	-0.475 (0.150)	**	0.195 (0.023)	+
Seed Size (Seed)	β	0.941 (0.142)	***	-0.078 (0.025)	*	-0.634 (0.190)	***	0.174 (0.025)
Days x Days	γ_{ii}	0.178 (0.044)		0.018 (0.010)		0.209 (0.129)	**	0.091 (0.003)
Seed x Seed	γ_{ii}	0.423 (0.044)		-0.126 (0.010)	***	0.522 (0.126)		0.069 (0.002)
Seed x Days	γ_{ij}	-0.165 (0.060)		-0.001 (0.012)		0.715 (0.170)	*	-0.106 (0.004)

Table 1.2- Site-specific phenotypic selection analysis on traits (days to germination and seed size) from early- and late-cohort *Quercus oleoides* seeds sampled planted into common gardens in NW Costa Rica (ADT= ambient dry treatment at low-elevation site, AWT= ambient wet treatment at high-elevation site). Directional selection gradients (β_i) were obtained from multiple regression of Aster predicted relative fitness on standardized trait values (days to germination and seed size). Univariate nonlinear selection gradients (γ_{ii}) and bivariate nonlinear selection gradients (γ_{ij}) were obtained from multiple regressions including quadratic and cross-product terms. Seeds from both populations were combined for phenotypic selection analyses. Directional selection gradients (β) were estimated using linear mixed effects models and effects were tested for significance using nested Aster model comparisons (DF=1 between nested models). +0.10 \geq P>0.05; * P \leq 0.05, ** P \leq 0.01; ***<0.001

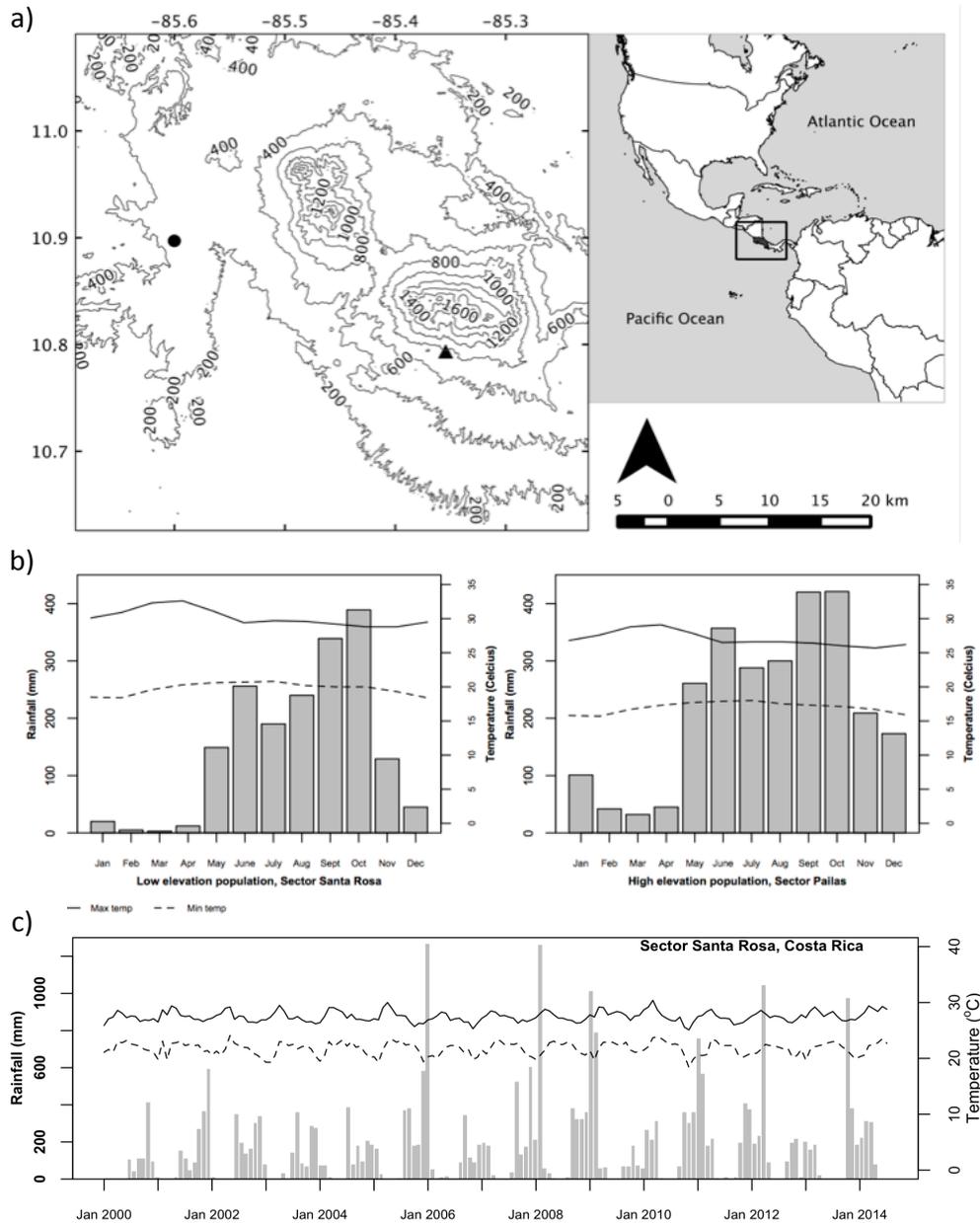


Figure 1.1 a) Garden sites where early- and late-cohort *Quercus oleoides* seeds were harvested and reciprocally planted in gardens at two elevations in Guanacaste Conservation Area in NW Costa Rica. The low-elevation site was located at Sector Santa Rosa (circle), high-elevation site at Sector Pailas (triangle). b) BioClim mean monthly rainfall and minimum and maximum temperatures at the low- and high-elevation sites (Hijmans et al. 2005). c) Mean monthly rainfall and minimum and maximum temperatures from 2000-2014 retrieved from meteorological station at low-elevation site (Sector Santa Rosa).

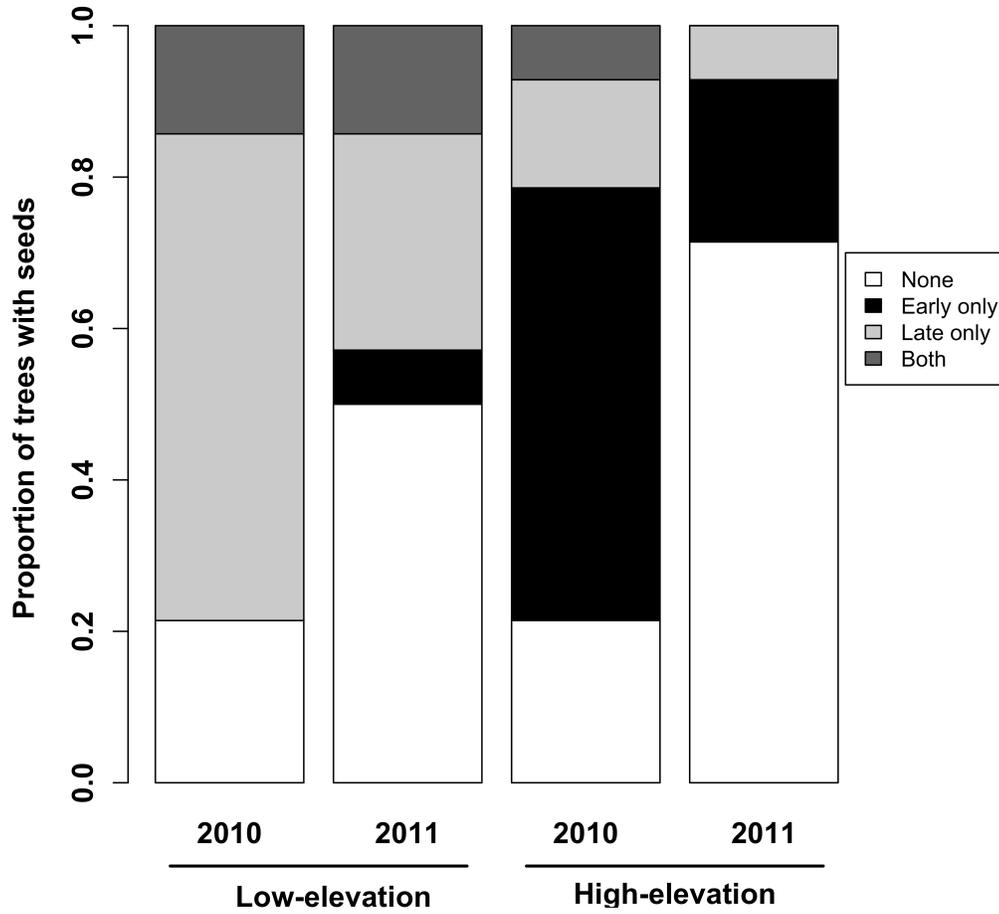


Figure 1.2- Proportion of monitored adult *Quercus oleoides* trees from low-and high-elevation populations in Guanacaste Conservation Area of NW Costa Rica. Proportions shown are for trees that either failed to reproduce or produced seeds at different time points during the wet seasons (early only, late only or at both production peaks) in 2010 and 2011.

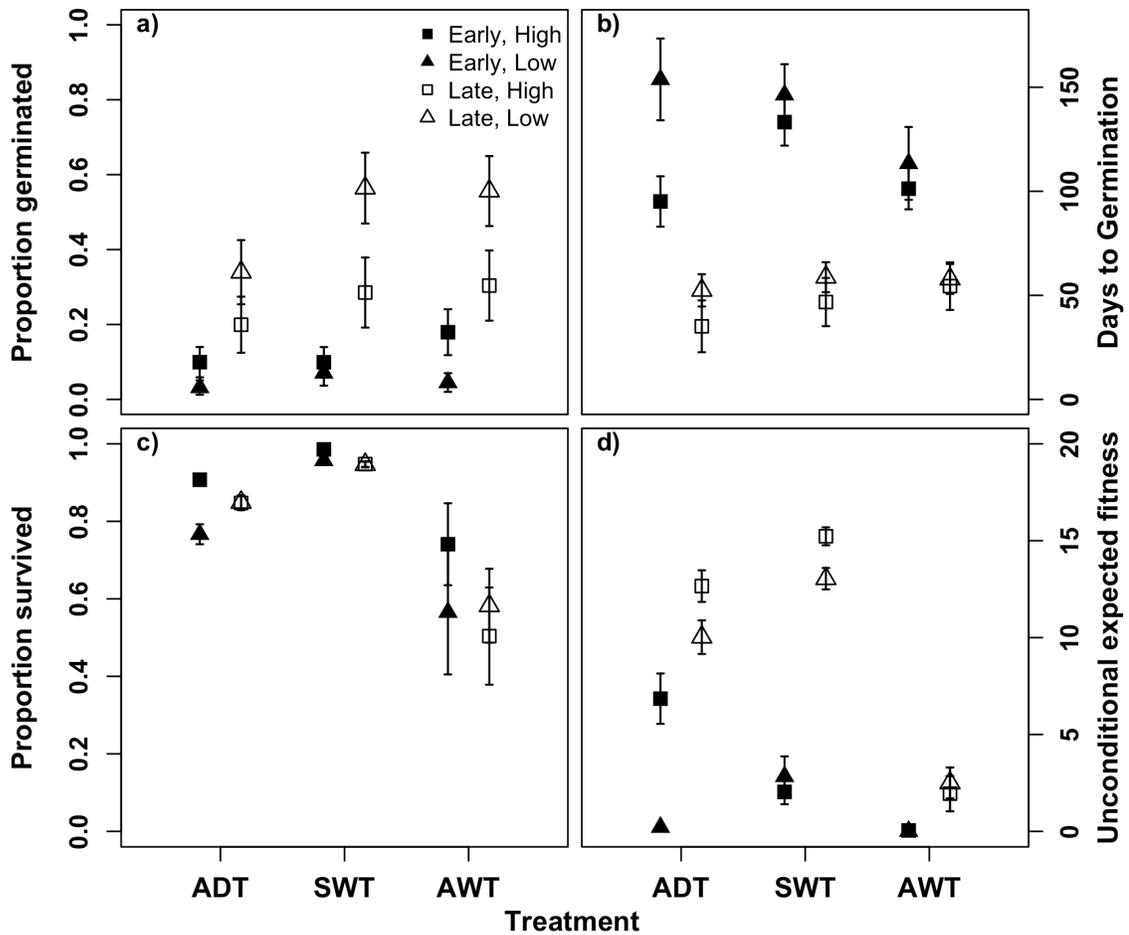


Figure 1.3- Predicted means (SE) for a) germination proportion, b) days to germination, c) survivorship, and d) Aster model estimates of seedling fitness measured on progeny from early- and late-cohort *Quercus oleoides* seeds sampled from a high-elevation and low-elevation populations and reciprocally planted into three watering treatments: ambient dry site at low elevation (ADT), supplemental water at low elevation (SWT) and ambient wet at high elevation (AWT).

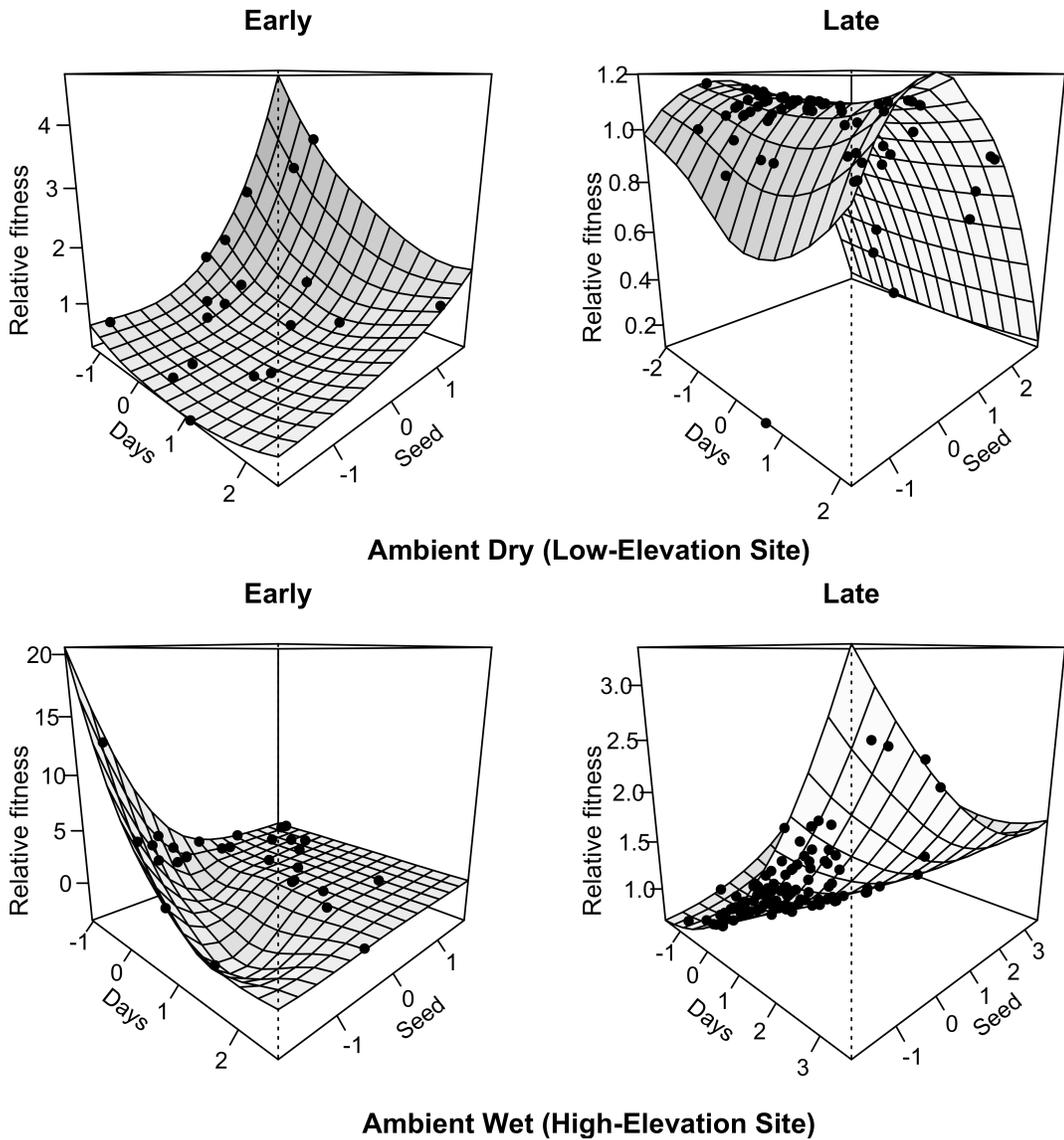


Figure 1.4- Bivariate fitness surfaces showing joint selection on days to germination and seed size in a) Ambient Dry Treatment (low-elevation site) and b) Ambient Wet Treatment (high-elevation site) for early- and late- cohorts seeds collected from two populations of *Q. oleoides* in NW Costa Rica. Traits were normalized to mean=0, SD=1.

Chapter 2: Evidence for high plasticity and within-population genetic variation for fitness but not local adaptation in tropical live oak seedlings (*Quercus oleoides*) of Central American dry forests

Climate change will alter patterns of selection that populations undergo by geographically shifting climatic spaces amenable to them. Large-scale habitat fragmentation impedes range shifts making phenotypic plasticity and adaptation important mechanisms for species persistence *in situ*. Understanding the extent to which populations exhibit local adaptation, phenotypic plasticity and the levels of within-population genetic variation for fitness will help elucidate how populations may respond to future changes in climate. Here we explore the environmental tolerances of populations from the broadly distributed tropical live oak species, *Quercus oleoides*. We collected seeds in the wet seasons of 2009 and 2010 from four populations with contrasting rainfall regimes and varying degrees of genetic divergence at neutral loci and geographic isolation. Common gardens were established near populations in Honduras, and two gardens were located in Costa Rica near populations at different elevations. Seeds were germinated in shadehouses and transplanted into common gardens, and some were planted directly as seeds into gardens after the onset of the following wet season (2010 and 2011 respectively). Added watering treatments at the gardens allowed us to examine the role of changes in water availability on seedling fitness (defined as the cumulative measure of survival and growth). Survival and growth measurements were collected at the end of the dry and wet seasons for two years after planting. In general we found no evidence that the broadly distributed tropical live oak consists of a series of locally adapted populations. Rather populations exhibit wide environmental tolerances and high within-population genetic variation for seedling fitness. Furthermore, added water during the dry season had a slight positive influence on seedling fitness, but overall seedling survivorship was high suggesting that *Q. oleoides* represents a lineage highly tolerant of drought.

Introduction

Climate change will drastically alter the global landscape by disrupting current patterns of natural selection on plants and animals. Many tree species have undergone large range expansions and contractions during past climate changes (Collignon et al. 2002, Kremer et al. 2002, Davis et al. 2005). However, large-scale habitat fragmentation in many regions may impede species ability to migrate (Malcolm et al. 2002), making phenotypic plasticity and adaptation important mechanisms for persistence (Rehfeldt et al. 2001) in both temperate and tropical regions. Understanding how adaptive processes have shaped populations in the past and the degree of local adaptation of isolated populations will help elucidate the genetic capacity of populations to persist *in situ*.

Local adaptation is defined as the homesite fitness advantage of a native population compared to non-native genotypes and display lower relative fitness in alternative environments (Hereford 2009). In a meta-analysis of local adaptation in plants, Leimu and Fischer (2008) found that 71% of the included studies demonstrated that local plants performed better than non-native genotypes. However, upon a stricter definition of local adaptation, including the pair-wise comparison of performance of both populations in a reciprocal planting design, they found that only 45.3% of the studies showed evidence of local adaptation. The degree of local adaptation has been shown to depend on dispersal ability (and gene flow), genetic drift (Lynch et al. 1999, Lenormand 2002, Petit and Hampe 2006, Savolainen et al. 2007), genetic architecture of traits (Antonovics 1976, Lande 1979, Conner and Via 1992, Etterson and Shaw 2001), and intensity and variability of selection (Huey and Hertz 1984, Via and Lande 1985, Etterson 2004b).

Rapid evolutionary responses to current climate change have been seen in some short-lived species (Bradshaw and Holzapfel 2001, Franks and Weis 2008) and in other systems potential evolutionary responses in populations of both short- and long-lived species have been found to lag behind predicted pace of climate changes (Rehfeldt et al. 2001, Etterson 2004b). For long-lived species, climate change will have both short- and long-term impacts on populations, with contemporary responses dependent on plasticity

in traits (Bradshaw 1965), and long-term population persistence determined by evolutionary processes (Rehfeldt et al. 2001). Long-lived species may likely have slower adaptive responses than short-lived species (Linhart and Grant 1996) because of their increased generation time, which reduces the opportunities for new genotypes to establish within the timeframe of present climate change. Additionally, trees are generally known to have low nucleotide substitution rates (Petit and Hampe 2006) and coupled with long generation times may slow adaptive responses.

Intraspecific genetic variation in key traits is essential for populations to adapt to environmental changes. High genetic diversity provides resilience both at the population and community levels in the face of fluctuating environmental conditions (Hughes and Stachowicz 2004). Variation in water availability has been found to be a strong selective agent resulting in genetic differentiation of physiological traits related to water-use (Silander and Antonovics 1979, Dudley 1996a, Heschel et al. 2002) and limited water availability has been found to be a driver of local adaptation (Dudley 1996). Barring the effects of gene flow, the degree of local adaptation is expected to increase with the extent of environmental difference between habitats (Lande 1976, Endler 1977, Slatkin 1985, Hereford 2009). In broadly distributed species, asymmetrical gene flow from central populations to populations at the periphery may impede adaptive responses (Moeller et al. 2011). However, theory predicts rapid divergence if populations at the periphery are isolated and there is sufficient environmental divergence between populations and heritability of quantitative traits (García-Ramos and Kirkpatrick 1997). Given, the complexity of factors influencing populations, it remains not well understood (Bradshaw 1965, Valladares et al. 2007) the extent to which broadly distributed species consist of a series of locally adapted populations (Fig. 2.1a) or consist of populations with broad environmental tolerances (Fig. 2.1b).

Quercus oleoides spans a geographic range from the Gulf Coast of Mexico to the lowlands of NW Costa Rica. Populations throughout Latin America experience differing seasonal and total annual rainfall (Fig. 2.2). Populations from Northern Mexico through Honduras represent a disjoint patchy network of partially isolated populations but do not show large divergence at neutral loci (Cavender-Bares et al. 2011). Dry forests of Belize

are characterized by wet season rainfall levels similar to that in Honduras but the dry season is milder compared to the severe dry season drought in Honduras (Hijmans et al. 2005). Interestingly, at the southern edge of the species range, populations in Costa Rica are both geographically and genetically distinct from the rest of the range (Cavender-Bares et al. 2011). Dry forest regions in the Costa Rican lowlands (<300m above sea level) are characterized by severe dry season drought and high rainfall during the wet season. In contrast, upland dry forest regions (~900 m above sea level) have a mild dry season, comparable to Belize and high rainfall during the wet season (Hijmans et al. 2005). Current climate change models predict that for dry forest regions of Latin America, changes in rainfall patterns will be more severe than changes in temperature. Tropical dry forest regions are predicted to be drier with the progression of climate change with alterations in both the seasonality and total annual rainfall (IPCC 2013b). Evaluating the intraspecific variation in seedling fitness (cumulative measure of survival and growth) in response to changes water availability will help elucidate how populations may respond to future changes in rainfall.

In this study, we address the issue of environmental tolerances (water availability) of populations in a broadly distributed species and pose the following questions: (1) Are populations of *Q. oleoides* locally adapted at the seedling stage? (2) If populations show evidence of local adaptation, can it be attributed to differences in water availability among sites? (3) Are there differences among populations in the extent to which seedlings are limited by water? (4) Is there greater genetic variation for seedling fitness within or among populations? We hypothesize that isolated populations will exhibit local adaptation in relation to seedlings fitness. Second, we hypothesize that seedlings will have highest fitness at their homesite and in watering treatments that are similar to their homesite. Alternatively, we hypothesize that within population genetic variation for fitness will be greater than among population variation such that populations do not differ in response to site or water limitation but genotypes within populations do. Third, we hypothesize that all seedlings regardless of population of origin are limited by dry season drought.

To test these hypotheses we used a reciprocal planting design experiment (Turesson 1922, Antonovics and Primack 1982, Bradshaw 1984, Schmid 1985) with two years of plantings: both seeds planted directly into common gardens and seeds planted into shadehouses and then transplanted into common gardens. Common gardens were established in Honduras and Costa Rica because they represent sites with the extreme rainfall conditions throughout the range, from the driest (Honduras) to the highest annual rainfall in Costa Rica. Watering treatments varying wet and dry season water levels allowed us examine population responses to changes in water availability and to examine intraspecific genetic diversity for fitness.

Methods

Seed collection

Seeds were collected in the wet season of 2009 and 2010 from four populations across the species' range (Belize, Honduras, and two populations in Costa Rica at different elevations). Populations were chosen because they are subject to contrasting wet and dry season rainfall regimes and span a large geographical scale. Seeds were collected from a total of 30-50 trees that were at least 50m apart from each population. A total of 37,460 seeds were collected in 2009 and 44,329 seeds in 2010 (Appendix 2- Table S2.1). Seeds were shipped to Zamorano University, Honduras and to Guanacaste Conservation Area in Costa Rica and were stored in 3°C refrigerators (unless in transit) until planted into shadehouses or into gardens. Seeds arrived to respective countries after the onset of the dry season and since *Q. oleoides* seeds are nondormant and metabolically active a subset of seeds were germinated in shadehouses in Honduras and Costa Rica in dry seasons of 2010 and 2011 to reduce seed mortality due to storage. In 2010, seeds were not planted in a randomized design in the shadehouses but were in the second year of planting in 2011. While masking our ability to examine very early seedling survival, transplants guaranteed ample sample sizes. The remaining seeds that were not planted into shadehouses were stored in refrigerators until the onset of the next wet season (either 2010 or 2011) and planted directly into common gardens. Seed size was measured at the time of planting, as the seed volume (V), calculated from seed height (h) and diameter

(d), assuming an ellipsoid: $V=4/3 \times (d/2)^2\pi+(h/2)$. Volume was converted to seed mass based on the empirical relationship between volume and fresh mass (M) without the seed coat, for 16 oak species: $M=0.636V-0.1213$, $R^2=0.97$ (Cavender-Bares et al. 2004).

Common garden sites

Common garden locations in Honduras and Costa Rica were chosen because they differ in both total annual rainfall and wet and dry season rainfall patterns. In Costa Rica two common garden sites were chosen, both nearby the high- and low- elevation populations where seeds were collected. For both the 2010 and 2011 plantings, seeds and seedlings were planted into common gardens at all sites in a randomized complete block design with maternal lineage represented evenly among blocks and individuals randomized within blocks. Seeds planted directly into gardens (hereafter ‘direct planting’ cohorts) were planted 1cm beneath the soil surface and 15cm apart. To prevent herbivory and photoinhibition, blocks were covered with wire mesh cages (0.6m x 0.6m x 0.6m) and 70% shade cloth. Cages were removed when plants were ~0.5m tall, after a year of growth. Germination was monitored weekly for the first five months. Transplants were planted in the same randomized design as the direct plantings but cages were not used. In 2010, transplants from the shadehouses were planted 25cm apart and well watered for two weeks after transplanting to encourage establishment. In 2011, transplants were planted 50cm apart to minimize competition and shading from nearby experimental plants and were also watered for two weeks post transplanting. All blocks were weeded biweekly to reduce competition effects.

Water treatments

To isolate the effects of water limitation, supplemental watering treatments were imposed. Each treatment was replicated in six blocks across two gardens at each site. At Zamorano University in Honduras, the location with the lowest annual and dry seasonal rainfall (hereafter referred to as the dry garden, DG) four treatments were established simulating all climatic scenarios natural populations are subjected to:

- 1) Ambient rainfall (no water added, hereafter, DG-Ambient)
- 2) Added water of 18mm/week during the dry season (hereafter referred to as dry season water-DG-DS Water or DG-DSW)
- 3) Added water up to 25mm/week during the wet season if it did not rain 25 mm/week (hereafter referred to as wet season-DG-WS Water or DG-WSW)
- 4) Added water during both the dry and wet seasons per DS and WS protocols (hereafter DG-Both Water or DG-Both)

In Costa Rica, at the low-elevation garden site, representing intermediate rainfall levels, (hereafter referred to as the intermediate garden, IG) two of the four watering treatments were established:

- 1) Ambient rainfall (no added water, hereafter IG-Ambient)
- 2) Added water of 18mm/week during the dry season (hereafter IG-DS Water or IG-DSW)

At the high-elevation garden, the site with highest annual rainfall (hereafter, the wet garden, WG-Ambient) seedlings were subjected to only ambient rainfall conditions. Water removal at sites was not feasible to create a full-factorial design and data were subset to include the relevant treatments to address the biological questions.

Statistical analyses

Given the unique conditions each cohort were subjected to, data from each planting cohort were analyzed separately. Survival and growth (stem height, leaf number, basal diameter and length of longest leaf) were monitored at the end of each season (December for the end of the wet season; May for end of the dry season) for two years after planting for both the 2010 and 2011 collections. Aboveground growth measurements of plant height (h), leaf number (l) and basal diameter (d) were converted to above ground biomass (B) using the allometric regression equation from *Q. oleoides* grown under greenhouse conditions, $B=1.4663(h+l+d)+ 39.794$, $R^2=0.758$ (Cavender-Bares, unpublished).

Growth and survival were analyzed separately at each measurement point to examine if populations differed in recruitment strategies and are reported in the appendix.

Survival was analyzed using a generalized linear mixed model with block (nested in treatment) and maternal family (nested in population) as random effects. Growth was analyzed using linear mixed effect models and residuals were checked visually and responses were transformed when appropriate (square root or logarithmic) to better meet assumptions of constant variance and normality. Both survival and growth analyses were conducted using the ‘lme4’ package in R, version 3.11.1.

A joint analysis of survival and growth was conducted to estimate cumulative seedling fitness using Aster models (Shaw et al. 2008). Aster models appropriately integrate multiple components of fitness and accommodate non-normal underlying distributions of fitness components (Shaw et al. 2008, Shaw and Geyer 2010). For the 2010 transplants, seedling fitness was estimated at the last measurement time (leaf count conditional on survival to the time). Leaf count was chosen as a fitness surrogate measure because it reflects plant growth and photosynthetic capacity while accounting for multiple stems and compensatory growth after herbivory. The graphical for seedling fitness model used was:

(1) Planted → survival dry season (DS) 2011 → Survival DS 2012 → leaf number DS 2012

with survival at each node (binomial distribution) conditional on survival to the previous node and fitness surrogate, final leaf count (Poisson distribution) conditional on survival to the DS 2012. While aboveground biomass would be preferable fitness proxy in the Aster models, leaf count was chosen because it is an integer and had the highest correlation of a single growth trait with aboveground biomass ($R^2 = 0.66$, Cavender-Bares, unpublished). The Aster models for the local adaptation analyses were parameterized as:

(2) $F_{ijklm} = T_i + P_j + S + L + MF_k + T_i * P_j + M_k(P_j) + B_l(T_i) + \epsilon_{ijklm}$

with treatment (T) i, population (P) j, seed mass (S), size at transplanting (L), as fixed effects. Maternal family (MF) k (nested in population j), and block (B) l (nested in treatment i) as random effects, and ϵ represents the residuals for plot m.

For 2010 direct planting cohort, seedling fitness was estimated using the graphical model:

(3) Germinated → Survival DS 2011 → Survival DS 2012 → Leaf number DS 2012

with survival at each node conditional on survival to the previous node and fitness surrogate, final leaf count conditional on survival to the DS 2012. The Aster model was parameterized as:

$$(4) F_{ijklm} = T_i + P_j + S + L + T_i * P_j + MF_k(P_j) + B_l(T_i) + \epsilon_{ijklm}$$

with treatment (T) i, population (P) j, seed mass (S), size at transplanting (L), as fixed effects. Maternal family (MF) k (nested in population j), and block (B) l (nested in treatment i) as random effects, and ϵ representing the residuals for plot m. Unfortunately, due to restrictions of sample size from poor germination rates and high seed mortality during storage, the garden by population interaction could not be assessed.

For the 2011 transplants, seedling fitness was estimated using the graphical model:

(5) Planted → Survival DS 2012 → Survival DS 2013 → Survival WS 2013 → Survival DS 2014 → Leaf number 2014

Final leaf count conditional on survival to the DS 2014. The Aster models were parameterized as:

$$(6) F_{ijklm} = T_i + P_j + S + L + MF + C + H + T_i * P_j + M_k(P_j) + B_l(T_i) + \epsilon_{ijklm}$$

with treatment (T) i, population (P) j, seed mass (S), size at transplanting (L), cut (C), and herbivory (H) as fixed effects. The effects of accidental cutting of plants by volunteers and the impact of herbivory across blocks were assessed through the indicator variables C and H. Maternal family (MF) k (nested in population j), and block (B) l (nested in treatment i) as random factors, and ϵ representing the residuals for plot m.

For 2011 direct plantings, seedling fitness was estimated using the graphical model:

(7) Germinated → Survival DS 2013 → Survival DS 2014 → Leaf number 2014

Final leaf count conditional on survival to the DS 2014. The Aster models were parameterized as:

$$(8) F_{ijklm} = T_i + P_j + S + L + MF + C + H + T_i * P_j + B_l(T_i) + \epsilon_{ijklm}$$

with treatment (T) i , population (P) j , seed mass (S), size at transplanting (L), cut (C), and herbivory (H) as fixed effects, block (B) l (nested in treatment i) as a random effects, and ϵ representing the residuals for plot m .

To address the question of local adaptation, data were subset to analyze the ambient rainfall treatments across gardens. Similarly, to address the question of how water availability throughout the year influences seedling fitness and to examine within-population genetic diversity, analyses were conducted separately for the Honduras and Costa Rica sites. Models examining treatments within site were constructed similar to those for the local adaptation analyses. To account for variation among seedlings in herbivory damage, a herbivory index was included in analyses of treatments within the dry garden (Honduras). All seedlings at the wet garden (Costa Rica high-elevation) were subjected to high levels of herbivore damage and a herbivory index was not included in analyses of intermediate and wet gardens because it is confounded with treatment (Chapter 1). Maternal family was included as a random effect (nested in population) to examine if populations harbor high within-population genetic variation for fitness. Differences in seedling fitness among maternal families would suggest genetically based differences in seedling performance given that seeds from each maternal tree are assumed to be half-sibs. To visualize the within-population variation in fitness, data from the direct planting cohorts were subset to include maternal families that were represented multiple times in treatments at the dry garden site. The dry garden site was chosen because it allowed for incorporation of all four watering treatments. The same graphical models were used from the population level fitness analyses but maternal family was included as a fixed effect in the place of population to allow for fitness estimates at the maternal family level.

Results

Test of local adaptation for nursery transplanted seedlings

We did not find clear evidence of local adaptation in the broadly distributed *Q. oleoides* after two years of growth in three common gardens with contrasting climates. There was not consistent evidence of higher fitness of populations at their home environment or lower fitness in the away environment in the four planting cohorts (transplanted in 2010 and 2011, and direct plantings in 2010 and 2011).

There was not a significant difference in overall seedling fitness in the 2010 transplant cohort between the dry (Honduras) and intermediate (CR low-elevation) gardens, but all seedlings at the wet garden (CR high-elevation) had fitness estimates near zero and were subjected to high herbivory (Table 2.1, Fig. 2.3a). Population main effect for this cohort was not significant but there was a significant garden by population interaction. Seedlings from Honduras (HN) had the lowest estimates of seedling fitness at their home site (dry garden) compared to all other populations. However, at the intermediate garden seedlings from HN had significantly higher estimates of fitness than seedlings from Belize (BZ) but not different from Costa Rica high-elevation (CRH) population seedlings. Additionally, seedlings from BZ had highest predicted mean fitness compared to all other populations at the dry garden but the lowest predicted mean fitness compared to all other populations at the intermediate garden. At the intermediate garden, seedlings from the Costa Rica low-elevation (CRL) population did show a significant home-site advantage with higher estimates of fitness compared to non-native populations. Furthermore, seedlings from the CRL population had lower estimates of fitness at the dry garden than at the home-site intermediate garden. The CRH population had lower fitness estimates in the dry garden than the intermediate garden, but zero fitness in the home-site. For all populations, size at transplanting had a significant positive effect on seedling fitness but there was no effect of seed size on fitness.

Separate analyses of survival and growth components of seedlings fitness showed that for all populations of the 2010 transplant cohort (although survivorship differed among the gardens) there was no difference between the dry and intermediate gardens with respect to growth traits (Appendix 2- Tables S2.2-S2.5, Figs. 2.1&2.2). By the end

of the dry season 2012, survivorship was highest at the intermediate garden, with a mean survival of 89% followed by the dry garden with a mean survival of 79% and 53% of seedlings survived at the wet garden.

Aster analyses of seedling fitness for the 2011 transplants showed a different pattern of seedling fitness than the 2010 transplants; there was a marginally significant effect of population, a significant garden effect, and a significant garden by population interaction (Table 2.1, Fig. 2.3b). Within the dry garden (Honduras), seedlings from HN had highest estimates of fitness. However, seedlings from HN had significantly higher estimates of fitness at the intermediate garden (IG) than at their home-site (dry garden). Seedlings from the CRL population had significantly higher estimates of fitness at their home-site (IG) than at the DG in Honduras but did not have a fitness advantage over seedlings from HN or BZ populations at the IG. For all populations of the 2011 cohort, seed size and plant size at transplanting both had a positive effect on fitness. Analyses of survivorship showed that survival was significantly lower at the wet garden than the other two gardens (post-hoc contrast, Estimate= -2.05 ±1.09, $Z_1=-1.88$, $P=0.06$, see Appendix 2- Tables S2.6 &S2.7, Fig. S2.3) but survivorship did not differ between the dry and intermediate gardens (post-hoc contrast, Estimate=-0.49± 1.14, $Z_1=-0.43$, $P=0.67$). Unlike the 2010 transplants, for all measurement points there was a consistent garden effect on growth traits, with seedlings at the intermediate garden having higher mean trait values than the dry and wet gardens (Appendix 2- Tables S2.8&S2.9, Fig. S2.4). Additionally, seedlings from HN showed significantly higher mean growth trait values compared to other populations, which likely explains the observed fitness advantage.

Test of local adaptation for direct planting cohort seeds

Analyses of seedling fitness from seeds planted directly into common gardens did not reveal consistent evidence for local adaptation. For the 2010 direct planting cohort, population was not significant but there was a significant garden effect (Table 2.1, Fig. 2.3c). At both the dry and intermediate gardens, seedlings from HN had the highest estimates of mean fitness. Seedlings from all populations had higher estimates of fitness at the DG than at the IG. Seed size, block, and maternal family also had significant

effects on fitness. Although there was a large effect of garden on seedling fitness, survivorship did not differ significantly among the gardens (Appendix 2- Tables S2.10 & S2.11, Fig. S2.5), but garden did significantly influence growth traits (Appendix 2- Tables S2.12 & S2.13, Fig. S2.6). Seedlings at the dry garden exhibited higher growth traits values (stem height, basal diameter, leaf number, aboveground biomass) on average than seedlings at the intermediate or wet gardens (regardless of population of origin). Seedlings at the wet garden had the lowest estimates of survivorship after one year of growth (post-hoc contrast, Estimate=-1.14±0.45, $Z_1=-2.54$, $P=0.1$), but by the end of DS 2012 there were no differences in seedling survivorship among the gardens.

Results from Aster analyses of seedlings fitness of the 2011 direct planting cohort there were significant effects of population and garden on fitness (Table 2.1, Fig. 2.3d). Seedlings from the CRL population had highest estimates of fitness compared to all other populations at both the dry and intermediate gardens. At the dry garden, seedlings from HN had the next highest estimates of fitness followed by CRH population and BZ seedlings with the lowest estimates. Separate analyses of survival and growth components showed that both survivorship and growth were higher at the dry garden compared to the intermediate garden (Appendix 2- Tables S2.14-S2.17, Figs S2.7 & S2.8). Seed size also had a positive effect on seedling fitness.

Fitness consequences of water limitation—dry garden

Seedlings that were transplanted into the dry garden in 2010 did not exhibit consistently higher fitness with water addition during dry season drought or during dry spells in the wet season (Table 2.2, Fig. 2.4a, Appendix 2- Tables S2.18-2.21, Figs. S2.9 & S2.10). However, herbivory at the dry garden had a significant impact on both survival and growth. In the 2011 transplant cohort, seedlings generally had higher estimates of fitness in water addition treatments that reduced dry season drought severity. However, seedlings from CRH and BZ populations (both originating from locations with high rainfall) had estimates of zero fitness with water addition in the DG-DSW (dry garden, dry season water addition) and DG-both treatments. The reduction in fitness of these seedlings compared to the DG-ambient and DG-WSW treatments can be attributed to

reductions in growth and not mortality, given that survivorship in the DG-ambient and DS-DSW treatments did not differ significantly from the DS-ambient and DSW-treatments (post-hoc contrast, Estimate=-.08±0.61, $Z_1 = -0.14$, $P=0.9$, Appendix 2- Tables S2.22-S2.25, Figs. S2.11& S2.12).

In contrast to the nursery-transplanted seedlings, cohorts planted directly from seeds into gardens in 2010 and 2011 did show fitness responses to water addition suggesting that early life stages are more sensitive to drought. The transplant cohorts may have been buffered from environmental stress during that vulnerable period. In the 2010 direct planting cohort, seedlings from Honduras and both populations from Costa Rica had higher estimates of mean seedling fitness in the watering treatments that reduced dry season drought (Table 2.2, Fig. 2.4c, Appendix 2- Tables S2.26-S2.29, Figs. S2.13 & S2.14). Seed size had a positive effect on fitness and herbivory significantly reduced fitness.

The 2011 direct planting cohort showed similar trends as the 2010 cohort with a significant effect of population and treatment (Table 2.2, Fig. 2.4d). Seedlings from all populations had a positive response to increased water availability in the dry season. Furthermore, seedlings from all populations that were watered during both the wet and dry seasons had higher estimates of fitness than their counterparts that were only watered in either the dry season or the wet season, suggesting that both dry season drought and total annual water availability may limit fitness. The fitness advantage of seedlings in treatments where water was added during the dry season can be attributed to both increased growth and survivorship (Appendix 2- Tables S2.30-S2.33, Figs. S2.15 & S2.16).

Fitness consequences of water limitation—Intermediate and Wet Gardens

Similar to findings for both the 2010 and 2011 transplants at the dry garden site in Honduras, water addition in the Costa Rica low-elevation garden did not enhance fitness (Table 2.3, Fig 2.5a&b, Appendix 2- Tables S2.34-S2.41, Figs S2.17-S2.20). Additionally, large negative fitness effects of herbivory at the wet garden suggest that biotic factors, when present, can have stronger effects on seedling fitness than abiotic

factors. In the 2010 and 2011 directly planted cohorts, seedlings from both Costa Rican populations had equivalently high estimates of mean fitness in both water treatments at the intermediate garden (Table 2.3, Fig. 2.5c&d, Appendix 2- Tables S2.42-S2.49, Figs. S2.21-S2.24). In contrast to the consistent positive effect of water addition during the dry season at the dry garden site in Honduras, added water during the dry season at the intermediate garden had either no effect (in 2010) or a slightly positive effect (2011 planting cohort).

Intraspecific genetic variation—dry garden

Maternal family random effect was significant in all fitness analyses indicating significant within-population variation for fitness that could reflect genetic variation. Visualization of predicted mean maternal family seedling fitness at the dry garden for both the 2010 and 2011 direct planting cohorts showed large differences among maternal families in seedling performance (Table 2.4, Fig. 2.6). There was no effect of watering treatment on predicted mean maternal family fitness in the 2010 cohort and only a marginal effect of treatment in the 2011 cohort. For both years, there was a significant maternal family by treatment interaction, with the rank order of maternal family fitness changing across watering treatments. Additionally, seedlings from some maternal families tolerated a wide range of simulated rainfall conditions as evidenced by multiple maternal families having consistently high fitness estimates across treatments.

Discussion

Collectively this study reveals several important findings that increase our understanding of how broadly distributed species tolerate a wide range of conditions. We did not find strong evidence that populations of the long-lived evergreen live oak, *Q. oleoides*, are locally adapted to regional abiotic and/or biotic conditions. Furthermore, we found evidence that populations harbor high within-population genetic variation for fitness conferring wide environmental tolerances at the population level. We also found evidence that plasticity of traits related to fitness allowed seedlings from maternal families to maintain homeostasis across a range of simulated rainfall conditions. Finally,

small-scale biotic factors when present have a larger effect on seedling fitness than changes in water availability.

No evidence for local adaptation

Local adaptation of the Costa Rican populations was expected given the genetic divergence at neutral loci, geographical isolation of these trees from the rest of the range, and the climatic differences between Costa Rica and Honduras (Cavender-Bares et al. 2011). Furthermore, local adaptation has been found in other tree systems that span large geographic ranges and encompass similar climatic variation (Rehfeldt et al. 1999, Hall et al. 2007). We did not find clear or consistent patterns indicating that populations of *Q. oleoides* are locally adapted to their native environment. Populations in Honduras share the same alleles at neutral loci as populations across Belize and Mexico (Cavender-Bares et al. 2011), suggesting gene flow among these populations that could hinder local adaptation of these tree populations to climate in Honduras (Slatkin 1985, Savolainen et al. 2007).

One possible explanation for the lack of evidence for local adaptation at the seedling stage may be that seedlings from all populations throughout the species range experience relatively similar climatic niches given their comparatively shallow roots as juveniles. As a consequence, all seedlings may have been subjected to high water availability during the wet season and reduced rainfall during the dry season. Although the intensity of these seasonal patterns differ, seedlings may be biologically subjected to similar selective pressures for high growth during the wet season, and as a result, drought tolerance through physiological mechanisms during the dry season. All seedlings, regardless of population of origin, may be under strong pressures to establish deep roots at very early life stages allowing them to withstand dry season drought upon sufficient taproot development. This scenario is plausible given the buffered response of the transplant cohorts to changes in water availability and the higher sensitivity of the direct planting cohorts to added water during the dry season at the dry garden site.

Another possible explanation for the lack of evidence for local adaptation using seedling fitness may be negative genetic correlations or selective tradeoffs in traits that

confer fitness at the seedling stage and those that confer fitness at the adult stage. In addition, fluctuating environments throughout the lifespan of an individual can constrain adaptation because contrasting traits confer a selective advantage at different times. *Q. oleoides* trees can live hundreds of years, a temporal over which, rainfall patterns are likely to vary (IPCC 2013a). Under this scenario selection on traits at the seedling stage would lead to reduced fitness at the adult stage and vice versa. If selection were stronger at the adult stage, evidence for local adaptation may not appear in early life history traits for this species. Even without tradeoffs, local adaptation may not be apparent at the juvenile stage, even if present with lifetime fitness. For example, in a 36 year study of *Pinus ponderosa* populations on serpentine soils evidence for local adaptation emerged only after 20 years of growth (Wright 2007).

Climatic fluctuations may contribute to high genetic variation within populations

Populations of *Q. oleoides* appear to harbor intraspecific diversity evidenced by the effect of maternal family on seedling fitness. Patterns of high decadal fluctuations in rainfall, characteristic of tropical regions (IPCC 2013a), may contribute to the maintenance of genetic diversity. Fluctuations in rainfall patterns may result in intergenerational changes in selective regimes that impede consistent adaptive responses to the current abiotic environment (Etterson and Shaw 2001). Genotypes with traits conferring high fitness during wetter periods may not maintain a selective advantage during periods of lower rainfall. In drier periods, other genotypes may confer higher fitness. Under this scenario varying selective pressures would act to maintain genetic variation within populations, consistent with the intraspecific genetic diversity we found in this study. The extent to which intergenerational temporal variation may maintain within-population genetic diversity depends on the intensity of selection and the additive genetic correlation for fitness in contrasting environments (Bull 1987, Gillespie and Turelli 1989). If selection varies between generations and the additive genetic correlation for fitness (r_{Aij}) is negative, this would indicate a genetic trade-off between fitness in the two environments i and j . In this scenario, genotypes may be maintained because few would have high performance in both environments Alternatively if r_{Aij} is positive and

near unity, genotypes with high fitness in both environments would likely be favored and result in a reduction of genetic variation within populations (Etterson 2004b). Given past fluctuations in precipitation patterns over the last several thousand years in lowland regions of Latin America (Curtis et al. 1996, Perry and Hsu 2000, Mendoza et al. 2007), climatic variability may have contributed to the maintenance of genetic diversity within populations.

Phenotypic plasticity

Along with high intraspecific diversity, multiple maternal families from both Honduras and Costa Rican populations maintained high-predicted mean fitness across watering treatments at the dry garden site. This fitness reaction norm and maintenance of fitness of maternal families across environments may be explained by plasticity in morphological and physiological traits influencing fitness (Bradshaw 1965, Sultan et al. 1998). Consistent with this we found high plasticity in carbon and water use traits in the experimental seedlings (chapter 3). Similar to our findings, Gimeno et al. (2009) found no evidence for local adaptation in the broadly distributed Mediterranean holm oak, *Q. ilex*. Instead, *Q. ilex* seedlings showed high physiological trait plasticity associated with large tolerances for both temperature and drought stress. In our study, the within-population genetic variation and maintenance of seedling fitness from maternal families suggest that populations of *Q. oleoides* may be well suited to persist *in situ* to changes in water availability (Rehfeldt et al. 2001). Maintenance of seedlings fitness in populations of *Q. oleoides* may help explain why the species persists across a much broader range of precipitation regimes compared to its closest relatives (species within the Virentes lineage, “live oaks,” Cavender-Bares *in review*).

Biotic interactions

The large effect of herbivory coupled with the relatively small effect of dry season drought on seedling fitness suggests that, when present, fine-scale and spatially heterogeneous biotic pressures may limit fitness more than landscape level abiotic factors, such as dry season drought. *Quercus oleoides* populations appear to be

reasonably well adapted to seasonal drought, given the high survivorship of all seedlings across all gardens where herbivory was absent or minimal. Consistent with the strong impact of herbivory in our study, Thomas et al. (2002), found that defoliation by herbivores in two Central European oak species significantly increased seedling mortality. They further found that herbivory increased drought sensitivity of damaged trees, an interaction that we did not investigate. Future examination of the effects of herbivory on physiological traits related to water-use would provide insight into how fine-scale biotic factors influence seedlings' tolerance of abiotic stressors.

Conclusion

Our study supports the conclusion that the broadly distributed tropical live oak, *Quercus oleoides*, consists of populations with wide environmental tolerances and high intraspecific variation rather than a series of locally adapted populations. Although water limitation influenced seedling fitness, local biotic factors (when present) were found to have a greater impact on fitness. Ultimately, results show that the high within-population genetic variation and maintenance of seedling fitness of the maternal families in *Q. oleoides* populations may promote persistence *in situ* with the progression of climate change. Plastic responses to changes in water availability promote persistence in the short-term and populations display the potential for long-term resilience as a consequence of high genetic diversity.

Effect	2010 Transplants			2011 Transplants		2010 Direct Planting		2011 Direct Planting	
	DF	Dev		Dev		Dev		Dev	
Population (P)	3	2.14		6.60	+	0.96		429.69	***
Garden (G)	2	1.13		6.45	*	10.43	**	29.501	***
Seed Mass	1	0.43		5.49	*	165.93	***	109.3	***
Size	1	3361.40	***	1678.10	***	--		--	
Cut	1	--		651.69	***	--		442.95	***
Garden x Pop	6	389.23	***	584.71	***	--		--	
Block (G)	1	7908.00	***	3751.50	***	3893.80	***	2314	***
MF (P)	1	7598.40	***	4860.00	***	4877.40	***	--	--

Table 2.1- Summary of nested model comparison of Aster models to test effects of factors on fitness of *Q. oleoides* seedlings. Both transplants and direct planting cohorts represent seeds collected from populations throughout the range and planted into common gardens in Honduras (dry garden), and Costa Rica (intermediate and wet gardens) in 2010 and 2011. Four planting cohorts were analyzed separately and include 2010 and 2011 transplants, and 2010 and 2011 direct plantings. Covariates of seed mass and size of plant at transplanting (size) were included in analyses when appropriate. Degrees of freedom (DF) shown are the difference between nested models. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***<0.001

Effect	DF	2010 Transplants		2011 Transplants		2010 Direct Planting		2011 Direct Planting	
		Dev		Dev		Dev		Dev	
Population (P)	3	1.48		6.59		13.34	**	4446.9	***
Treatment (T)	3	1.31		8.47	*	17.20	**	8.2966	*
Herbivory	1	6.54	*	8.70	**	147.45	***	1352.8	***
Seed mass	1	27.03	***	3.82	+	33.31	***	240.56	***
Size	1	2811.80	***	1667.60	***	--		--	
Cut	--	--		638.37	***	--		20544	***
T x P	6	375.77	***	585.18	***	1176.50	***	--	
Block (T)	1	14393.00	***	3687.90	***	18362.00	***	23948	***
MF (P)	1	0		4866.70	***	12742.00	***	--	

Table 2.2- Summary of nested model comparisons of Aster models to test effects of factors on fitness of *Q. oleoides* seedlings. Both transplants and direct planting cohorts represent seeds collected from populations throughout the range and planted into common garden in Honduras (dry garden), and administered one of four watering treatments at that site (ambient rainfall, added water during DS, added water during WS, and artificially watered both seasons). Four planting cohorts were analyzed separately and include 2010 and 2011 transplants, and 2010 and 2011 direct plantings. Covariates of seed mass and size of plant at transplanting (size) were included in analyses when appropriate. Degrees of freedom (DF) shown are the difference between nested models. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***<0.001

Effect	DF	2010		2011		2010		2011	
		Transplants		Transplants		Direct Planting		Direct Planting	
		Dev		Dev		Dev		Dev	
Population (P)	3	4.88		6.10		11.38	*	56.05	***
Treatment (T)	2	6.98	*	15.87	***	5.05	+	6.68	*
Seed Mass	1	0.50		21.74	***	--		0.38	
Size	1	4244.20	***	207.54	***	26.03	***		
T x P	6	341.50	***	452.97	***	--		84.17	***
Block (T)	1	35656	***	3556.30	***	2160.60	***	878.81	***
MF (P)	1	11630	***	5734.60	***	674.11	***	--	

Table 2.3- Summary of nested model comparisons of Aster models to test effects of factors on fitness of *Q. oleoides* seedlings. Both transplants and direct planting cohorts represent *Q. oleoides* seeds collected from populations throughout the range and planted into common gardens at low- and high-elevation garden sites in Costa Rica. Four planting cohorts were analyzed separately and include 2010 and 2011 transplants, and 2010 and 2011 direct plantings. Treatment represents the three possible watering treatments at the sites: Intermediate garden- ambient rainfall treatment, intermediate garden- added water during DS, and wet garden-ambient rainfall. Covariates of seed mass and size of plant at transplanting (size) were included in analyses when appropriate. Degrees of freedom (DF) shown are the difference between nested models. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***<0.001

Effect	2010 Direct Planting			2011 Direct Planting		
	DF	Dev		DF	Dev	
Maternal Family (MF)	10	6527.7	***	24	10689	***
Treatment (T)	3	5.23		3	6.74	+
Seed Mass	1	1.52		1	66.79	***
Herbivory	1	418.65	***	--	--	--
MF x T	30	8214.9	***	72	12744	***
Block (T)	1	12288	***	1	17404	***
Seedling (MF)	--	--		1	4823	***

Table 2.4- Summary of nested model comparisons of Aster models to test effect significance examining genetic variation within population for seeds collected from populations of *Q. oleoides* across Central America and planted directly into a common garden at Zamorano University in Honduras in 2010 and 2011. Seedlings were administered one of four watering treatments at that site (ambient rainfall, added water during DS, added water during WS, and artificially watered both seasons). Degrees of freedom (DF) shown are the difference between nested models. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***<0.001

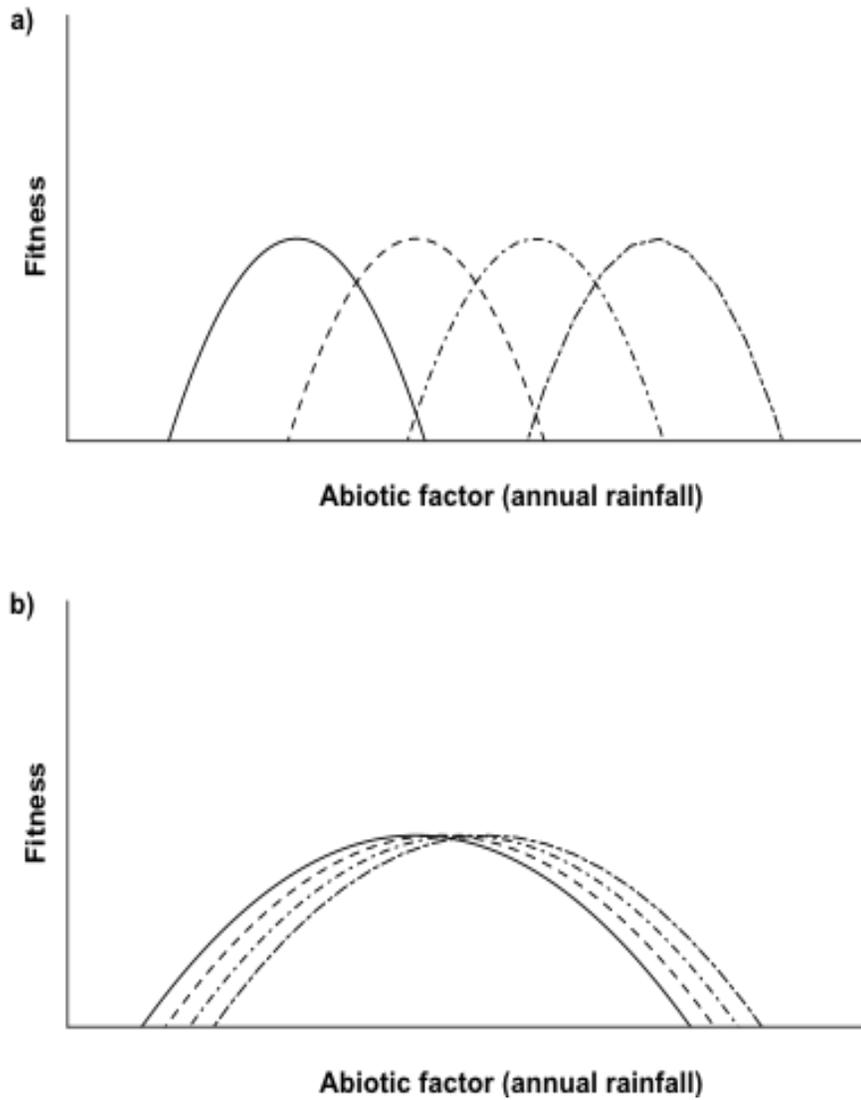


Figure 2.1- Hypothetical distribution of populations of *Q. oleoides* along abiotic environmental axis (rainfall) showing a) populations adapted to local rainfall conditions or b) spanning broad environmental niches. Lines represent different hypothetical populations found through the species range.

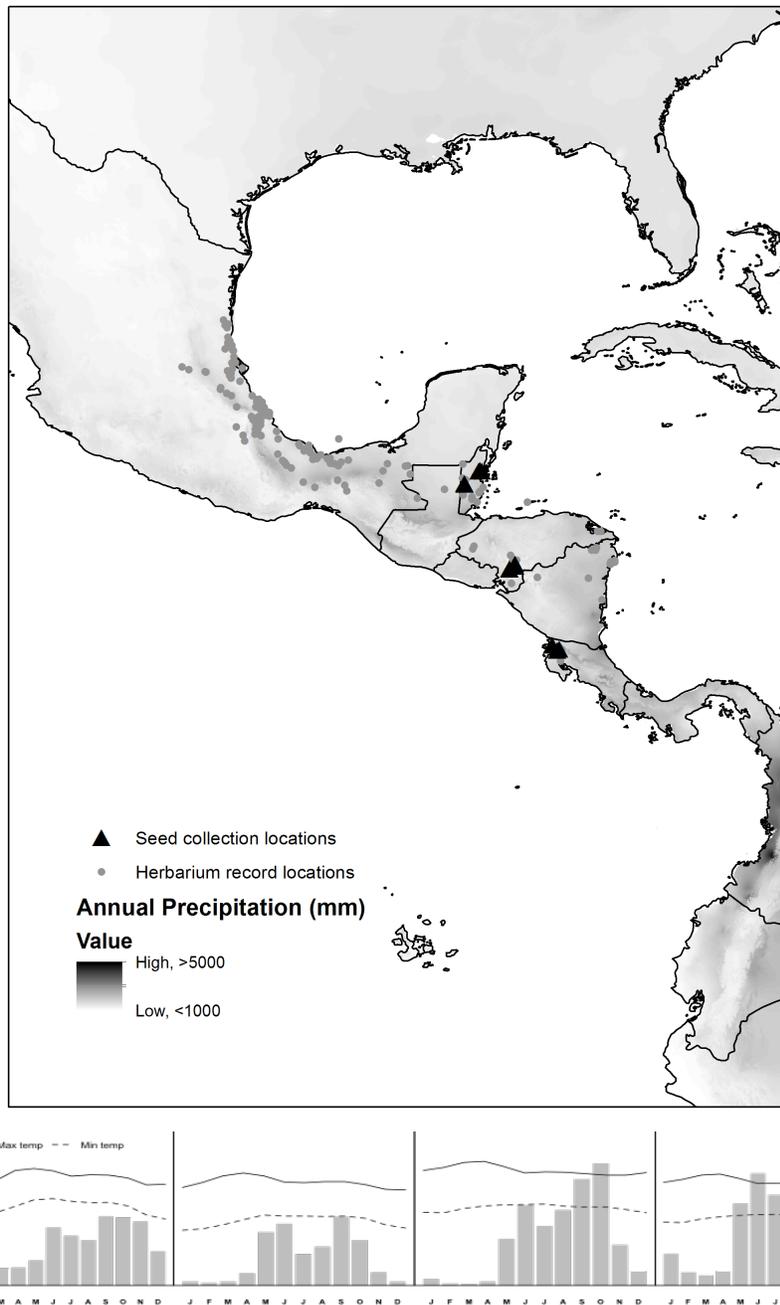


Figure 2.2- Range of *Quercus oleoides* showing historical herbarium records (grey circle) and seed collection sites from four populations throughout the range (Belize, Honduras, Costa Rica high-elevation, Costa Rica low-elevation). Populations throughout the range experience contrasting rainfall patterns (Hijmans et al. 2005).

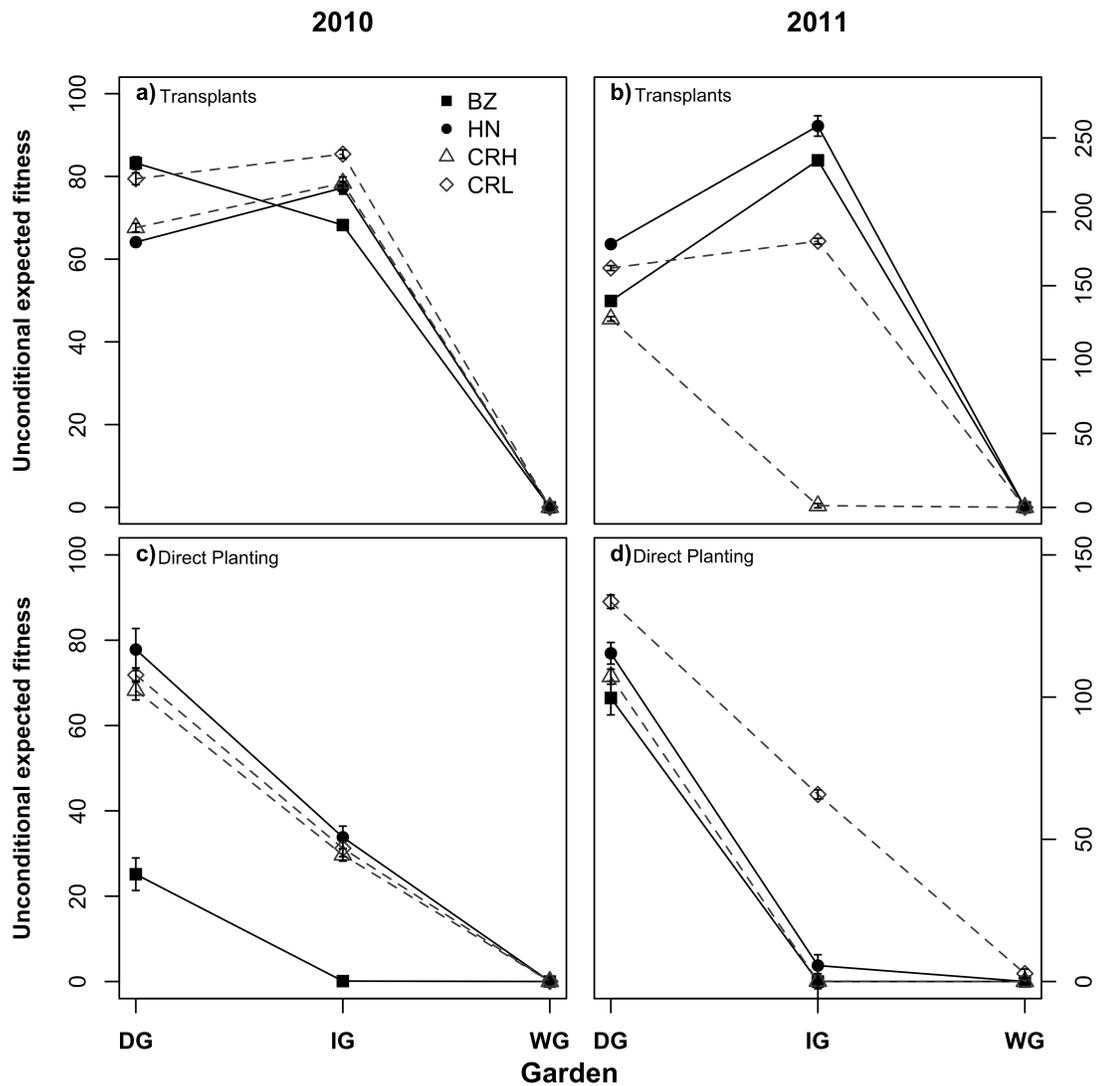


Figure 2.3- Aster predicted mean seedling fitness (\pm SE) from seeds collected from populations of *Q. oleoides* throughout the range (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and planted into common gardens in Honduras (dry garden, DG), Costa Rica low-elevation (intermediate garden, IG), and Costa Rica high-elevation (wet garden, WG). Unconditional expected fitness (with 95% confidence intervals) is the predicted number of leaves of a ‘typical’ individual under the different conditions for **a)** 2010 transplant cohort; **b)** 2011 transplants; **c)** 2010 direct planting; **d)** 2011 direct planting

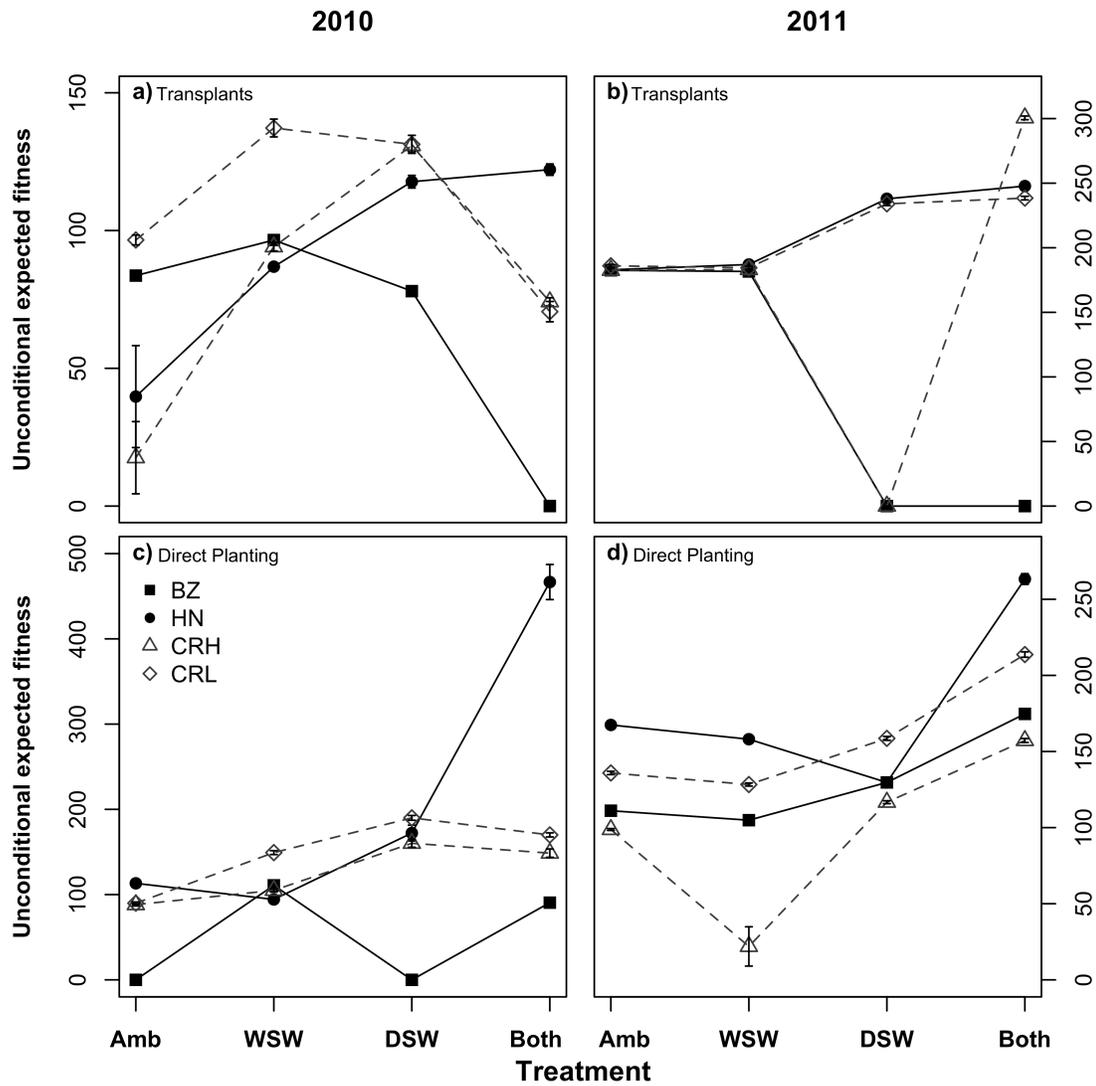


Figure 2.4- Aster predicted mean seedling fitness from seeds collected from populations of *Q. oleoides* throughout the range (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and planted into the common garden in Honduras (dry garden) and administered one of four watering treatments: Ambient, wet season water (WSW), dry season water (DSW) and watered both seasons (Both). Unconditional expected fitness (with 95% confidence intervals) is the predicted number of leaves of a 'typical' individual under the different conditions for **a)** 2010 transplant cohort; **b)** 2011 transplants; **c)** 2010 direct planting; **d)** 2011 direct planting

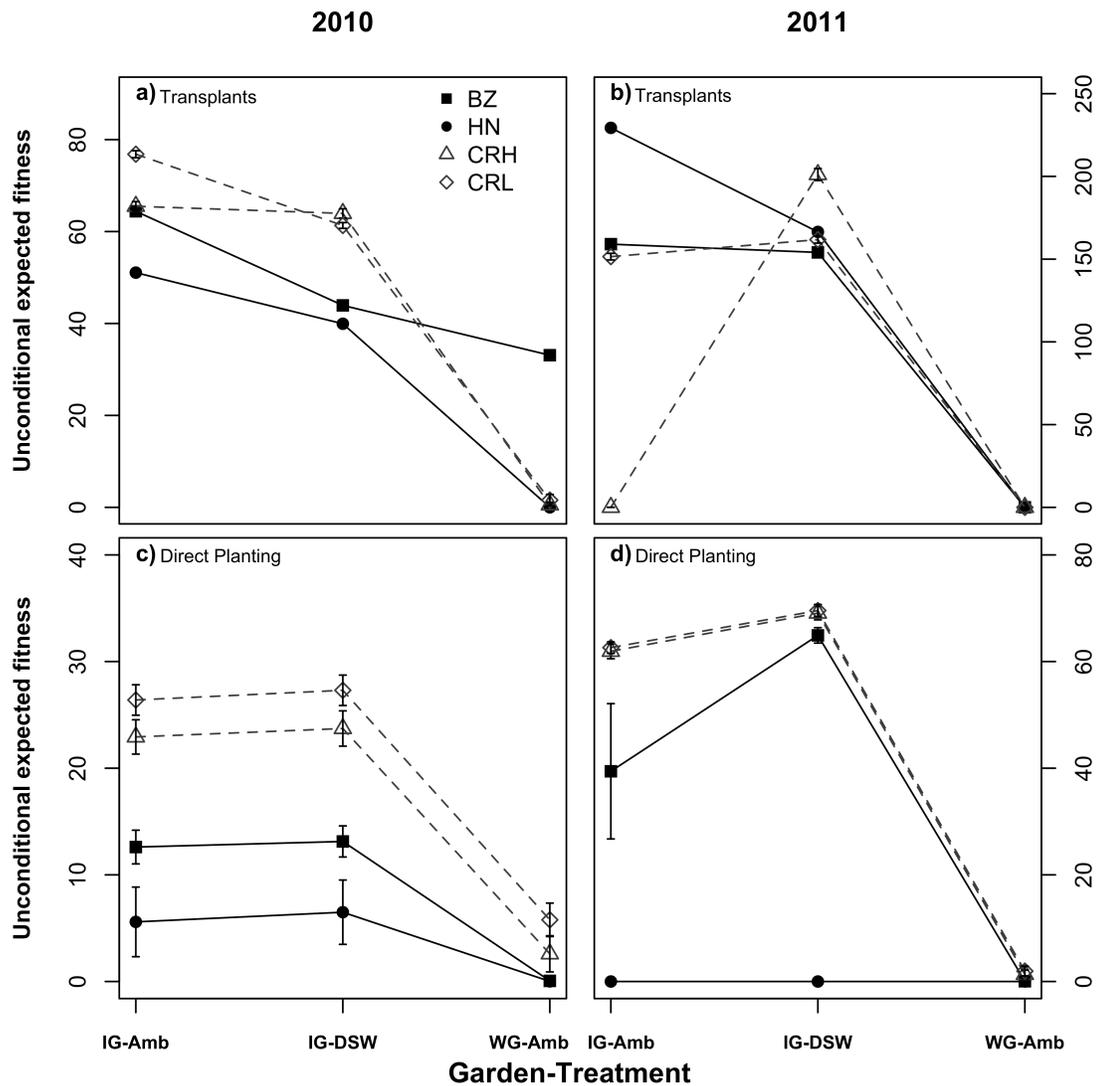


Figure 2.5- Aster predicted mean seedling fitness from seeds collected from populations of *Q. oleoides* throughout the range (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and planted into the common garden into the intermediate and wet gardens in Costa Rica (IG, low-elevation and WG, high-elevation gardens respectively). Unconditional expected fitness (with 95% confidence intervals) is the predicted number of leaves of a ‘typical’ individual under the different conditions for **a)** 2010 transplant cohort; **b)** 2011 transplants; **c)** 2010 direct planting; **d)** 2011 direct planting

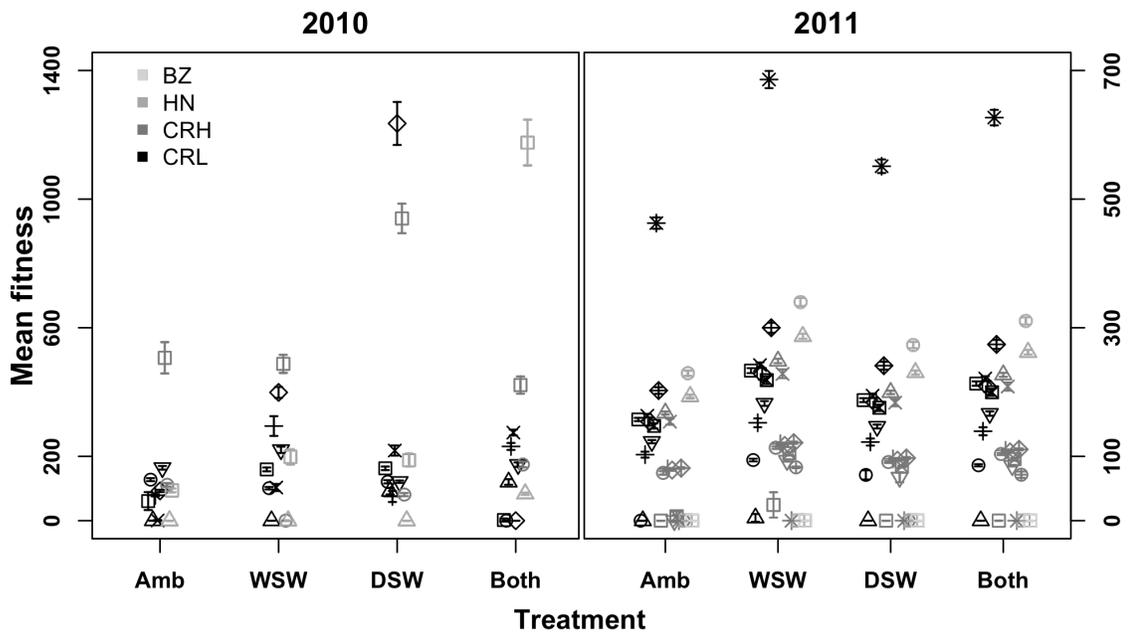


Figure 2.6- Aster predicted fitness of maternal families of *Q. oleoides* seeds collections in 2010 and 2011 from four natural populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and planted into a common garden in Honduras and administered four watering treatments: Ambient, wet season water (WSW), dry season water (DSW) and watered both seasons (Both). Symbols represent a maternal family within each population.

Chapter 3: Selection and plasticity in physiological and morphological traits in tropical live oak seedlings from populations across the seasonal dry forests of Central America

Broadly distributed species incur a wide range of environmental conditions, and populations may respond to this heterogeneity through adaptation to local conditions, high within population genetic diversity, and/or phenotypic plasticity. To explore the extent that populations of the broadly distributed tropical live oak, *Quercus oleoides*, exhibit these strategies we collected seedlings from four populations with contrasting rainfall regimes in Central America and planted them into a common garden in Honduras and two gardens in Costa Rica. Watering treatments were added within gardens to isolate the effects of water availability and drought stress on seedlings. Physiological and morphological traits including maximum photosynthetic rate (A), stomatal conductance (g_s), intrinsic water use efficiency (A/g_s), carbon isotope discrimination ($\delta^{13}C$, integrated water use efficiency), specific leaf area (SLA), stomatal density and stomatal pore index (SPI) were measured on seedlings after two years of growth. We found that seedlings from contrasting populations did not exhibit differentiation in traits related to carbon and water use. All seedlings regardless of population of origin showed high plastic responses in A , g_s and A/g_s to seasonal changes in water availability with significantly higher intrinsic water use efficiency in the dry season. Seedlings exhibited plastic responses in SLA to both seasonal changes in water availability and differences among garden sites. Seedlings showed limited plasticity in $\delta^{13}C$ but significant within-population genetic variation for this trait, though not for other traits measured. We found that selection generally favored increased water use efficiency and lower SLA regardless of season or garden site. Overall, populations of *Q. oleoides* show high survival across treatments and seasons. We conclude that they are well-adapted to the environmental variability and respond to short-term changes in rainfall patterns through phenotypic plasticity. However, they show limited within-population genetic variation for most traits studied, which may limit their adaptive potential to respond to environmental change.

Introduction

Broadly distributed species often span a wide range of environmental conditions. Adaptation to local conditions (Kawecki and Ebert 2004, Savolainen et al. 2007) and/or phenotypic plasticity (Bradshaw 1965, Valladares et al. 2007) are two primary contributors to the persistence of that allow plant populations given this variability. The predictability and scale of environmental heterogeneity is thought to influence the extent to which populations display these two strategies. If environmental variability is coarse-grained, such that individuals in populations experience only a narrow subset of the possible conditions, selection would likely favor those expressing a fixed phenotype that confers high fitness in that environment, resulting in specialization and adaptive differentiation among populations from contrasting environments (Levene 1953, Levins 1962, Weinig 2000). Alternatively, if environmental variability is fine-grained such that individuals in populations experience a broad range of possible conditions, selection may favor phenotypic plasticity, such that different phenotypes are expressed under contrasting environments (Levins 1963, Bradshaw 1965, Schlichting and Levin 1990, Weinig 2000).

Beyond adaptation and plasticity, if selection pressures vary across generations, such that different genotypes are favored at different times, genetic variation within populations may be maintained (Felsenstein 1976, Hedrick 1986, Etterson 2004b). However, the maintenance of additive genetic variance by intergenerational temporal variation is not guaranteed (Bull 1987, Gillespie and Turelli 1989). Long-lived tree species are frequently associated with plastic responses to environmental variability, given their long generation times (Delagrange et al. 2004, Rozendaal et al. 2006, Sack et al. 2006, Valladares et al. 2007, Ramírez-Valiente et al. 2010). However, tree species have also been shown to be well adapted to local conditions (Rehfeldt et al. 1999, Rehfeldt et al. 2002, Ramírez-Valiente et al. 2009). The extent to which populations of long-lived and broadly distributed species display specialization (adaptation to local conditions), high genetic diversity, and/or phenotypic plasticity has consequences for

how they may respond to future environmental changes (Davis et al. 2005, Jump and Peñuelas 2005).

Contrasting selection pressures on fitness-related traits have been shown to result in adaptive phenotypic differentiation among populations in broadly distributed species (Endler 1986, Linhart and Grant 1996, Dudley 1996a, Kittelson and Maron 2001, Kawecki and Ebert 2004). However, differentiation in traits need not be adaptive and may be the result of genetic drift among relatively isolated populations (Gandon and Nuismer 2009). The extent that genetic differentiation in traits is adaptive among spatially structured populations is dependent on the relative strengths of selection and gene flow (Slatkin 1987, Rehfeldt 1999, Storz 2002, Baines et al. 2004). Abiotic factors such as photoperiod (Vaartaja 1959, Heide 1974, Howe et al. 1995), temperature (Partanen et al. 1998, Robakowski et al. 2012), altitude (Housman et al. 2002, Stinson 2004, Premoli et al. 2007), and water availability (Schemske 1984, Bennington and McGraw 1995, Dudley 1996a, Heschel et al. 2002) have been shown to be important selective forces resulting in clinal variation in traits among populations in broadly distributed species.

While local adaptation has been found in many systems, phenotypic plasticity is also commonly found in populations exposed to high environmental variability (Bradshaw 1965, Valladares et al. 2007, Ramírez-Valiente et al. 2015). Phenotypic plasticity, a single genotype's production of a range of phenotypes for a trait in different environments (Bradshaw 1965) has been found to be adaptive (Schlichting 1986, Pigliucci et al. 1995), neutral (Caruso 2004) or maladaptive with observable fitness costs (Scheepens and Stöcklin 2013). Studies of plant species that inhabit heterogeneous environments have found that phenotypic plasticity is common (Weinig 2000, Donohue et al. 2001, Gianoli and González-Teuber 2005), and theory predicts that plasticity should be larger in populations that inhabit more heterogeneous environments (Bradshaw and Hardwick 1989, Alpert and Simms 2002). In the Mediterranean holm oak, *Quercus ilex*, populations were found to respond to thermal and water availability changes through phenotypic plasticity and were not adapted to local conditions (Gimeno et al. 2009). In both xeric and Mediterranean environments, plants have been found to produce leaves

with differing resistances to drought depending on the water availability at the time they were flushed (Ehleringer 1982, Mulkey et al. 1992, Poorter et al. 2009). Furthermore, studies have shown genetic differentiation among populations in their ability to respond plastically to environmental changes (Miller and Fowler 1994, Bennington and McGraw 1996, Donohue et al. 2001). While the role of phenotypic plasticity in population responses to environmental variability has been extensively studied in both Mediterranean and temperate systems, few studies have examined the role of plasticity in broadly distributed and long-lived species of highly seasonal tropical systems (but see (Ramírez-Valiente et al. 2015)).

The extent and mechanisms by which plant populations respond to environmental variability has important implications for their response to global change. Climatic zones to which species are physiologically adapted are predicted to spatially shift with climate change (Etterson 2004b, Parmesan 2006, Lawler et al. 2009, Cavender-Bares et al. 2011, IPCC 2013b). Current models estimate that much of the tropics, including the neotropics of Central America, will be drier by 2100 (IPCC 2013b). Differential drought sensitivity of plants has been shown to directly affect plant species distributions in the tropics (Engelbrecht et al. 2007). Dry season drought in seasonal tropical forests has been found to have large impacts on species survival and growth (Gentry 1988, Veenendaal et al. 1998, Hawkins et al. 2003). Likewise, short dry spells during the wet season have been found to influence seedling survival (Pearson et al. 2003, Engelbrecht et al. 2006), and it remains unclear whether plants are more limited by total annual rainfall or severity of dry season drought.

Compounding the effects of climate change, extensive land-use change, and habitat fragmentation in tropical systems (Malhi and Phillips 2004, Portillo-Quintero and Sanchez-Azofeifa 2010) limit migration and dispersal of many species to regions where they may be better adapted in the future. This constraint on species' ability to spatially shift ranges in response to changing conditions makes *in situ* adaptation and phenotypic plasticity important mechanisms for species persistence.

The goal of this study is to tease apart the relative contributions of genetic and plastic variation in phenotypic trait expression, given the importance of this issue in understanding both the short- and long-term responses of populations to climate change. We explore the ecophysiological and morphological responses of seedlings from different populations of the broadly distributed neotropical live oak, *Q. oleoides*, to changes in seasonal water availability. Given that populations do not exhibit evidence for local adaptation but harbor high variation within population through maternal family performance (chapter 2), we ask: (1) Do seedlings from populations with contrasting rainfall regimes show genetic differentiation in morphological and ecophysiological traits related to carbon and water use according to their population of origin? (2) Does water limitation during the dry season or during dry spells in the wet season have greater impact on physiological function of seedlings? (3) Do seedlings from populations that experience contrasting seasonality of rainfall differ in their plastic responses to changes in water availability, through manipulations of dry season severity, total annual rainfall or both? and (4) How do patterns of natural selection on traits related to carbon and water use vary under different environmental conditions?

Specifically, we hypothesize that:

- 1) populations will exhibit higher within-population variation than among-population variation in traits related to carbon and water use similar to the patterns of variation found in fitness (chapter 2).
- 2) plasticity and genetically based variation within-population will contribute phenotypic variation in physiological and morphological traits related to carbon and water use
- 3) populations with greater seasonal differences in rainfall will display higher levels of plasticity in traits related to water use,
- 4) populations will be limited by both dry season drought and short dry spells during the wet season, and
- 5) phenotypic selection will vary with moisture regime (either seasonally or among water-manipulation treatments). Specifically, we predict that selection will favor trait values conferring high water use efficiency and resistance to

water loss when dry season drought is severe but not in watering treatments that reduce dry season drought severity.

Methods

Common gardens and seed collection-

Seeds from four populations of *Q. oleoides* (Belize- BZ, Honduras-HN, Costa Rica high-elevation-CRH, and Costa Rica low elevation-CRL) were collected in 2009 and shipped to Zamorano University Honduras and Guanacaste Conservation Area in Costa Rica. Populations were chosen from location with contrasting wet and dry season rainfall regimes spanning a large geographical scale. Seeds were collected from a total of 30-50 trees that were at least 50m apart from each population. A total of 37,460 seeds were collected and stored in 3°C refrigerators (unless in transit) until planted into shadehouses or into gardens. Seeds arrived to respective countries after the onset of the dry season; because *Q. oleoides* seeds are nondormant and metabolically active a subset of seeds were germinated in shadehouses in Honduras and Costa Rica in dry seasons of 2010 and 2011 to reduce seed mortality during storage. The remaining seeds that were not planted into shadehouses were stored in refrigerators until the onset of the next wet season and planted directly into common gardens. Seed size was measured at the time of planting, as the seed volume (V), calculated from seed height (h) and diameter (d), assuming an ellipsoid: $V=4/3 \times (d/2)^2\pi+(h/2)$. Volume was converted to seed mass based on the empirical relationship between volume and fresh mass (M) without the seed coat, for 16 oak species: $M=0.636V-0.1213$, $R^2=0.97$ (Cavender-Bares et al. 2004).

Common gardens were established to examine patterns of genetic differentiation and the role of phenotypic plasticity in seedling responses to changes in water availability. One garden was established at Zamorano University in Honduras, the site with the lowest total annual rainfall across the species range and will hereafter be referred to as the ‘dry garden (DG)’. In Costa Rica, two gardens were established near the natural populations where seeds were collected (within 5km); one was established at the low-elevation site (‘intermediate garden (IG)’) in which trees experience a severe dry season but high rainfall during the wet season. The ‘wet garden (WG)’ was established at the

high-elevation site in Costa Rica, the area with the highest annual rainfall throughout the species range (chapter 2).

A subset of collected seeds was planted into shadehouses at the Zamorano University, Honduras and Sector Santa Rosa in the Guanacaste Conservation Area, Costa Rica to increase germination success and later transplanted into the common gardens after the start of the wet season in 2010 (hereafter referred to as the ‘transplant cohort’). The remaining seeds were stored in refrigerators and planted directly into common gardens (hereafter the ‘direct planting’ cohort) at the same time as the transplant cohort. Cohorts were planted near each other but treated as separate experiments. Transplanted seedlings and seeds were planted in a complete block randomized design with seedlings (and seeds) randomized within block and maternal family represented evenly among blocks.

Watering treatments—

Four watering treatments were established at the dry garden: ambient rainfall (‘Ambient’), supplemental watering during the dry season (‘DS Water’ or ‘DSW’), added water during the wet season (‘WS Water’ or ‘WSW’), and a treatment in which water was supplemented during both the dry and wet seasons (‘Both Water’ or ‘Both’). Two watering treatments were established at the intermediate garden: ambient rainfall (‘Ambient’), and supplemented water during the dry season (‘DSW’). The wet garden allowed for only one treatment: ambient rainfall (watering protocol outlined in chapter 2). Decagon soil moisture probes (10HS) were set out in two of the six blocks per treatment at each site in May 2012. Probes were tested for proper calibration according to manufacturers instructions and were installed 30mm beneath the soil surface. Probes were connected to HOBO microstation data loggers (H21-002) and programmed to record volumetric soil water content at six-hour intervals.

Physiological and morphological traits related to carbon and water use—

After two years of growth, physiological measurements were collected on seedlings from both the transplants and directly planted cohorts during the wet season

(June 2012) and dry season (March 2013). Traits related to carbon and water use were chosen based on their known role in drought resistance and amenability to be rapidly collected or quantified in the field. Leaf-level physiological traits, including maximum photosynthetic rate (A), stomatal conductance (g_s), and intrinsic water use efficiency (A/g_s) were measured at saturating light levels using LI-6400 (LiCOR, Lincoln, Nebraska, USA) during the wet season (June 2012) and dry season (March 2013). Gas exchange measurements were conducted between 800 and 1100 hours using a flow rate of $300\mu\text{mol/s}$, light intensity at $1500\mu\text{mol m}^{-2} \text{s}^{-1}$, ambient CO_2 concentrations, and humidity was controlled within a range of 60-75%. Measurements were taken on the newest fully developed leaf for each plant and three measurements were taken per leaf after A had reached the asymptote. Due to equipment malfunction, gas exchange measurements were only collected on seedlings at the dry garden. Additionally at the dry garden, leaf water potential was measured in all plants with more than 25 leaves at predawn and midday on the same day gas exchange measurements were collected. Leaves were removed from plants and immediately put into a moist bag and cooler until measured. All leaves were processed within 1.5 hours of collection and showed no evidence of a time effect on leaf water potential.

Specific leaf area (SLA) is defined as the leaf area divided by dry leaf mass. A low SLA, resulting from thicker leaves, higher leaf density or a combination of both, is a good indicator of stress tolerance (Weiher et al. 1999, Wright et al. 2004). Leaves were collected from seedlings in all gardens during the wet season 2012 and dry season 2013 and dried at 60°C immediately after collection. To maintain consistency in SLA measurements and reduce error due to leaf folding or shrinkage, all leaves were treated identically; leaves were pressed during drying and similar aged leaves were used for all measurements (Gilmore et al. 1995, Nageswara Rao et al. 2001, Queenborough and Porras 2013). SLA leaves were shipped to the University of Minnesota where they were scanned and weighed. ImageJ (National Institutes of Health, version 1.46) was used to measure leaf lamina area.

Leaves were also collected for carbon isotope discrimination (ratio of $^{13}\text{CO}_2/^{12}\text{CO}_2$, $\delta^{13}\text{C}$). Leaves collected for $\delta^{13}\text{C}$ were shipped to Cornell Isotope Laboratory

directed by Dr. Jed P. Sparks to be processed for $\delta^{13}\text{C}$ composition. Stable carbon isotope ratio is quantified as the difference between foliar $\delta^{13}\text{C}$ and atmospheric CO_2 and has been shown to be empirically correlated with long-term water use efficiency (Farquhar et al. 1989). Since seedlings from both Honduras and Costa Rica gardens were planted at the same time and in open pastures, we assume that differences in $\delta^{13}\text{C}$ in the air are negligible between the two sites. $\delta^{13}\text{C}$ provides an integrated measure of water use efficiency because both water use efficiency (WUE) and $\delta^{13}\text{C}$ depend on intercellular concentration of CO_2 (C_i). Low C_i may reflect high carboxylation efficiency, or more commonly low stomatal conductance (Larcher 2003). Foliar nitrogen was quantified to estimate carboxylation capacity and was included as a covariate in analyses of $\delta^{13}\text{C}$. Other factors known to influence $\delta^{13}\text{C}$ through intercellular CO_2 concentration include light, vapor pressure deficit, and mesophyll resistance (Farquhar et al. 1989, O'Leary et al. 1992, Cavender-Bares and Bazzaz 2000).

Stomatal density (SD) and stomatal pore index (SPI) were measured on leaves collected in the dry season 2013. Stomatal peels were made on the abaxial surface of fresh leaves immediately after collection using nail polish and tape to fix peels to microscope slides. Slides were shipped to the University of Minnesota and processed using light microscope under the 40x objective with a Nikon camera set up and SPOT software and calibrated at 540 pixels= 0.1mm. Image J was used to count stomata at three locations per leaf, avoiding leaf veins. Stomatal density was calculated as the number of stomata in the field of view divided by the area of the field of view using 40x objective (0.066mm^2). Stomatal pore index (SPI, a dimensionless index of stomatal area per lamina, Sack et al. 2003) was also calculated as, $\text{SPI} = \text{guard cell length}^2 \times \text{SD}$ because it has been shown to correlate with plant hydraulic conductance (Hubbard et al. 2001, Sack et al. 2005). Stomata on the edges were included if more than 50% of the guard cells surrounding the stomatal pore were visible.

Statistical Analyses—

Analyses of leaf-level physiological and morphological traits related to carbon and water use were conducted using mixed effects models. Data were subset and the

ambient rainfall water treatments (from all sites) were analyzed jointly and then separate analyses were conducted within each garden to examine the effects of changes in water availability on physiological and morphological traits. The two 2010 cohorts (transplants and direct planting) were analyzed separately. At the dry garden (HN site), traits included maximum photosynthetic rate (A), stomatal conductance (g_s), intrinsic WUE (A/g_s), integrated WUE ($\delta^{13}C$), specific leaf area (SLA), stomatal density (SD), and stomatal pore index (SPI). Traits included in the analyses across garden sites (ambient rainfall blocks only) were SLA, $\delta^{13}C$, SD and SPI. Analyses of traits in seedlings from the transplant cohort of *Q. oleoides* seedlings were modeled as:

$$(1) R_{ijklmn} = T_i + P_j + S_k + SM + L + H + T_i * P_j + MF_l(P_j) + ID_m(MF_l(P_j)) + B_n(T_i) + \epsilon_{ijklmno}$$

with treatment (or garden, T) i, population (P) j, season (S) k, seed mass (SM), size at transplanting (L), and herbivory (H) as fixed effects. Maternal family (MF) l (nested in population j), seedling (ID) m nested in maternal family l, nested in population j, and block (B) n nested in treatment I as random effects, and ϵ representing the residuals for plot o. Additional covariates were included when appropriate; time of day and machine were included as covariates for leaf-level gas exchange measurements. Foliar nitrogen was included as a covariate in the analyses of $\delta^{13}C$.

Analyses of the physiological and morphological traits in seedlings from the directly planted cohort were similar to the transplants and were modeled as:

$$(2) R_{ijklmn} = T_i + P_j + S_k + SM + T_i * P_j + MF_l(P_j) + ID_m(MF_l(P_j)) + B_n(T_i) + \epsilon_{ijklmno}$$

with treatment (or garden, T) i, population (P) j, season (S) k, and seed mass (S), as fixed effects. Maternal family (MF) l (nested in population j), seedling ID m nested in maternal family l nested in population j and block (B) n (nested in treatment i) as random effects, and ϵ representing the residuals for plot o. The same covariates used for the 2010 transplant models (except size at transplanting) were included when appropriate for the direct planting models. Additionally, for traits that were measured during both the dry

and wet season, genetic variation within populations was assessed through differences among maternal families (significant maternal family random effect) in mean traits values within a treatment (and season). Genetic variation in trait plasticity was assessed using an interaction term between season and maternal family, which if significant would indicate that maternal families differed in the alteration of their phenotypes in response to changes in environmental conditions (seasonal water availability). Seedling ID was included as a random effect in models where traits were measured on plants during both the dry and wet season to account for the correlation of residuals within an individual between seasons.

Phenotypic selection analyses were conducted on the transplant cohort but not the direct planting cohort due to limitations in sample size. Aster models were used to assess phenotypic selection on morphological and physiological traits related to carbon and water use (Shaw et al. 2008). The graphical model to estimate seedling fitness was leaf count at the end of the experiment (Dec. 2013) conditional on survival to Dec. 2013. Analyses were conducted both within each garden site to examine how differences among watering treatments influenced patterns of selection. Analyses were also conducted across gardens sites (including on the ambient rainfall blocks at each site) to assess regional differences in selective pressures. Populations were pooled to ensure ample sample sizes and expand phenotypic distribution of traits. Principal component analysis and variance inflation factors were used to reduce data dimensionality due to multicollinearity of predictor variables. Prior to analyses of fitness landscapes using Aster models, a linear model was constructed by regressing final leaf number on traits to examine correlation among traits. Variance inflation factors were estimated using the 'vif' function in 'MASS' package and variables with inflation factors greater than five were not included in the selection analyses (Hsieh et al. 2003). After examining interdependence of variables, the traits included in selection analyses were intrinsic WUE (A/g_s , included only in analyses within dry garden site), carbon isotope discrimination ($\delta^{13}C$), and specific leaf area (SLA).

Traits were standardized to be centered on zero and have a standard deviation of one prior to analysis. Individual expected fitness was predicted from the Aster models

and used for the selection analyses. Partial selection gradients (β') were estimated from the slope of regressing predicted individual relative fitness (individual fitness divided by mean fitness for treatments/season) on standardized trait values as a measure of direct selection on traits (Lande and Arnold 1983, Shaw and Geyer 2010). Due to limitations in sample sizes at the dry garden site, quadratic regressions were not included in those analyses, but were able to be included in the selection analyses of $\delta^{13}\text{C}$ and SLA at the intermediate and wet garden analyses. Separate multiple quadratic regressions were used to assess nonlinear (stabilizing/disruptive) selection, which included the cross-product terms between traits to examine joint selection. Linear mixed models were used for selection analyses with block and maternal family (nested in population) as random effects. Aster models were used to estimate the fitness landscape using backward nested model comparison (Shaw et al. 2008, Shaw and Geyer 2010).

Results

Climate, watering treatments, soil water content, leaf water potential

Meteorological data from stations at Zamorano University (Honduras, dry garden site) and Sector Santa Rosa in the Guanacaste Conservation Area (Costa Rica- low elevation, intermediate garden) showed site differences in both total annual rainfall and dry season severity from 2000-2014 (Fig. 3.1a, b). Mean monthly minimum and maximum temperatures were slightly higher at the dry garden site and weather patterns at the two sites during the experiment (2010-2013) were comparable to decadal trends. Volumetric soil moisture measurements at the intermediate and wet gardens showed that soil moisture levels were consistently higher at the wet garden site (Fig. 3.2a). Added water during the dry season at the intermediate garden (IG-DSW) increased volumetric soil moisture to levels similar to the wet garden site. There were numerous spikes in soil moisture ($0.50\text{m}^3/\text{m}^3$) at both the intermediate and wet gardens during the wet seasons, consistent with rainfall events and saturating soil conditions. Watering treatments at the dry garden that increased water levels during the dry season ('DSW' and 'Both' treatments) increased volumetric soil moisture during the dry season (Fig. 3.2b). However, treatments aimed to increase water availability in the wet season ('WSW' and

‘Both’) did not increase volumetric soil moisture above ambient levels. All treatments had similar soil moisture values during the wet season at the dry garden site.

Predawn and midday leaf-level water potential measurements on seedlings from the transplant cohort at the dry garden showed no differences among treatments in the wet season (Table 3.1, Fig. 3.3a, b). However, transplant cohort seedlings in treatments that increased water availability during the dry season (‘DSW’ and ‘Both’) showed significantly higher (less negative) predawn water potential suggesting that treatments did increase plant available water. By midday, all seedlings from the transplant cohort exhibited similar leaf-level water potential measurements during the dry season regardless of treatment. Interestingly, watering during the dry season did not influence leaf predawn water potential of seedlings from the direct planting cohort (Fig. 3.3c). Directly planted seedlings exhibited significantly lower midday water potentials, on average, in the dry season than in the wet season across treatments (Fig. 3.3d). There was a significant treatment by population interaction with seedlings from CRH (Costa Rica high-elevation) exhibiting significantly higher midday leaf water potentials in the ‘Both’ treatment, and there were no differences among populations in the other three treatments (Appendix 3- Table S3.1).

Test of genetic differentiation in traits from nursery transplanted seedlings in ambient rainfall plots across sites-

We did not find strong evidence for differentiation among *Q. oleoides* populations with contrasting rainfall regimes in SLA, $\delta^{13}\text{C}$ (although marginally significant), SD or SPI (Table 3.2, Fig. 3.4a-d, Appendix 3- Table S3.2). On average, populations exhibited plastic responses to site differences, indicated by significant garden effects for all traits except SLA. There was a marginally significant interaction between garden and population for $\delta^{13}\text{C}$ (DF=6, $\chi^2=13.76$, $P=0.08$) but not SLA, suggesting that seedlings from contrasting populations have differential capacities to respond plastically to environmental changes for $\delta^{13}\text{C}$ but not SLA. On average, seedlings from BZ and HN populations exhibited higher (less negative) $\delta^{13}\text{C}$ compared to both high and low elevation CR populations at the dry garden, but there were no differences among

populations at either the intermediate or wet gardens. Garden by season interaction was significant for both $\delta^{13}\text{C}$ (DF=2, $\chi^2= 10.98$, $P=0.004$) and SLA (DF=2, $\chi^2= 36.31$, $P<0.001$). For SLA, seedlings had significantly higher mean SLA values during the wet season at the dry garden but there were no seasonal differences among seedlings at either the intermediate or wet gardens (Fig. 3.4a, *post-hoc contrasts*, Appendix 3- Table S3.3). For $\delta^{13}\text{C}$, the opposite pattern was found; there were no detectable seasonal differences in mean trait values at the dry garden but seedlings at both the intermediate and wet gardens had significantly lower (more negative) mean $\delta^{13}\text{C}$ values during the dry season (Fig. 3.4b, *post-hoc contrasts*, Appendix 3- Table S3.3). Additionally, there was a significant population by season interaction for SLA (DF= 3, $\chi^2= 9.95$, $P=0.02$, *post-hoc contrasts*, Appendix 3-Table S3.4) but not $\delta^{13}\text{C}$. Maternal family was not significant for SLA suggesting limited within population genetic variation for this trait. Maternal family (MF) was significant for $\delta^{13}\text{C}$ but there was not a significant season by MF interaction indicating that seedlings from different maternal families did not differ in their ability to plastically respond to changes in seasonal water availability. Population was not a significant factor in SD or SPI but there was a significant garden effect for SD and SPI. On average, seedlings at the wet garden had significantly lower SD but high SPI. SPI was lowest for seedlings at the intermediate garden. The inconsistency between SD and SPI is likely due to stomatal pore length in which seedlings had fewer but larger stomata in the wet garden and at the intermediate garden seedlings had a high density of smaller stomata (Appendix 3-Table S3.5, Fig. S3.1).

Results from the directly planted cohort seedlings also showed no evidence that populations exhibit differentiation in traits related to carbon and water use. Although seedlings from the directly planted cohort exhibited less capacity to respond plastically to changes in environment, results generally support findings from the transplant cohort (Appendix 3- Tables S3.6&3.7, Fig. S3.2).

Effects of water limitation on physiological function of seedlings—dry garden

Analyses of gas exchange traits measured on seedlings from the transplant cohort at the dry garden site revealed significant main effects of population and season on A, g_s ,

and A/g_s (Table 3.3, Fig 3.5a-c, Appendix 3- Table S3.8). There were no differences among treatments in any traits during the wet season (*post-hoc* contrasts, Appendix 3- Table S3.9). Significant main effect factors were also involved in interactions so we restrict our interpretation to those interactions. There was a significant treatment by season interaction for A , g_s , and A/g_s , with seedlings in treatments that increased water availability during the dry season ('DSW' and 'Both') exhibiting higher mean trait values during the dry season for A and g_s and thus lower A/g_s . Furthermore, a *post-hoc* examination of maximum photosynthetic rate on a leaf area (A_{area}) and leaf mass (A_{mass}) basis also indicates that A_{mass} and A_{area} measured during the dry season increased in treatments that raised dry season water availability. However, there were no detectable differences between seedlings in the DSW and Both treatments suggesting that dry season drought is more limiting than total annual water availability (Appendix 3- Tables S3.S10 & S3.11, Fig. S3.3) We found a significant population by season interaction for A and g_s but not A/g_s . Across treatments, seedlings from both CR populations had significantly lower mean trait values compared to seedlings from BZ and HN during the dry season but there were no differences among populations during the wet season (*post-hoc* contrasts- Appendix 3- Table S3.12).

Mixed effects analyses of traits reflecting longer-term responses of seedlings to environmental conditions, $\delta^{13}C$ and SLA (but not SD) had significant main effects of population and season (Table 3.3, Fig. 3.5d-f, Appendix 3- Table S3.13). There was a significant treatment by season interaction for $\delta^{13}C$ but not SLA. Overall, there were no differences in mean $\delta^{13}C$ values among seedlings in the treatments during the wet season, but in the dry season seedlings in treatments that reduced dry season severity had significantly lower (more negative) $\delta^{13}C$ values on average (*post-hoc* contrasts, Appendix 3- Table S3.9), indicating more discrimination against the heavy isotope and lower integrated WUE with increasing water availability. Interestingly, the only factors found to influence SD were plant size at time of transplanting and block (Fig. 3.5f). For all traits, block was significant but maternal family was not (except for $\delta^{13}C$), such that no genetic variation was detectable for most traits related to carbon and water use. The maternal family by season interaction for $\delta^{13}C$ was not significant, indicating no variation

among maternal families in their plastic responses to seasonal changes. Foliar nitrogen did not influence $\delta^{13}\text{C}$. Herbivory had a significant negative impact on all traits except $\delta^{13}\text{C}$ and SPI. Plant size at transplanting had a significant positive impact on $\delta^{13}\text{C}$, SLA, SD and SPI. Time of collection significantly influenced A but not g_s or A/g_s , and machine was significant for g_s and A/g_s traits included using gas exchange measurements.

Analyses of the 2010 direct planting cohort differed somewhat from the transplant cohort but were consistent with the findings that seedlings exhibit high plastic response to seasonal changes (Appendix 3- Tables S3.14-S3.16, Fig. S3.4).

Effects of water limitation on physiological function of seedlings—intermediate and wet gardens

Seedlings from the transplant cohort at the intermediate and wet gardens in Costa Rica exhibited different responses to seasonal changes and to manipulations of dry season drought severity than seedlings at the dry garden. There was a significant season main effect for SLA and $\delta^{13}\text{C}$ but main effects of population and treatment were not significant (Table 3.4, Fig. 3.6, Appendix 3-Table S3.17). There was a significant interaction between treatment and season for both SLA, and $\delta^{13}\text{C}$. Contrary to patterns behind the interaction at the dry garden, seedlings in both treatments (IG-Amb and IG-DSW) at the intermediate garden exhibited significantly higher SLA mean trait values during the dry season but there were no seasonal differences in mean SLA among seedlings at the wet garden (WG-Amb treatment, *post-hoc contrasts*, Appendix 3- Table S3.18). Seedlings in the WG-Amb and IG-Amb treatments had significantly higher wet season mean $\delta^{13}\text{C}$ values, but there were no seasonal differences detected when water was supplemented during the dry season at the intermediate garden (IG-DSW treatment). Additionally there was a significant population by treatment interaction for $\delta^{13}\text{C}$ but these differences are averaged across season and we do not attempt to interpret their meaning. The only significant factor influencing SD was treatment, with seedlings in either treatment at the intermediate garden exhibiting higher stomatal densities on average than seedlings at the wet garden. The only factors that influenced SPI were block and seed mass. Block was significant for all traits and maternal family was significant for $\delta^{13}\text{C}$ but season by

maternal family was not significant for SLA or $\delta^{13}\text{C}$ providing no evidence that maternal families differ in plastic responses to seasonal changes. Leaf nitrogen had a significant positive effect on $\delta^{13}\text{C}$ indicating that carboxylation capacity did influence $\delta^{13}\text{C}$ signatures.

Seedlings from the direct planting cohort at the intermediate and wet gardens exhibited slightly different trends than the transplant cohort in those gardens. Treatment main effect was significant for SLA and SPI but not $\delta^{13}\text{C}$ or SD. For both SLA and SPI, seedlings at the wet garden had significantly higher mean trait values than seedlings in either treatment at the intermediate garden (Appendix 3- Tables S3.19 & S3.20, Fig. S3.5). There was not a significant effect of population for any trait nor was population involved in any significant interactions. Season main effect was not significant for SLA or $\delta^{13}\text{C}$ but there was a significant interaction between treatment and season for $\delta^{13}\text{C}$ (DF=2, $\chi^2 = 17.38$, $P < 0.001$). Seedlings in both treatments at the intermediate garden exhibited significantly higher $\delta^{13}\text{C}$ values during the dry season than the wet season on average but the converse was found at the wet garden with seedlings having higher mean $\delta^{13}\text{C}$ during the wet season (*post-hoc contrasts*, Appendix 3- Table S3.21). While results from the direct planting cohort differ from the transplant cohort, they do not provide evidence for differentiation among populations or that populations exhibit high within-population genetic variation for traits.

Test of changes in phenotypic selection across sites

Phenotypic selection analyses of $\delta^{13}\text{C}$ and SLA in the ambient rainfall treatments across gardens indicate that selection is generally in the same direction across seasons and sites (Table 3.5, Fig. 3.7). Regardless of site or season, seedlings with higher $\delta^{13}\text{C}$ values were favored by selection, except in the wet garden during the dry season where directional selection was not detected. Furthermore, seedlings with lower SLA values had a significant fitness advantage on average (except wet garden during the wet season, no direct selection detected). The shape of selection surfaces differed somewhat across sites and season. At the dry garden site, γ_{ii} for $\delta^{13}\text{C}$ was positive regardless of season and negative at the intermediate garden during the dry season. However, visualization of

selection surfaces of the observed data do not support the interpretation of stabilizing or disruptive selection because the maximum (or minimum) occurred at the edge of the phenotypic distribution for every garden (Fig. 3.7). γ_{ii} for SLA was only detected at the dry garden during the wet season and was positive. Visualization of the selection surface supports the interpretation of disruptive selection as the minimum is at the intermediate phenotypes and not the edge of the distribution. Joint selection that favored combinations of $\delta^{13}\text{C}$ and SLA beyond direct selection alone was found at the dry and intermediate gardens regardless of season but was not detected at the wet garden. When significant, γ_{ij} was negative across gardens and seasons with selection favoring individuals with phenotypes associated with high water use efficiency and drought resistance, higher $\delta^{13}\text{C}$ and lower SLA values on average.

Test of changes in phenotypic selection with moisture regime- dry and intermediate gardens

Phenotypic selection analyses at the dry garden site indicate that patterns of selection on traits were relatively consistent across seasons and watering treatments for $\delta^{13}\text{C}$ (except in the WSW treatment) and SLA but not A/g_s (Table 3.6). There was significant directional selection for higher intrinsic water use efficiency (A/g_s) for seedlings in the ambient and WSW treatments regardless of season. No directional selection was detected for A/g_s during the wet season in the 'Both' treatment but β was negative during the dry season (nested model comparison of season \times A/g_s -DF=1, Dev=5.87, P=0.02). Selection consistently favored seedlings with higher $\delta^{13}\text{C}$ values in all treatments regardless of season, except in the WSW treatment where selection favored lower $\delta^{13}\text{C}$ in both seasons. Seedlings exhibiting lower SLA values on average had a significant fitness advantage regardless of season or treatment.

Phenotypic selection analyses between the two treatments at the intermediate garden revealed that patterns of selection on $\delta^{13}\text{C}$ differed between seasons in the DSW treatment but not in the ambient treatment (Table 3.7, Fig. 3.8). Selection favored plants with lower $\delta^{13}\text{C}$ during the wet season and higher $\delta^{13}\text{C}$ during the dry season in the DSW treatment (season \times $\delta^{13}\text{C}$, DF=1, Dev=6.68, P<0.01). But selection consistently favored

individuals with high $\delta^{13}\text{C}$ values on average in the ambient treatment in both seasons. Selection on $\delta^{13}\text{C}$ also differed between treatments during the wet season (treatment \times $\delta^{13}\text{C}$, $\text{DF}=1$, $\text{Dev}=134.51$, $P<0.001$) but not dry season. Selection favored individuals with higher $\delta^{13}\text{C}$ in the ambient treatment but lower $\delta^{13}\text{C}$ in the DSW treatment during the wet season. Selection consistently favored plants with thicker leaves at the intermediate garden, regardless of treatment or season. Joint selection on traits generally favored individuals with higher $\delta^{13}\text{C}$ and lower SLA (except in the DSW treatment during the wet season).

Discussion

Collectively, results from this study indicate that populations of *Q. oleoides* exhibit high tolerance to dry season drought and to changes in water availability but do not show clear and consistent differences among populations in traits related to carbon and water use. These results are consistent with previous findings that populations of *Q. oleoides* are not adapted to specific local conditions but exhibit broad environmental tolerances in relation to seedling fitness (chapter 2). Contrary to the significant within-population genetic variation found for fitness (chapter 2), we found that plasticity contributes more to phenotypic trait variation than within population genetic differences. Seedlings from populations that experience higher seasonality in rainfall exhibited greater plastic responses in instantaneous physiological traits. However, we did not find consistent evidence that populations differ in their plastic responses in integrated measures of carbon and water use based on their population of origin. Phenotypic selection in ambient rainfall plots generally favored individuals exhibiting trait values associated with increased integrated water use efficient (higher $\delta^{13}\text{C}$) and thicker (lower SLA) leaves regardless of season or environment. Seedlings from populations of *Q. oleoides* throughout Central America appear to be well situated to tolerate dry season drought and changes in water availability in the short-term through plasticity but may be limited in their adaptive capacity to respond to environmental change.

Variation in traits related to carbon and water use

Ecotypic differentiation in morphological and physiological traits has been found among populations of Mediterranean oak species (Balaguer et al. 2001, Ramírez-Valiente et al. 2010, Peguero-Pina et al. 2014) and in xanthophyll pigments of *Q. oleoides* populations (Ramírez-Valiente et al. 2015). However, we do not find evidence of differentiation among populations in traits measured in this study. Consistent with other studies on drought responses of oak seedlings, including *Q. oleoides* (e.g, Cavender-Bares et al 2007; Ramírez-Valiente et al. 2015), we found that seedlings exhibit high plasticity in leaf level traits. We find little evidence that populations harbor significant genetic variation for most traits related to carbon and water use.

All seedlings, regardless of population of origin, responded similarly to changes in environmental conditions (site) but not to seasonal changes in water availability. At the dry garden, seedlings from both CR populations (where seasonal rainfall difference is the largest) exhibited significantly greater plastic responses to seasonal changes with greater reductions in A and g_s on average compared to seedlings from either BZ or HN. These results agree with predictions that phenotypic plasticity should be greater in populations from more heterogeneous environments (Bradshaw and Hardwick 1989, Alpert and Simms 2002, Gianoli and González-Teuber 2005). While the direction of plastic responses is consistent with ecophysiological expectations (Cavender-Bares et al. 2007), this does not imply that it is adaptive. One way to test whether phenotypic plasticity is adaptive is to conduct selection analyses across environments by regressing fitness on trait values expressed by genotypes (Pigliucci and Schlichting 1996). In this approach, plasticity may be seen as adaptive if individuals with greater plastic changes in trait values in the stressful environment are associated with fitness advantages (Heschel et al. 2002, Gianoli and González-Teuber 2005). Limitations in sample size did not allow us assess whether this differentiation among populations reflects adaptive divergence. Furthermore, while seedlings from CR populations exhibited reduced A and g_s on average in response to drought this did not result in a significant increase in intrinsic water use efficiency. Seedlings from all populations exhibited significantly higher A/g_s in the dry season, which is consistent with the direction of selection gradients using standardized trait values during the dry season at the dry garden. Our results show the direction of

standardized selection gradients is consistent with the direction of seedling plastic responses to drought suggesting that higher plasticity in A/g_s may be adaptive (Dudley 1996a).

In general, seedlings did not exhibit differentiation in $\delta^{13}\text{C}$ nor did they exhibit high plasticity in $\delta^{13}\text{C}$ in response to seasonal changes in water availability. Although supplemental watering during the dry season increased gas exchange rates and decreased intrinsic water use efficiency, this pattern was not reflected in integrated water use efficiency. The lack of clear seasonal differences of $\delta^{13}\text{C}$ in seedlings could be due to $\delta^{13}\text{C}$ reflecting a bias towards carbon assimilation at the time of leaf production. This known bias may make determination of differences in seasonal water use efficiency problematic in species that only flush leaves once or twice during a growing season (Cavender-Bares and Bazzaz 2000). *Quercus oleoides* seedlings do not produce leaves during the dry season but rather will produce new leaves primarily at the beginning of the wet season (Janzen 1983), though they may opportunistically produce leaves throughout the wet season (personal observation). Other studies have shown that once leaves are fully mature, $\delta^{13}\text{C}$ leaf signatures may not change even through the progression of drought (Damesin et al. 1998), which could explain the lack of strong seasonal differences in $\delta^{13}\text{C}$. Further research that examines the relationship between leaf production phenology, water availability and associated leaf isotopic signatures is needed to understand how $\delta^{13}\text{C}$ varies across leaf cohorts in wet and dry season leaves of *Q. oleoides* seedlings.

Although seedlings exhibited little plasticity in response to seasonal changes, they did exhibit plastic responses in $\delta^{13}\text{C}$ to environmental differences between the gardens. All seedlings, regardless of population of origin, exhibited significantly lower (more negative) $\delta^{13}\text{C}$ at the intermediate and wet gardens compared to the dry garden. These results suggest that the lower annual rainfall at the dry garden results in all seedlings, regardless of population of origin, having higher water use efficiency (higher $\delta^{13}\text{C}$) on average, although we cannot rule out other differences between sites. Maternal families differed in $\delta^{13}\text{C}$, indicating significant within population genetic variation for $\delta^{13}\text{C}$ and

future studies investigating the underlying components of genetic variance would provide insight into the adaptive capacity of populations to changes in rainfall patterns.

Overall, mean seedling SLA values at the gardens were similar in magnitude and range for other evergreen species in tropical dry forest systems (Chaturvedi et al. 2011). Similar to findings by Mulkey (1992), seedlings at the dry garden had significantly lower SLA during the dry season indicating higher drought resistance. Studies investigating the relationship between drought stress and leaf mass area (LMA) have shown that leaves produced under water stress have smaller and more tightly packed cells reducing intercellular air spaces (Maximov and Yapp 1929, Shields 1950) and/or they have thicker cell walls conferring higher resistance to water loss (Poorter et al. 2009). At the intermediate and wet gardens seedlings exhibited either significantly higher mean SLA during the dry season or there were no detectable seasonal differences. Studies of LMA and waterlogging have shown that saturation of roots and extended periods of anaerobic conditions impede water uptake in some species resulting in water stress at the shoot and leaf levels. In these cases, waterlogging has been found to be associated with higher LMA and thus lower SLA (Poorter et al. 2009). Given that wet season rainfall levels in Costa Rica are the highest in the range of *Q. oleoides*, seedlings may undergo extended periods of soil saturation and stress associated with waterlogging. These extended periods of waterlogging could explain the results that seedlings produced leaves with high mean SLA in the wet season or the lack of seasonal differences in SLA at the Costa Rica gardens. Waterlogging could also explain the significantly lower SPI in seedlings at the intermediate garden given the poor draining soils and shallow bedrock depth at the intermediate garden (personal observation). Lower SPI and thus lower stomatal area has been found in other species in response to prolonged waterlogging (Savage and Cavender-Bares 2012). However, our SPI was significantly higher in seedlings at the wet garden than at the intermediate garden, which is not consistent with expectations of the effects of waterlogging on SPI. Here, high herbivory may underlie the low SLA since thicker leaves provide more protection from herbivore damage (Poorter et al. 2004) and are associated with increased longevity of other species with sclerophyllous leaves (Wright and Cannon 2001). Soils at the wet garden are moderately well-drained (and

better drained compared to the intermediate garden). Given that it is the site with the highest annual rainfall, the overall high SPI in seedlings is likely associated with increased hydraulic conductance (Sack et al. 2005), and leaves are able to support higher flux and gas exchange rates.

Seedlings limited by dry season drought severity

Seedlings exhibited greater plastic responses to seasonal changes in water availability than to site differences or watering treatments within sites. Manipulations of dry season drought severity revealed that seedlings maintained higher gas exchange rates when water was supplemented during the dry season. These results indicate that dry season drought limits carbon uptake; however, unlike other studies of tropical dry forest systems (Gentry 1988, Veenendaal et al. 1998, Hawkins et al. 2003) increasing dry season drought severity did not significantly reduce seedling survivorship (chapter 2). The high plasticity in gas exchange traits in *Q. oleoides* seedlings is consistent with results from Gimeno (2009), where populations of the Mediterranean holm oak, *Q. ilex*, exhibited high environmental tolerances and without evidence of local adaptation. Our findings are congruent with the expectations of drought tolerance through decreased stomatal conductance (at the expense of carbon gain) and higher water use efficiency (Cohen 1970, Zangerl and Bazzaz 1984, Dudley 1996, Heschel et al. 2002, Gimeno et al. 2009).

We did not find evidence that short dry spells during the wet season significantly reduce seedling survival or growth (chapter 2) nor did they influence carbon and water use traits in seedlings. However, our ability to detect the impacts of short dry spells may have been limited by higher than normal wet season rainfall in Honduras during 2010 when seedlings were most vulnerable. Short dry spells in the wet season have been shown to influence seedling survival in other tropical dry forest species (Pearson et al. 2003, Engelbrecht et al. 2006) and further investigation during years with pronounced dry periods in the wet season would provide a more integrated view of *Q. oleoides* seedling vulnerability.

Phenotypic selection

Phenotypic selection analyses both within and across gardens revealed that seedlings with trait values associated with higher integrated water use efficiency and lower SLA had significant fitness advantages. While there were seasonal differences in the magnitude of selection gradients, the direction of selection was consistent across seasons and gardens. Within the dry garden, phenotypic selection generally favored increased intrinsic and integrated water use efficiencies, except in the DSW and “Both” treatments. Our findings of higher reductions in gas exchange traits being favored by selection, the high plasticity of these traits and the maintenance of seedling fitness among maternal families (chapter 2) across moisture regimes suggest that populations may respond plastically to climate change (Bradshaw 1965, Schlichting 1986, Sultan 1987, Schlichting and Pigliucci 1998, Donohue et al. 2001). Higher $\delta^{13}\text{C}$ was consistently favored in the ambient rainfall treatment regardless of season. Seasonal and total annual rainfall represents the critical primary environmental gradients across the range of the species. The lack of differences in selection detected among the gardens suggest that while annual rainfall patterns differ among sites, all sites exert similar selective pressure on seedlings and favor individuals traits conferring higher water use efficiency and lower SLA. Furthermore, the lack of differences in selection across sites may explain the lack of differentiation among populations in carbon and water use traits.

Documenting strong phenotypic selection does not imply populations are capable of adaptive responses to environmental changes (Lande 1979, Cheverud 1984, Walsh and Blows 2009). Three requirements must be met for populations to exhibit adaptive evolution through natural selection: variation in phenotypic traits, fitness variation associated with trait variation, and trait variation must be heritable (Darwin 1859). While we find large phenotypic trait variation and strong correlations between fitness and traits, most of the phenotypic variation appears to be plastic responses to seasonal and/or environmental changes. Furthermore we did not find that maternal families differ in their plastic responses, and this suggests low genetic variation for plasticity. We did find that populations of *Q. oleoides* harbor within-population genetic variation for $\delta^{13}\text{C}$ but not for other trait investigated. Further investigation into the heritability of $\delta^{13}\text{C}$ would elucidate

the capacity of populations to exhibit adaptive responses in $\delta^{13}\text{C}$ to changes in water availability. The lack of consistent high within-population genetic variation for A/g_s and SLA in function may limit the adaptive potential of *Q. oleoides* populations.

Conclusion

We found that the broadly distributed neotropical live oak comprises populations with wide environmental tolerances rather than a series of locally adapted populations. There was little evidence that populations exhibit differentiation in traits related to carbon and water use. All seedlings, regardless of population of origin, showed plastic responses to environmental heterogeneity in the same direction as selection, consistent with adaptive plasticity. At the dry garden, all seedlings displayed drought avoidance by closing stomates and minimizing water loss and metabolism in the dry season. However, when water is supplemented in the dry season, seedlings are capable of maintaining higher carbon gain at the expense of water loss. Selection in the ambient rainfall plots across garden sites strongly favored increased integrated water use efficiency ($\delta^{13}\text{C}$) and reductions in SLA regardless of season. While we found evidence of strong selection, populations do not appear to harbor sufficient genetic variation for adaptive changes in SLA but they may have sufficient adaptive potential for $\delta^{13}\text{C}$. Overall, populations of *Q. oleoides* appear to maintain fitness under variable climatic regimes and are likely able to respond to changes in rainfall in the short-term through phenotypic plasticity.

Effect	DF	Transplant		Directly Planted	
		PD	MD	PD	MD
		χ^2	χ^2	χ^2	χ^2
Treatment (T)	3	9.61 *	5.66	0.81	2.03
Population (P)	3	4.06	0.44	0.74	2.90
Season (S)	1	341.41 ***	1110.90 ***	345.51 ***	0.00
Seed Mass	1	0.55	0.00	2.23	0.07
Size at Planting	1	0.19	1.38	--	--
Machine	2	5.92	93.20 ***	3.02	1.85
Herbivory	1	2.13	0.00	1.20	0.90
T x P	9	10.80	2.32	6.55	15.68 +
T x S	3	42.03 ***	23.30 ***	4.31	0.90
P x S	3	2.22	10.71	3.29	1.95
T x P x S	9	5.67	17.94 *	7.72	7.42
Block (T)	2	84.41 ***	95.65 ***	60.21 ***	0.00
MF (P)	2	0.00	0.00	0.00	0.00
ID (MF (Pop))	3	0.00	0.00	0.00	0.00

Table 3.1- Summary of nested model comparison to test for effect significance of factors in mixed effects model of leaf predawn and midday water potentials for seedlings in the transplant and direct planting cohorts. Leaf water potential was measured on experimental seedlings from *Q. oleoides* seeds collected from four populations throughout Central America (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and germinated in shadehouses and transplanted (transplant cohort) or directly planted (directly planted) the dry garden site (Honduras). Seedlings were subjected to one of four watering treatments: ambient rainfall (Amb.), supplemental water during the wet season (WWS), supplemental water during the dry season (DSW), and supplemental water during both seasons (Both). Measurements were collected during the wet season (2012) and dry season (2013). Degrees of freedom (DF) shown is the difference between the nested models. Block, maternal family (MF), and seedling (ID) were treated as random effects. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***<0.001

Effect	$\delta^{13}\text{C}$			SLA		SD		SPI	
	DF	χ^2		χ^2		χ^2		χ^2	
Garden (G)	2	9.61	**	1.13		4.99	+	6.3189	*
Population (P)	3	7.03	+	3.50		2.08		1.5108	
Season (S)	1	25.13	***	176.57	***	--		--	
Seed Mass	1	0.07		0.06		1.92		0.0068	
Size at Planting	1	7.41	**	5.06		1.19		3.2448	
Nitrogen	1	0.03		--		--		--	
G x P	6	13.76	+	2.29		3.48		6.7771	
G x S	2	10.98	**	36.31	***	--		--	
P x S	3	3.14		9.95	*	--		--	
G x P x S	6	4.74		3.93		--		--	
Block (T)	2	74.45	***	164.15	***	21.64	***	22.321	***
MF (Pop)	2	19.77	***	0.00		4.0779		4.6003	
ID (MF (P))	3	9.27	*	0.00		--		--	
MF (P) x S	4	2.75		0.03		--		--	

Table 3.2–Summary of nested model comparisons to test for effect significance in mixed effects models of carbon isotope discrimination ($\delta^{13}\text{C}$), specific leaf area (SLA), stomatal density (SD), and stomatal pore index (SPI). Traits on experimental seedlings from *Q. oleoides* seeds collected from four populations throughout Central America (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and germinated in shadehouses and transplanted (transplant cohort) into common gardens at Honduras and Costa Rica. Measurements were collected during the wet season (2012) and dry season (2013). Degrees of freedom (DF) shown is the difference between the nested models. Block, maternal family (MF), and seedling (ID) were treated as random effects. +0.10 \geq P>0.05; * P \leq 0.05, ** P \leq 0.01; ***<0.001

Effect	DF	A	g _s		A/g		δ ¹³ C		SLA	SD	SPI				
		χ ²	χ ²		χ ²	χ ²	χ ²	χ ²	χ ²	χ ²					
Treatment (T)	3	4.61		6.71	+	5.58		3.01	3.04	0.16	4.97				
Population (P)	3	8.21	*	8.94	*	1.35		7.60	+	10.07	*	0.37	2.97		
Season (S)	2	186.91	***	512.82	***	479.83	***	29.07	***	178.73	***	--	--		
Seed Size	1	0.10		0.00		0.08		0.45		0.13		0.25	2.02		
Planting Size	1	2.34		0.75		0.12		3.18	+	8.88	**	4.60	*	5.12	*
Herbivory	1	12.64	***	15.23	***	12.39	***	2.22		9.12	**	0.08		0.10	
Nitrogen	1	--		--		--		0.19		--	--	--		--	
Time	1	6.60	**	1.85		0.53		--		--	--	--		--	
Machine	2	5.27		36.08	***	75.96	***	--		--	--	--		--	
T x P	9	6.87		3.52		9.55		0.00		8.32		10.50		11.73	
T x S	3	45.49	***	43.90	***	11.08	*	0.00		4.74		--		--	
P x S	3	10.02	*	8.39	*	3.43		0.00		4.36		--		--	
T x P x S	9	6.36		8.47		5.92		2205.30	***	15.41		--		--	
Block (T)	2	84.45	***	134.64	***	65.14	***	16.90	***	52.37	***	8.57	*	8.43	*
MF (P)	2	0.34		0.53		77.75	***	11.17	***	4.55		--		--	
ID (MF (P))	3	7.28	+	0.00		0.00		18.85	***	21.31	***	--		--	
MF (P) x S	4	0.15		0.37		1.42		1.50		0.06		0.00		0.00	

Table 3.3-Summary of nested model comparisons to test for effect significance in mixed effects models of leaf level traits related to carbon and water-use: maximum photosynthetic rate (A), stomatal conductance (g_s), intrinsic water-use efficiency (A/g), carbon isotope discrimination (δ¹³C), specific leaf area (SLA), stomatal density (SD), and stomatal pore index (SPI). Traits were measured on experimental seedlings from *Q. oleoides* seeds collected from four populations throughout Central America (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and germinated in shadehouses and transplanted (transplant cohort) into the dry garden site (Honduras). Seedlings were subjected to one of four watering treatments. Measurements were collected during the wet season (2012) and dry season (2013). Degrees of freedom (DF) shown is the difference between the nested models. Block, maternal family (MF), and seedling (ID) were treated as random effects. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***<0.001

Effect	$\delta^{13}\text{C}$		SLA		SD		SPI	
	DF	χ^2	DF	χ^2	χ^2		χ^2	
Treatment (T)	2	2.30	12,14	3.96	5.22	+	4.17	
Population (P)	3	6.43	+	11,14	2.34		1.91	1.82
Season (S)	2	18.12	***	13,14	69.28	***	--	--
Seed Mass	1	1.47		30,31	1.07		5.81	*
Size at Planting	1	1.25		30,31	1.04		0.27	2.83
Nitrogen	1	6.31	**	--	--		--	--
T x P	6	15.04	*	19,25	0.34		9.11	3.94
T x S	2	7.41	*	23,25	27.78	***	--	--
P x S	3	0.45		22,25	6.04		--	--
T x P x S	6	10.90	+	25,31	10.31		--	--
Block (T)	2	70.47	***	25,27	162.81	***	17.17	***
MF (Pop)	2	8.77	**	29,31	0.00		3.00	2.26
ID (MF (P))	3	15.84	***	31,32	0.00		--	--
MF (P) x S	4	0.58		29,31	1.77		--	--

Table 3.4–Summary of nested model comparisons to test for effect significance in mixed effects models of carbon isotope discrimination ($\delta^{13}\text{C}$), specific leaf area (SLA), stomatal density (SD), and stomatal pore index (SPI). Traits were measured on experimental seedlings from *Q. oleoides* seeds collected from four populations throughout Central America (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and germinated in shadehouses and transplanted (transplant cohort) into common gardens in Costa Rica- intermediate (IG) and wet (WG) gardens. Seedlings at the intermediate garden were subjected to two watering treatments: ambient rainfall and added water during the dry season. Due to the design not being full-factorial treatment represents the three possible conditions: IG-ambient rainfall, IG-DS Water and WG-ambient rainfall. Measurements were collected during the wet season (2012) and dry season (2013). Degrees of freedom (DF) shown is the difference between the nested models. Block, maternal family (MF), and seedling (ID) were treated as random effects. +0.10 \geq P>0.05; * P \leq 0.05, ** P \leq 0.01; ***<0.001

Trait	Wet Season		Dry Season	
			Dry Garden	
$\delta^{13}\text{C}$	β_i	0.352 (0.060) ***	0.257 (0.048) ***	***
SLA	β_i	-0.258 (0.060) ***	-0.491 (0.049) ***	***
$\delta^{13}\text{C}^2$	γ_{ii}	0.033 (0.035) ***	0.050 (0.020) ***	***
SLA ²	γ_{ii}	0.253 (0.030) ***	--	
$\delta^{13}\text{C}$ x SLA	γ_{ij}	-0.260 (0.050) ***	-0.298 (0.027) ***	***
Intermediate Garden				
$\delta^{13}\text{C}$	β	0.180 (0.024) ***	0.288 (0.041) ***	***
SLA	β	-0.078 (0.024) ***	-0.696 (0.104) ***	***
$\delta^{13}\text{C}^2$	γ_{ii}	0.008 (0.015) ***	-0.118 (0.032) ***	***
SLA ²	γ_{ii}	--	--	
$\delta^{13}\text{C}$ x SLA	γ_{ij}	-0.116 (0.026) ***	-0.412 (0.080) ***	***
Wet Garden				
$\delta^{13}\text{C}$	β	0.260 (0.056) ***	0.144 (0.029)	
SLA	β	0.015 (0.057)	-0.290 (0.008) ***	***
$\delta^{13}\text{C}^2$	γ_{ii}	0.233 (0.023) **	0.058 (0.024)	
SLA ²	γ_{ii}	--	--	
$\delta^{13}\text{C}$ x SLA	γ_{ij}	-0.362 (0.023) ***	-0.062 (0.062)	

Table 3.5-Site and season specific phenotypic selection analyses. Standardized selection gradients, β_i (SE) were obtained from linear multiple regressions of Aster predicted relative fitness on traits (all populations within a site combined). γ_{ii} and γ_{ij} were obtained from separated regressions that included quadratic and cross-product terms. γ_{ii} for SLA could only be estimated at the dry garden during the dry season and was not detected in other analyses and dropped due to failure of model convergence. Nested Aster model comparisons were used to test significance. +0.10 \geq P>0.05; * P \leq 0.05, ** P \leq 0.01; ***<0.001

		Wet Season		Dry Season	
Trait		Ambient			
A/g	β	0.003 (0.042)	***	0.335 (0.029)	***
$\delta^{13}\text{C}$	β	0.311 (0.040)	***	0.204 (0.030)	***
SLA	β	-0.224 (0.041)	***	-0.372 (0.031)	***
		WS-Water			
A/g	β	0.162 (0.066)	***	0.014 (0.040)	**
$\delta^{13}\text{C}$	β	-0.010 (0.063)	***	-0.242 (0.041)	***
SLA	β	-0.392 (0.064)	***	-0.660 (0.043)	***
		DS-Water			
A/g	β	-0.221 (0.023)	***	--	
$\delta^{13}\text{C}$	β	0.366 (0.024)	***	0.300 (0.043)	***
SLA	β	-0.149 (0.020)	***	-0.131 (0.042)	***
		Both-Water			
A/g	β	0.009 (0.020)		-0.121 (0.036)	***
$\delta^{13}\text{C}$	β	0.113 (0.022)	***	0.348 (0.038)	***
SLA	β	-0.126 (0.022)	***	-0.341 (0.043)	***

Table 3.6- Analyses of phenotypic selection within the four watering treatments at the dry garden site. Seedlings were subjected to one of four treatments: ambient rainfall (ambient), added water during the wet season (WS Water), added watering during the dry season (DS Water) and added water during both season (Both). Standardized selection gradients, β_i (SE) were obtained from linear multiple regressions of Aster predicted relative fitness on traits (all populations within a treatment combined) for traits measured during the wet season (2012) and dry season (2013). +0.10 \geq P>0.05; * P \leq 0.05, ** P \leq 0.01; ***<0.001

Trait	Wet Season			Dry Season		
			IG-Ambient			
$\delta^{13}\text{C}$	β	0.180 (0.024)	***	0.288 (0.041)	***	
SLA	β	-0.078 (0.024)	***	-0.696 (0.104)	***	
$\delta^{13}\text{C}^2$	γ_{ii}	0.008 (0.015)	***	-0.118 (0.032)	***	
SLA ²	γ_{ii}	--		--		
$\delta^{13}\text{C} \times \text{SLA}$	γ_{ij}	-0.116 (0.026)	***	-0.412 (0.080)	***	
			IG- DS Water			
$\delta^{13}\text{C}$	β	-0.044 (0.017)	***	0.116 (0.012)	***	
SLA	β	-0.162 (0.017)	***	-0.285 (0.012)	***	
$\delta^{13}\text{C}^2$	γ_{ii}	-0.054 (0.007)	***	-0.056 (0.007)	***	
SLA ²	γ_{ii}	--		--		
$\delta^{13}\text{C} \times \text{SLA}$	γ_{ij}	0.099 (0.011)	***	-0.057 (0.007)	***	

Table 3.7- Analyses of phenotypic selection within the two watering treatments at the intermediate garden (IG) site. Seedlings were either subjected to ambient rainfall (IG-Ambient) or were watered during the dry season (IG-DS Water). Standardized selection gradients, β_i (SE) were obtained from linear multiple regressions of Aster predicted relative fitness on traits (all populations within a treatment combined) for traits measured during the wet season (2012) and dry season (2013). $+0.10 \geq P > 0.05$; * $P \leq 0.05$, ** $P \leq 0.01$; *** < 0.001

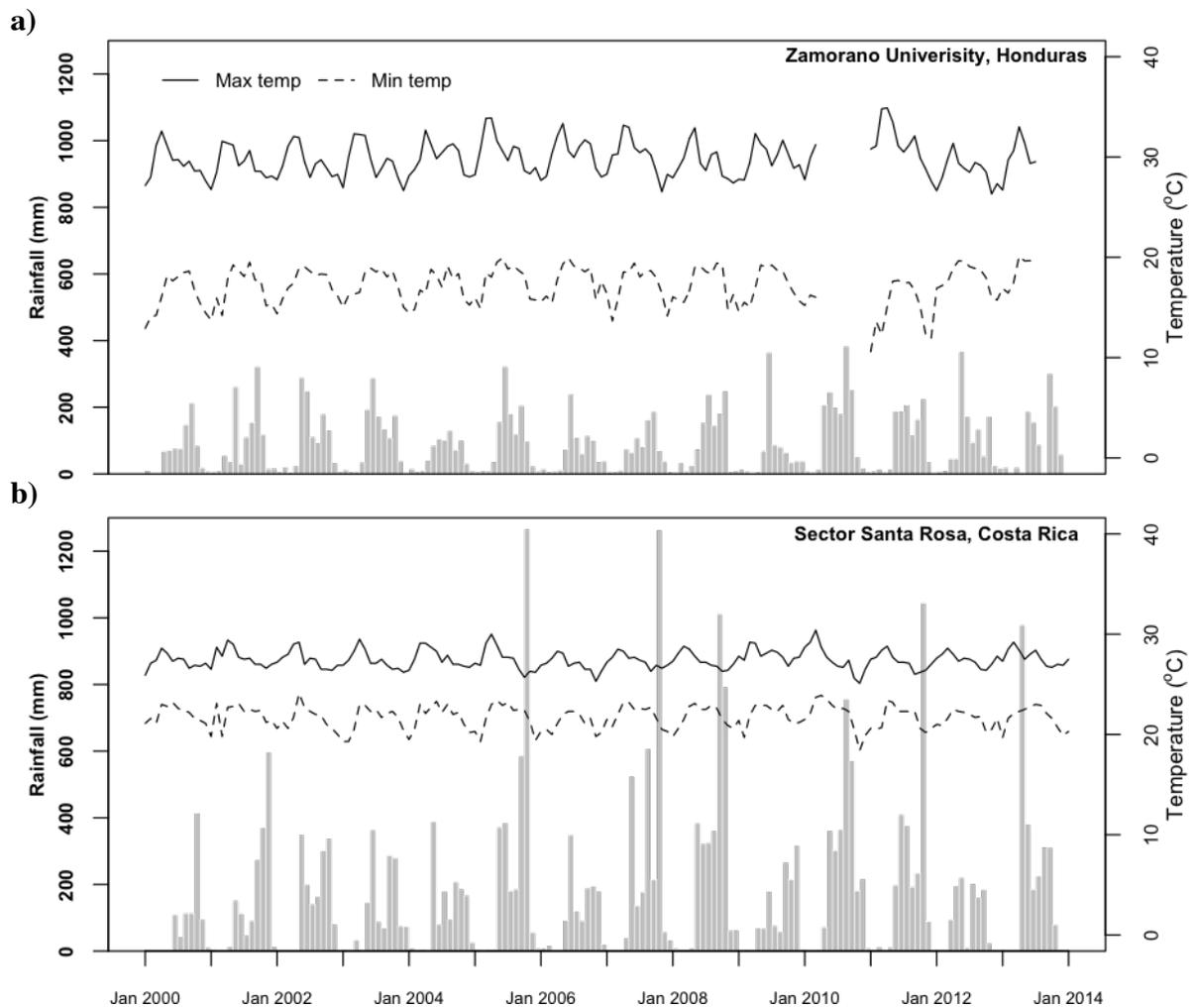


Figure 3.1- Mean monthly rainfall and mean monthly minimum and maximum temperatures from meteorological stations from 2000-2014 at two out of the three common garden sites- dry garden (at Zamorano University, HN) and intermediate garden (at Sector Santa Rosa in the Guanacaste Conservation Area, Costa Rica).

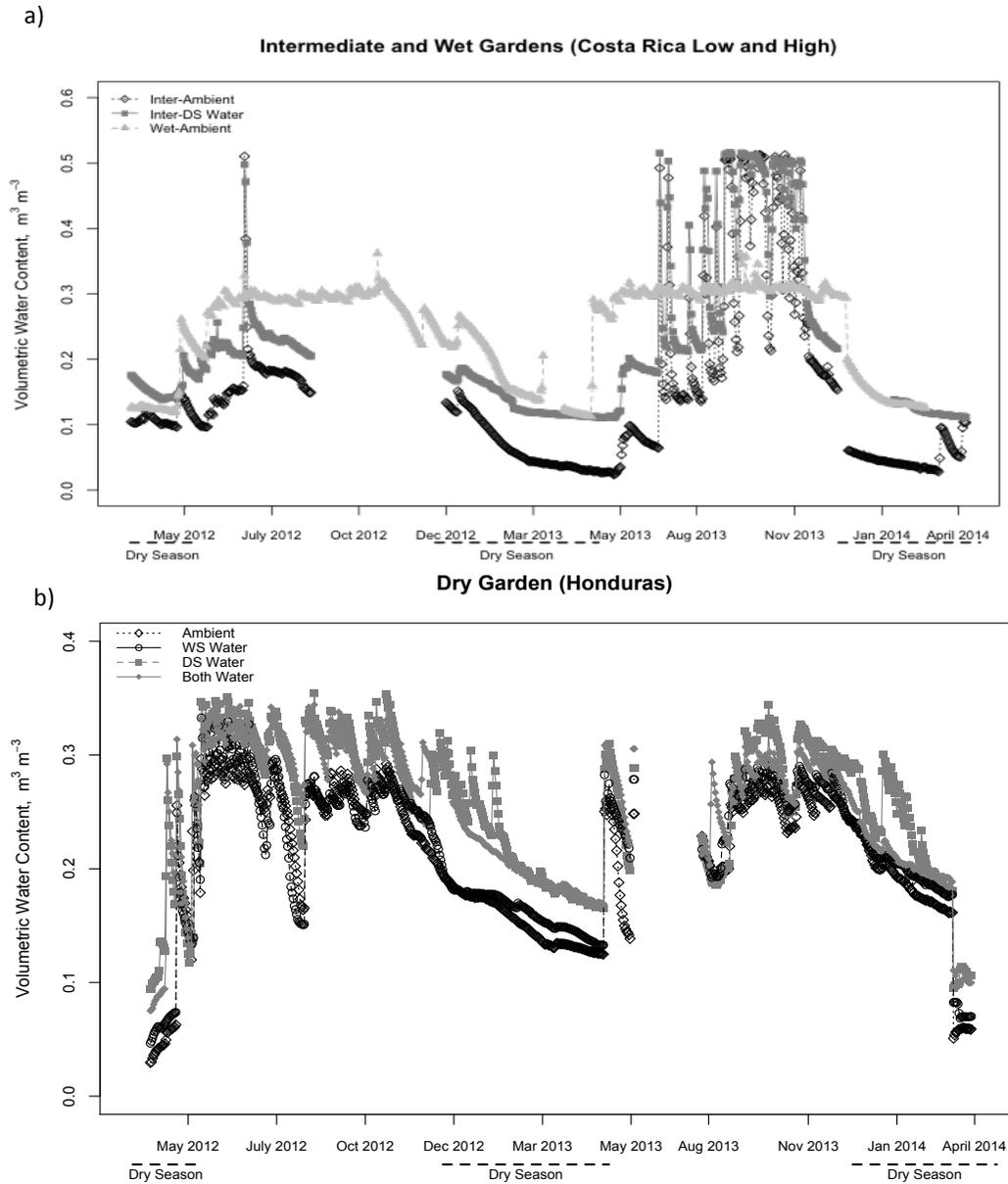


Figure 3.2- Volumetric soil water content ($\text{m}^3 \text{m}^{-3}$) collected from May 2012 to April 2014 of the watering treatments at the a) intermediate and wet gardens (Sector Santa Rosa and Sector Pailas in the Guanacaste Conservation Area, respectively) and b) dry garden located at Zamorano University Honduras. Scale of y-axis differs between a and b and field capacity of soil is $0.5 \text{m}^3/\text{m}^3$, which is also the upper range of Decagon soil moisture probes.

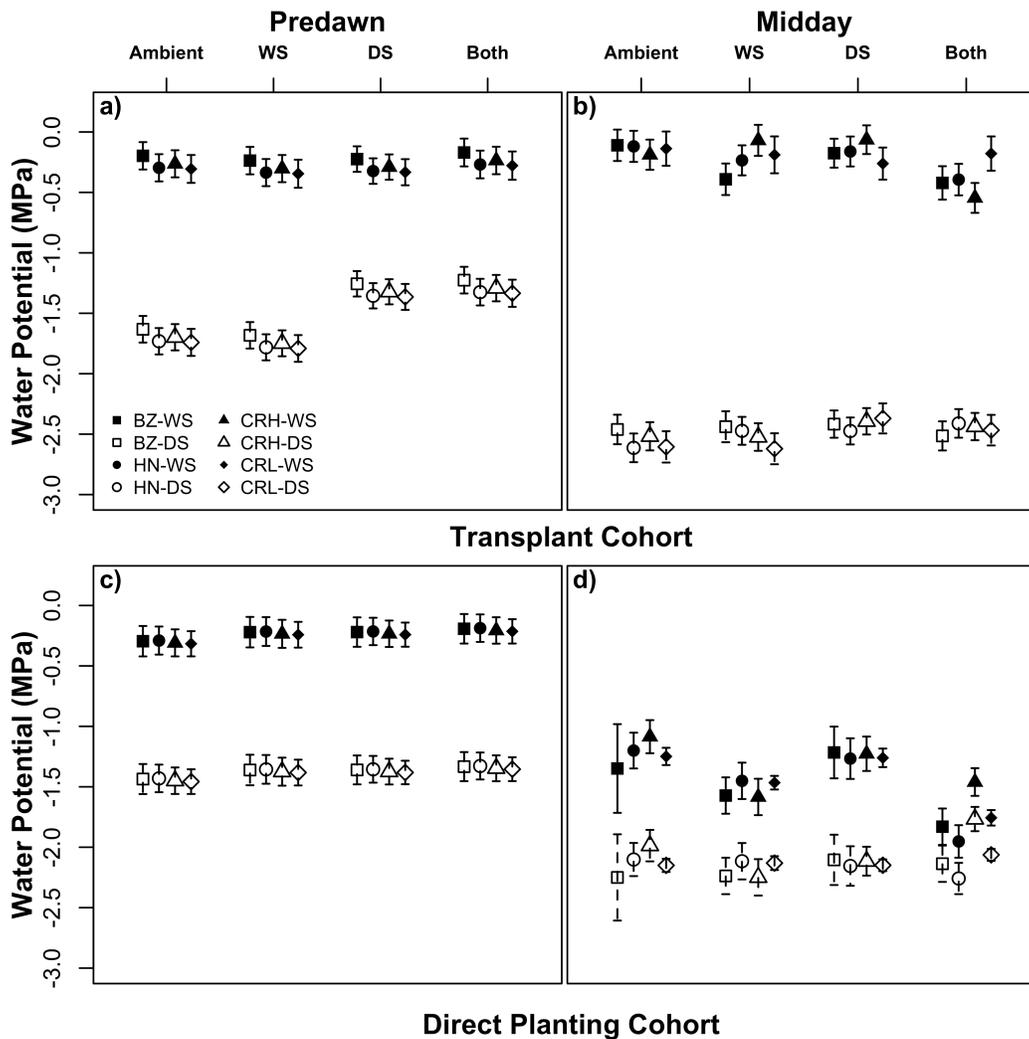


Figure 3.3- Predawn and midday leaf water potential were measured on experimental seedlings from *Q. oleoides* seeds collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) throughout Central America and germinated in shadehouses and transplanted (transplant cohort) into a common garden in Honduras with four watering treatments. Treatments are indicated as follows: “Ambient” = no additional watering; “WS”= wet season watering; “DS”= dry season watering; “Both” = watering in wet and dry seasons. a) and b) transplanted and c) and d) direct planting cohorts at the dry garden site (Zamorano University- Honduras). Close symbols show wet season values (June 2012); open symbols show dry season values (March 2013).

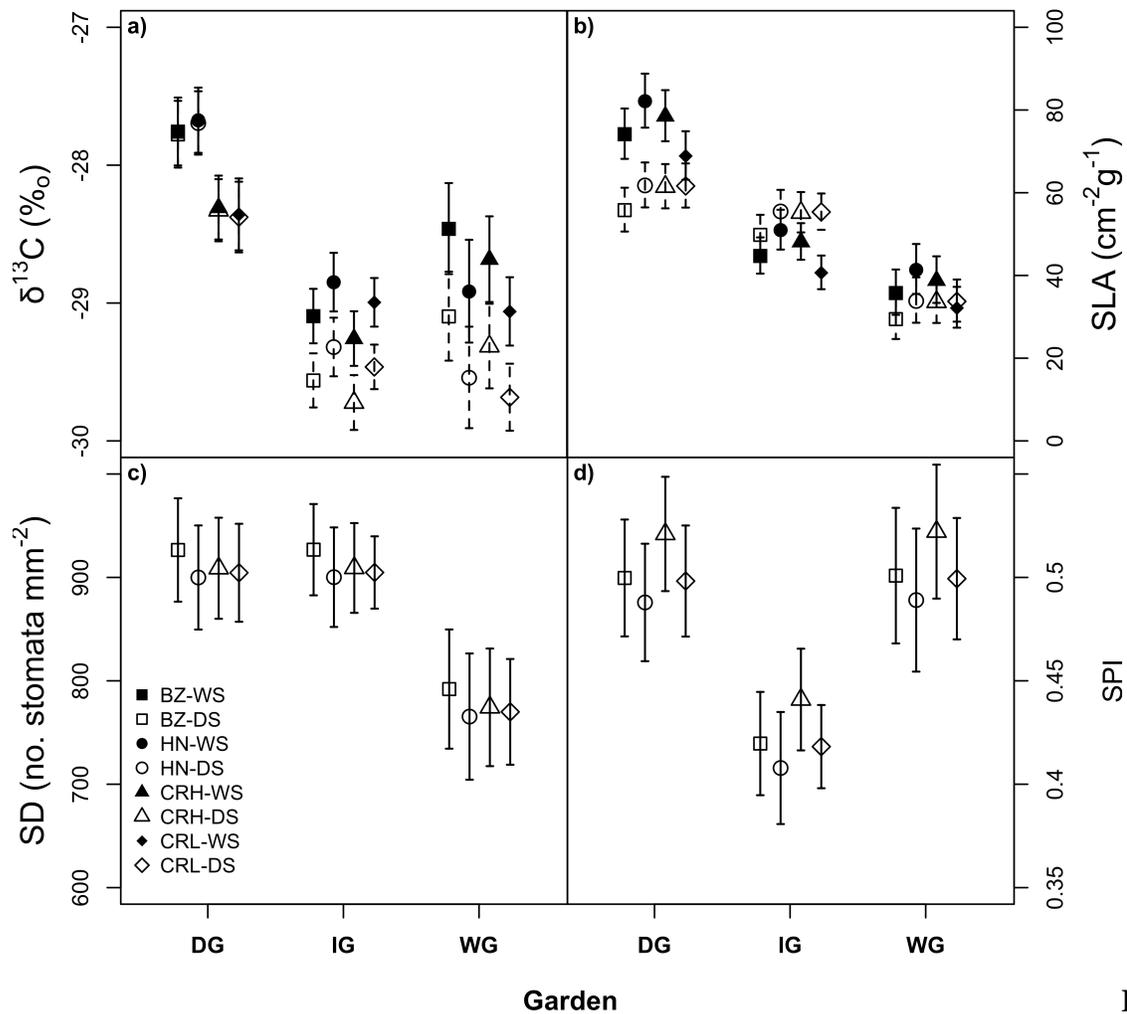


Figure 3.4- Mixed effects model predicted mean (SE) for leaf-level traits related to carbon and water-use, a) carbon isotope discrimination ($\delta^{13}\text{C}$), b) specific leaf area (SLA), c) stomatal density (SD), and d) stomatal pore index (SPI). The four populations are abbreviated as in Fig. 3.3. Seedlings were transplanted into common gardens in Honduras (dry garden, DG), Costa Rica- intermediate garden (IG) and wet garden (WG). Measurements were collected during the wet season (WS- closed symbols) and dry season (DS- open symbols).

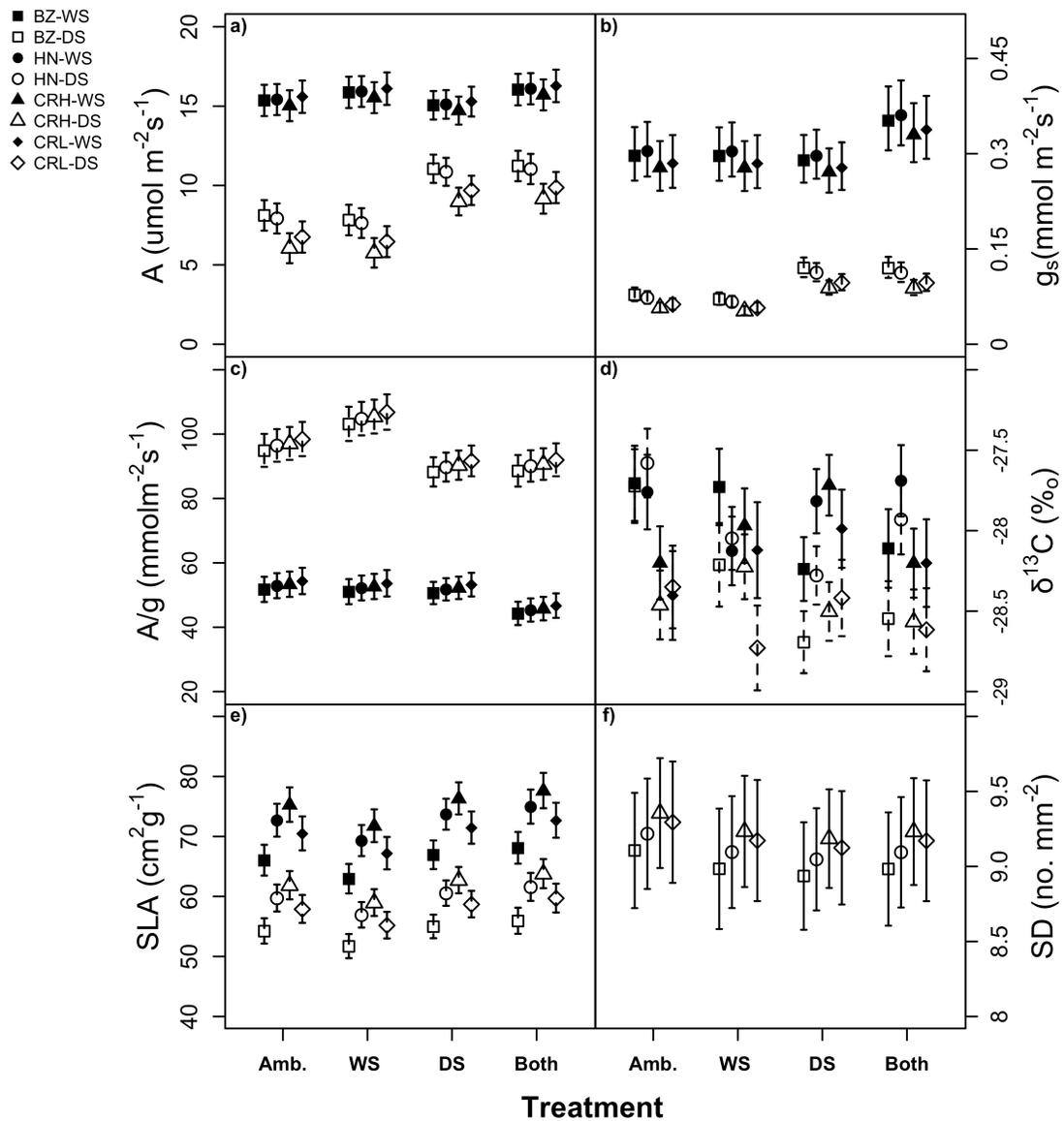


Figure 3.5- Mixed effects model predicted mean (SE) for leaf-level traits related to carbon and water-use, a) maximum photosynthetic rate (A), b) stomatal conductance (g_s), c) intrinsic water-use efficiency (A/g), d) carbon isotope discrimination ($\delta^{13}\text{C}$), e) specific leaf area (SLA), and f) stomatal density (SD). Population and treatment abbreviations are as in Fig. 3.3. Measurements were collected during the wet season (closed symbols) and dry season (open symbols) except for SD, which was only collected during the dry season.

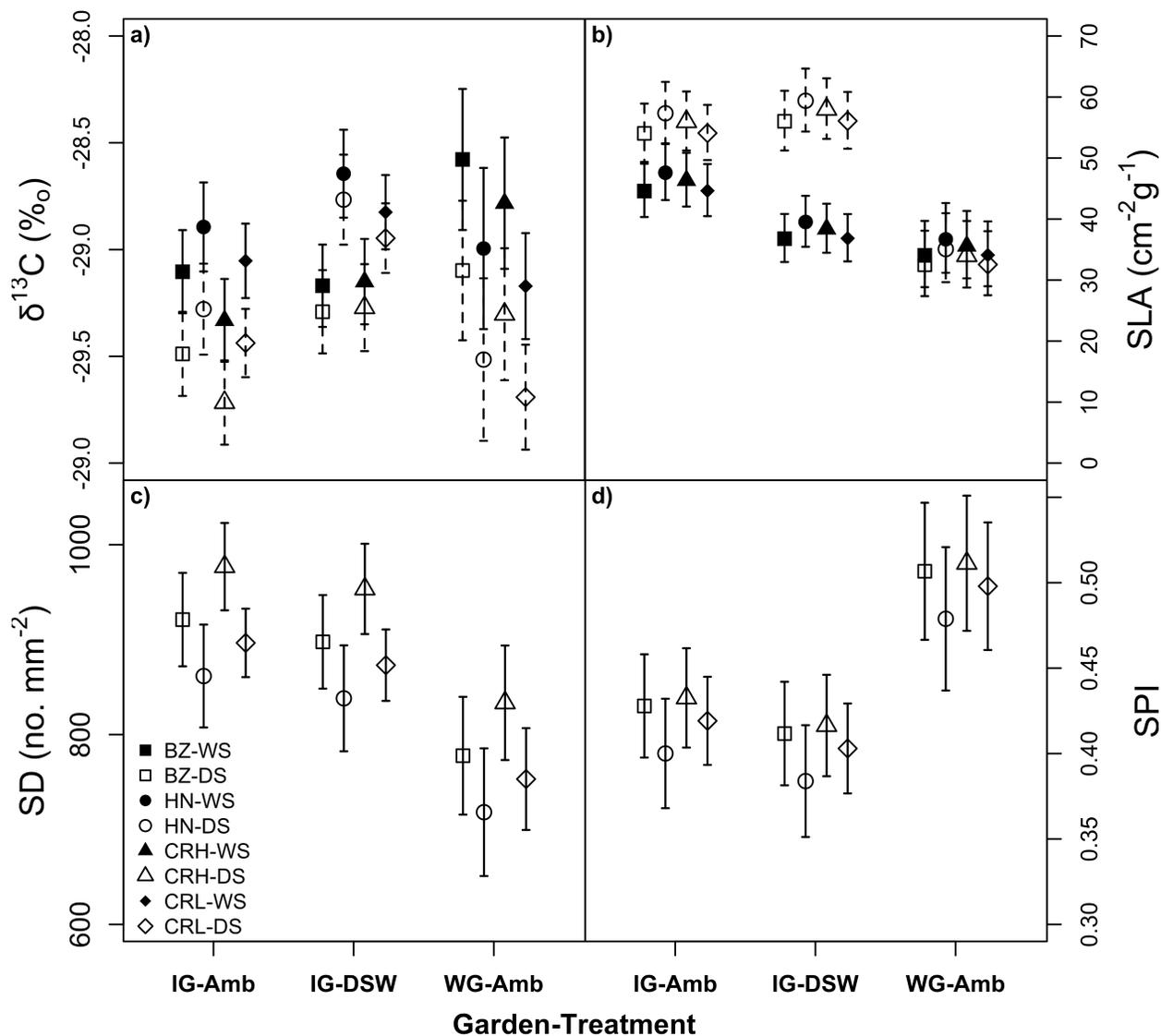


Figure 3.6- Mixed effects model predicted mean (SE) for leaf-level traits related to carbon and water-use, a) specific leaf area (SLA), b) carbon isotope discrimination ($\delta^{13}\text{C}$), c) stomatal density (SD), and d) stomatal pore index (SPI). Population abbreviations are the same as in Fig. 3.3. Seedlings at the intermediate garden were subjected to two watering treatments: ambient rainfall and added water during the dry season. Due to the design not being full-factorial, treatment represents the three possible conditions: IG-ambient rainfall, IG-DS Water and WG-ambient rainfall. Symbols are the same as in Fig. 3.3.

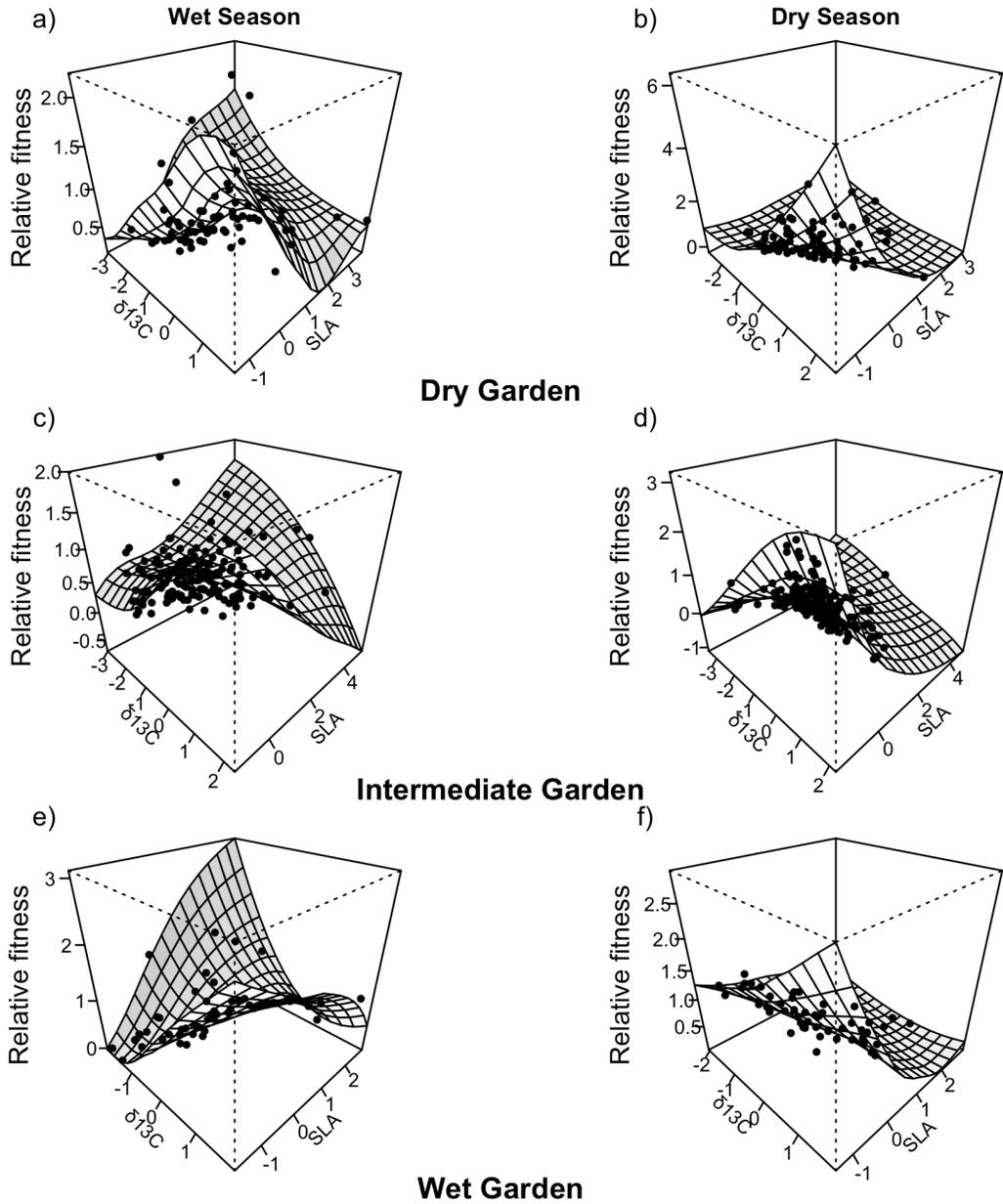


Figure 3.7- Interpolated site and season specific bivariate fitness surfaces of joint selection on carbon isotope discrimination ($\delta^{13}\text{C}$) and specific leaf area (SLA) at: a and b) dry garden (Honduras), c and d) intermediate (Costa Rica low-elevation), and e and f) wet (Costa Rica high-elevation) gardens. Relative fitness values are Aster predicted estimates of seedling fitness at the end of the wet season 2013, and traits are the standardized values (mean=0, SD=1) from measurements in the wet season 2012 (June) and dry season (March) 2013. Points are observed values used in local regressions of fitness landscape surfaces.

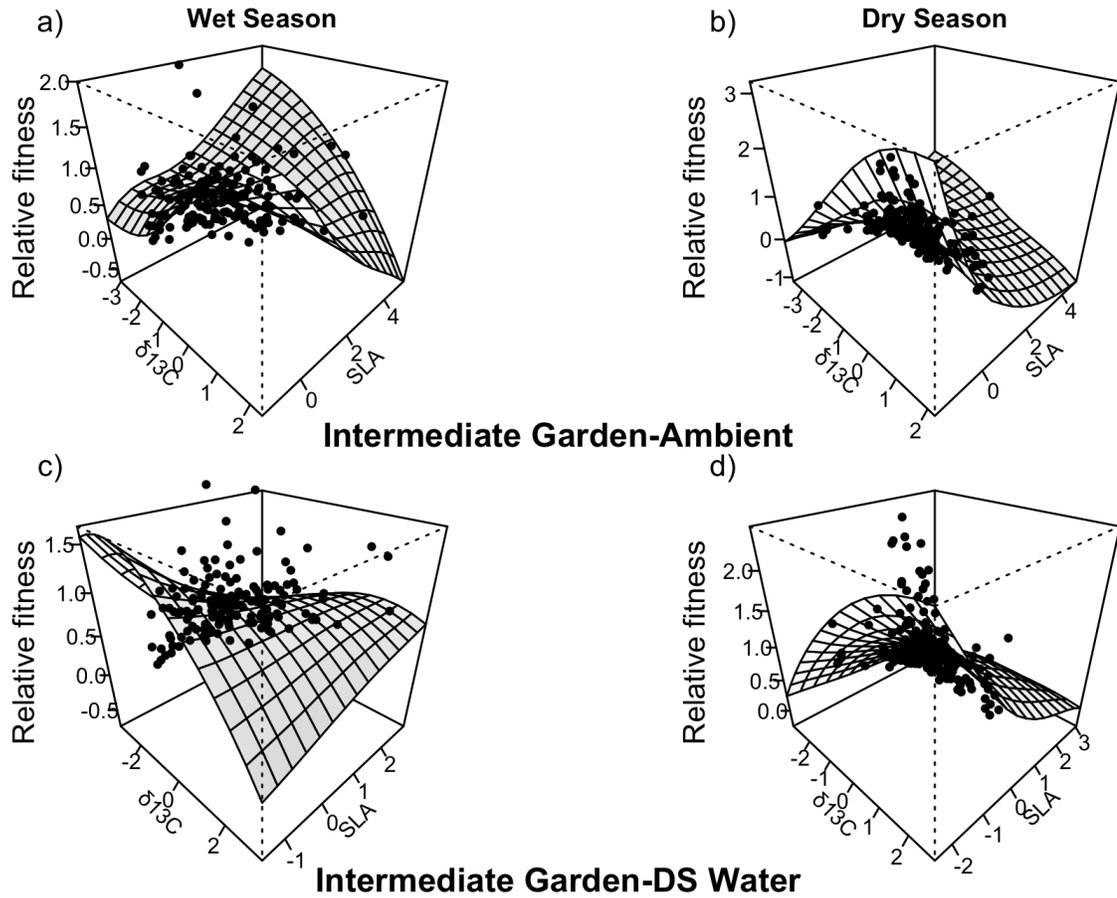


Figure 3.8- Interpolated treatment and season specific bivariate fitness surfaces of joint selection on carbon isotope discrimination ($\delta^{13}\text{C}$) and specific leaf area (SLA) at the intermediate garden site. Seedlings were subjected to one of two watering treatments: a and b) ambient rainfall (ambient), and c and d) added water during the dry season (DS Water). Points are observed values used in local regressions of fitness landscape surfaces.

References

- Alpert, P., and E. Simms. 2002. The relative advantages of plasticity and fixity in different environments: when is it good for a plant to adjust? *Evolutionary Ecology* **16**:285-297.
- Alvarado, V., and K. J. Bradford. 2002. A hydrothermal time model explains the cardinal temperatures for seed germination. *Plant Cell and Environment* **25**:1061-1069.
- Antonovics, J. 1976. The Nature of limits to natural selection. *Annals of the Missouri Botanical Garden* **63**:224-247.
- Antonovics, J., and R. B. Primack. 1982. Experimental ecological genetics in *Plantago*: VI. the demography of seedling transplants of *P. lanceolata*. *Journal of Ecology* **70**:55-75.
- Asquith, N. M., S. J. Wright, and M. J. Clauss. 1997. Does mammal community composition control recruitment in neotropical forests? Evidence from Panama. *Ecology* **78**:941-946.
- Baines, J. F., A. Das, S. Mousset, and W. Stephan. 2004. The role of natural selection in genetic differentiation of worldwide populations of *Drosophila ananassae*. *Genetics* **168**:1987-1998.
- Balaguer, L., E. Martínez-Ferri, F. Valladares, M. E. Pérez-Corona, F. J. Baquedano, F. J. Castillo, and E. Manrique. 2001. Population divergence in the plasticity of the response of *Quercus coccifera* to the light environment. *Functional Ecology* **15**:124-135.
- Baskin, C., and L. Baskin. 2001. Seeds. Ecology, biogeography, and evolution of dormancy and germination. Academic Press, San Diego, CA.
- Benard, R., and C. Toft. 2007. Effect of seed size on seedling performance in a long-lived desert perennial shrub (*Ericameria nauseosa*: Asteraceae). *International Journal of Plant Sciences* **168**:1027-1033.
- Bennington, C. C., and J. B. McGraw. 1995. Natural selection and ecotypic differentiation in *Impatiens pallida*. *Ecological Monographs* **65**:303-323.
- Bennington, C. C., and J. B. McGraw. 1996. Environment-dependence of quantitative genetic parameters in *Impatiens pallida*. *Evolution* **50**:1083-1097.
- Berjak, P., J. Farrant, and N. W. Pammenter. 1989. The basis of recalcitrant seed behaviour. Pages 89-108 in R. Taylorson, editor. *Recent Advances in the Development and Germination of Seeds*. Springer US.
- Boucher, D. H. 1983. *Quercus oleoides* (Roble Encino, Oak) Pages 319-322 in D. H. Janzen, editor. *Costa Rican Natural History*. The University of Chicago Press.
- Bradford, K. J., and A. M. Haigh. 1994. Relationship between accumulated hydrothermal time during seed priming and subsequent seed germination rates. *Seed Science Research* **4**:63-69.
- Bradshaw, A. D. 1965. Evolutionary significance of phenotypic plasticity in plants. Pages 115-155 in E. W. Caspari and J. M. Thoday, editors. *Advances in Genetics*. Academic Press.

- Bradshaw, A. D. 1984. Ecological significance of genetic variation between populations. *in* R. Dirxo and J. Sarukhán, editors. Perspectives in Plant Population Ecology. Sunderland: Sinauer Associates Inc.
- Bradshaw, A. D., and K. Hardwick. 1989. Evolution and stress—genotypic and phenotypic components. *Biological Journal of the Linnean Society* **37**:137-155.
- Bradshaw, W. E., and C. M. Holzapfel. 2001. Genetic shift in photoperiodic response correlated with global warming. *Proceedings of the National Academy of Sciences* **98**:14509-14511.
- Brodie, E. D., A. J. Moore, and F. J. Janzen. 1995. Visualizing and quantifying natural selection. *Trends in Ecology & Evolution* **10**:313-318.
- Bull, J. J. 1987. Evolution of phenotypic variance. *Evolution* **41**:303-315.
- Bustamante, R. O., A. A. Grez, J. A. Simonetti, R. A. Vásquez, and A. M. Walkowiak. 1993. Antagonistic effects of frugivores on seeds of *Cryptocarya alba* (Mol.) *Looser* (Lauraceae): consequences on seedling recruitment. *Acta Oecologica* **14**:739-745.
- Caruso, C. M. 2004. The quantitative genetics of floral trait variation in *Lobelia*: Potential constraints on adaptive evolution. *Evolution* **58**:732-740.
- Castro, J. 2006. Short delay in timing of emergence determines establishment success in *Pinus sylvestris* across microhabitats. *Annals of Botany* **98**:1233-1240.
- Cavender-Bares, G.-R., Deren Eaton, Andrew Hipp, Paul Manos. *in review*. Phylogeny and biogeography of the American live oaks (*Quercus* subsection Virentes): a genomic and population genetics approach. *Molecular Ecology*.
- Cavender-Bares, J., and F. A. Bazzaz. 2000. Changes in drought response strategies with ontogeny in *Quercus rubra* : implications for scaling from seedlings to mature trees. *Oecologia* **124**:8-18.
- Cavender-Bares, J., A. Gonzalez-Rodriguez, A. Pahlich, K. Koehler, and N. Deacon. 2011. Phylogeography and climatic niche evolution in live oaks (*Quercus* section Virentes) from the tropics to the temperate zone. *Journal of Biogeography* **38**:962-981.
- Cavender-Bares, J., A. Keen, and B. Miles. 2006. Phylogenetic structure of Floridian plant communities depends on taxonomic and spatial scale. *Ecology* **87**:S109-S122.
- Cavender-Bares, J., K. Kitajima, and F. A. Bazzaz. 2004. Multiple trait associations in relation to habitat differentiation among 17 Floridian oak species *Ecological Monographs* **74**:635-662.
- Cavender-Bares, J., L. Sack, and J. Savage. 2007. Atmospheric and soil drought reduce nocturnal conductance in live oaks. *Tree Physiol* **27**:611-620.
- Chaturvedi, R. K., A. S. Raghubanshi, and J. S. Singh. 2011. Leaf attributes and tree growth in a tropical dry forest. *Journal of Vegetation Science* **22**:917-931.
- Cheverud, J. M. 1984. Quantitative genetics and developmental constraints on evolution by selection. *Journal of Theoretical Biology* **110**:155-171.
- Cohen, D. 1970. Expected efficiency of water utilization in plants under different competition and selection regimes. *Israel Journal of Botany* **19**:50-54.

- Collignon, A.-M., H. V. d. Syde, and J.-M. Favre. 2002. Geographical variation in random amplified polymorphic DNA and quantitative traits in Norway spruce. *Canadian Journal of Forest Research* **32**:266-282.
- Conner, J., and S. Via. 1992. Natural selection of body size in *Tribolium*: Possible genetic constraints on adaptive evolution. *Heredity* **69**:73-84.
- Crawley, M. J., and C. R. Long. 1995. Alternate bearing, predator satiation and seedling recruitment in *Quercus Robur L.* *Journal of Ecology* **83**:683-696.
- Curtis, J. H., D. A. Hodell, and M. Brenner. 1996. Climate Variability on the Yucatan Peninsula (Mexico) during the Past 3500 Years, and Implications for Maya Cultural Evolution. *Quaternary Research* **46**:37-47.
- Damesin, C., S. Rambal, and R. Joffre. 1998. Seasonal and annual changes in leaf $\delta^{13}C$ in two cooccurring Mediterranean oaks: relations to leaf growth and drought progression. *Functional Ecology* **12**:778-785.
- Darwin, C. 1859. *On the origins of species by means of natural selection*. London: Murray.
- Daskalakou, E., and C. Thanos. 1996. Aleppo Pine (*Pinus Halepensis*) Postfire Regeneration: the Role of Canopy and Soil Seed Banks. *International Journal of Wildland Fire* **6**:59-66.
- Davis, M. B., R. G. Shaw, and J. R. Etterson. 2005. Evolutionary responses to changing climate. *Ecology* **86**:1704-1714.
- de Lillis, M., and A. Fontanella. 1992. Comparative phenology and growth in different species of the Mediterranean maquis of central Italy. *Vegetatio* **99-100**:83-96.
- Deacon, N. 2010. Population genetic structure, pollen dispersal, and local adaptation in *Quercus oleoides* forests of Costa Rica. University of Minnesota, Twin Cities.
- Deacon, N. J., and J. Cavender-Bares. *accepted*. Limited pollen dispersal contributes to population genetic structure but not local adaptation in *Quercus oleoides* forests of Costa Rica. *PLoS ONE*.
- Delagrange, S., C. Messier, M. J. Lechowicz, and P. Dizengremel. 2004. Physiological, morphological and allocational plasticity in understory deciduous trees: importance of plant size and light availability. *Tree Physiology* **24**:775-784.
- Donohue, K. 2002. Germination timing influences natural selection on life-history characters in *Arabidopsis thaliana*. *Ecology* **83**:1006-1016.
- Donohue, K. 2009. Completing the cycle: maternal effects as the missing link in plant life histories. *Philosophical Transactions of the Royal Society B: Biological Sciences* **364**:1059-1074.
- Donohue, K., L. Dorn, C. Griffith, E. Kim, A. Aguilera, C. R. Polisetty, and J. Schmitt. 2005. Niche construction through germination cueing: life-history responses to timing of germination in *Arabidopsis thaliana*. *Evolution* **59**:771-785.
- Donohue, K., E. Hammond Pyle, D. Messiqua, M. Shane Heschel, and J. Schmitt. 2001. Adaptive divergence in plasticity in natural populations of *Impatiens capensis* and its consequences for performance in novel habitats. *Evolution* **55**:692-702.
- Donohue, K., R. Rubio de Casas, L. Burghardt, K. Kovach, and C. G. Willis. 2010. Germination, postgermination adaptation, and species ecological Ranges. *Annual Review of Ecology, Evolution, and Systematics* **41**:293-319.

- Donovan, L., S. Dudley, D. Rosenthal, and F. Ludwig. 2007. Phenotypic selection on leaf water use efficiency and related ecophysiological traits for natural populations of desert sunflowers. *Oecologia* **152**:13-25.
- Dudley, S. A. 1996. The response to differing selection on plant physiological traits: evidence for local adaptation. *Evolution*:103-110.
- Dudley, S. A. 1996a. Differing selection on plant physiological traits in response to environmental water availability: a test of adaptive hypotheses. *Evolution*:92-102.
- Ehleringer, J. 1982. The influence of water stress and temperature on leaf pubescence development in *Encelia farinosa*. *American Journal of Botany* **69**:670-675.
- El Omari, B., X. Aranda, D. Verdaguer, G. Pascual, and I. Fleck. 2003. Resource remobilization in *Quercus ilex* L. resprouts. *Plant and Soil* **252**:349-357.
- Endler, J. A. 1977. Geographic variation, speciation, and clines. Princeton University Press.
- Endler, J. A. 1986. Natural selection in the wild. Princeton University Press.
- Engelbrecht, B. M. J., L. S. Comita, R. Condit, T. A. Kursar, M. T. Tyree, B. L. Turner, and S. P. Hubbell. 2007. Drought sensitivity shapes species distribution patterns in tropical forests. *Nature* **447**:80-U82.
- Engelbrecht, B. M. J., J. W. Dalling, T. R. H. Pearson, R. L. Wolf, D. A. Galvez, T. Koehler, M. T. Tyree, and T. A. Kursar. 2006. Short dry spells in the wet season increase mortality of tropical pioneer seedlings. *Oecologia* **148**:258-269.
- Etterson, J. R. 2004a. Evolutionary potential of *Chamaecrista fasciculata* in relation to climate change. I. Clinal patterns of selection along an environmental gradient in the great plains. *Evolution* **58**:1446-1458.
- Etterson, J. R. 2004b. Evolutionary potential of *Chamaecrista fasciculata* in relation to climate change. II. Genetic architecture of three populations reciprocally planted along an environmental gradient in the great plains. *Evolution* **58**:1459-1471.
- Etterson, J. R., and R. G. Shaw. 2001. Constraint to adaptive evolution in response to global warming. *Science* **294**:151-154.
- Evans, A. S., and R. J. Cabin. 1995. Can Dormancy Affect the Evolution of Post-Germination Traits? The Case of *Lesquerella fendleri*. *Ecology* **76**:344-356.
- Farquhar, G. D., K. T. Hubick, A. G. Condon, and R. A. Richards. 1989. Carbon isotope fractionation and plant water-use efficiency. Pages 21-40 in P. W. Rundel, J. R. Ehleringer, and K. A. Nagy, editors. *Stable Isotopes in Ecological Research*. Springer New York.
- Felsenstein, J. 1976. The theoretical population genetics of variable selection and migration. *Annual Review of Genetics* **10**:253-280.
- Ferreira, C. S., M. T. F. Piedade, W. J. Junk, and P. Parolin. 2007. Floodplain and upland populations of Amazonian *Himatanthus sukuuba*: Effects of flooding on germination, seedling growth and mortality. *Environmental and Experimental Botany* **60**:477-483.
- Finch-Savage, W. E., and H. A. Clay. 1994. Water relations of germination in the recalcitrant seeds of *Quercus robur* L. *Seed Science Research* **4**:315-322.

- Footitt, S., Z. Huang, H. A. Clay, A. Mead, and W. E. Finch-Savage. 2013. Temperature, light and nitrate sensing coordinate Arabidopsis seed dormancy cycling, resulting in winter and summer annual phenotypes. *The Plant Journal* **74**:1003-1015.
- Franks, S. J., and A. E. Weis. 2008. A change in climate causes rapid evolution of multiple life-history traits and their interactions in an annual plant. *Journal of Evolutionary Biology* **21**:1321-1334.
- Galloway, L. F. 2002. The Effect of Maternal Phenology on Offspring Characters in the Herbaceous Plant *Campanula americana*. *Journal of Ecology* **90**:851-858.
- Gandon, S., and Scott L. Nuismer. 2009. Interactions between genetic drift, gene flow, and selection mosaics drive parasite local adaptation. *The American Naturalist* **173**:212-224.
- García-Ramos, G., and M. Kirkpatrick. 1997. Genetic models of adaptation and gene flow in peripheral populations. *Evolution* **51**:21-28.
- Garwood, N. C. 1983. Seed germination in a seasonal tropical forest in Panama: a community study. *Ecological Monographs*:159-181.
- Garwood, N. C., and J. R. B. Lighton. 1990. Physiological ecology of seed respiration in some tropical species. *New Phytologist* **115**:549-558.
- Gentry, A. H. 1988. Changes in plant community diversity and floristic composition on environmental and geographical gradients. *Annals of the Missouri Botanical Garden* **75**:1-34.
- Geyer, C. J., S. Wagenius, and R. G. Shaw. 2007. Aster models for life history analysis. *Biometrika* **94**:415-426.
- Gianoli, E., and M. González-Teuber. 2005. Environmental heterogeneity and population differentiation in plasticity to drought in *Convolvulus chilensis* (Convolvulaceae). *Evolutionary Ecology* **19**:603-613.
- Gilbert, F., P. Willmer, F. Semida, J. Ghazoul, and S. Zalut. 1996. Spatial variation in selection in a plant-pollinator system in the wadis of Sinai, Egypt. *Oecologia* **108**:479-487.
- Gillespie, J. H., and M. Turelli. 1989. Genotype-environment interactions and the maintenance of polygenic variation. *Genetics* **121**:129-138.
- Gilmore, D. W., R. S. Seymour, W. A. Halteman, and M. S. Greenwood. 1995. Canopy dynamics and the morphological development of *Abies balsamea*: effects of foliage age on specific leaf area and secondary vascular development. *Tree Physiology* **15**:47-55.
- Gimeno, T. E., B. País, J. P. Lemos-Filho, and F. Valladares. 2009. Plasticity and stress tolerance override local adaptation in the responses of Mediterranean holm oak seedlings to drought and cold. *Tree Physiology* **29**:87-98.
- Gómez-Aparicio, L., I. M. Pérez-Ramos, I. Mendoza, L. Matías, J. L. Quero, J. Castro, R. Zamora, and T. Marañón. 2008. Oak seedling survival and growth along resource gradients in Mediterranean forests: implications for regeneration in current and future environmental scenarios. *Oikos* **117**:1683-1699.
- Gross, K., and A. Smith. 1991. Seed mass and emergence time effects on performance of *Panicum dichotomiflorum* Michx. across environments. *Oecologia* **87**:270-278.

- Hall, D., V. Luquez, V. M. Garcia, K. R. St Onge, S. Jansson, and P. K. Ingvarsson. 2007. Adaptive population differentiation in phenology across a latitudinal gradient in European Aspen (*Populus tremula*, L.): a comparison of neutral markers, candidate genes and phenotypic traits. *Evolution* **61**:2849-2860.
- Hardegree, S. P., and S. S. Van Vactor. 1999. Predicting germination response of four cool-season range grasses to field-variable temperature regimes. *Environmental and Experimental Botany* **41**:209-217.
- Hawkins, B. A., R. Field, H. V. Cornell, D. J. Currie, J.-F. Guégan, D. M. Kaufman, J. T. Kerr, G. G. Mittelbach, T. Oberdorff, E. M. O'Brien, E. E. Porter, and J. R. G. Turner. 2003. Energy, water, and broad-scale geographic patterns of species richness. *Ecology* **84**:3105-3117.
- Hedrick, P. W. 1986. Genetic polymorphism in heterogeneous environments: a decade later. *Annual Review of Ecology and Systematics* **17**:535-566.
- Heide, O. M. 1974. Growth and dormancy in Norway spruce ecotypes (*Picea abies*) I. Interaction of photoperiod and temperature. *Physiologia Plantarum* **30**:1-12.
- Hereford, J. 2009. A quantitative survey of local adaptation and fitness trade-offs. *The American Naturalist* **173**:579-588.
- Heschel, M. S., K. Donohue, N. Hausmann, and J. Schmitt. 2002. Population differentiation and natural selection for water-use efficiency in *Impatiens capensis* (Balsaminaceae). *International Journal of Plant Sciences* **163**:907-912.
- Hijmans, R. j., S. E. Cameron, J. L. Parra, P. G. Jones, and A. Jarvis. 2005. Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* **25**:1965-1978.
- Housman, D. C., M. V. Price, and R. A. Redak. 2002. Architecture of coastal and desert *Encelia farinosa* (Asteraceae): consequences of plastic and heritable variation in leaf characters. *American Journal of Botany* **89**:1303-1310.
- Howe, G. T., W. P. Hackett, G. R. Furnier, and R. E. Klevorn. 1995. Photoperiodic responses of a northern and southern ecotype of black cottonwood. *Physiologia Plantarum* **93**:695-708.
- Hsieh, F. Y., P. W. Lavori, H. J. Cohen, and J. R. Feussner. 2003. An overview of variance inflation factors for sample-Size calculation. *Evaluation & the Health Professions* **26**:239-257.
- Hubbard, R. M., M. G. Ryan, V. Stiller, and J. S. Sperry. 2001. Stomatal conductance and photosynthesis vary linearly with plant hydraulic conductance in ponderosa pine. *Plant, Cell & Environment* **24**:113-121.
- Huey, R. B., and P. E. Hertz. 1984. Is a jack-of-all-temperatures a master of none? *Evolution* **38**:441-444.
- Hughes, A. R., and J. J. Stachowicz. 2004. Genetic diversity enhances the resistance of a seagrass ecosystem to disturbance. *Proceedings of the National Academy of Sciences of the United States of America* **101**:8998-9002.
- IPCC. 2013a. Climate Change 2013: The Physical Science Basis. Intergovernmental Panel on Climate Change.

- IPCC. 2013b. Climate Change 2013: The Physical Science Basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change.
- Iwasa, Y. O. H., and T. Kubo. 1997. Optimal size of storage for recovery after unpredictable disturbances. *Evolutionary Ecology* **11**:41-65.
- Janzen, D. H. 1983. Costa Rican natural history. University of Chicago Press.
- Jones, R., B. Allen, and R. Sharitz. 1997. Why do early-emerging tree seedlings have survival advantages?: a test using *Acer rubrum* (Aceraceae). *American Journal of Botany* **84**:1714.
- Jump, A. S., and J. Peñuelas. 2005. Running to stand still: adaptation and the response of plants to rapid climate change. *Ecology Letters* **8**:1010-1020.
- Kalisz, S. 1986. Variable selection on the timing of germination in *Collinsia verna* (Scrophulariaceae). *Evolution* **40**:479-491.
- Kawecki, T. J., and D. Ebert. 2004. Conceptual issues in local adaptation. *Ecology Letters* **7**:1225-1241.
- Khurana, E., and J. S. Singh. 2001. Ecology of seed and seedling growth for conservation and restoration of tropical dry forest : a review. *Environmental Conservation* **28**:39-52.
- Kissing, L. B., and J. S. Powers. 2010. Coarse woody debris stocks as a function of forest type and stand age in Costa Rican tropical dry forest: long-lasting legacies of previous land use. *Journal of Tropical Ecology* **26**:467-471.
- Kittelson, P. M., and J. L. Maron. 2001. Fine-scale genetically based differentiation on life-history traits in the perennial shrub *Lupinus arboreus*. *Evolution* **55**:2429-2438.
- Klemens, J., N. Deacon, and J. Cavender-Bares. 2010. Limits to pasture recolonization in a fragmented tropical dry forest: a case study of the tropical live oak *Quercus oleoides* with implications for restoration. *Seasonally Dry Tropical Forests*.
- Köchy, M., and K. Tielbörger. 2007. Hydrothermal time model of germination: Parameters for 36 Mediterranean annual species based on a simplified approach. *Basic and Applied Ecology* **8**:171-182.
- Kremer, A., J. Kleinschmit, J. Cottrell, E. P. Cundall, J. D. Deans, A. Ducouso, A. O. König, A. J. Lowe, R. C. Munro, R. J. Petit, and B. R. Stephan. 2002. Is there a correlation between chloroplastic and nuclear divergence, or what are the roles of history and selection on genetic diversity in European oaks? *Forest Ecology and Management* **156**:75-87.
- Lafond, G. P., and R. J. Baker. 1986. Effects of temperature, moisture stress, and seed size on germination of nine spring wheat cultivars. *Crop Science* **26**:563-567.
- Lammi, A., P. Siikamaki, and K. Mustajarvi. 2001. Genetic diversity, population size, and fitness in central and peripheral populations of a rare plant *Lychnis viscaria*. *Conservation Biology* **13**:1069-1078.
- Lande, R. 1976. Natural selection and random genetic drift in phenotypic evolution. *Evolution* **30**:314-334.
- Lande, R. 1979. Quantitative genetic analysis of multivariate evolution, applied to brain: body size allometry. *Evolution*:402-416.

- Lande, R., and S. J. Arnold. 1983. The measurement of selection on correlated characters. *Evolution* **37**:1210-1226.
- Larcher, W. 2003. *Physiological plant ecology: ecophysiology and stress physiology of functional groups*. Springer Science & Business Media.
- Lawler, J. J., S. L. Shafer, D. White, P. Kareiva, E. P. Maurer, A. R. Blaustein, and P. J. Bartlein. 2009. Projected climate-induced faunal change in the Western Hemisphere. *Ecology* **90**:588-597.
- Leger, E. A., E. K. Espeland, K. R. Merrill, and S. E. Meyer. 2009. Genetic variation and local adaptation at a cheatgrass (*Bromus tectorum*) invasion edge in western Nevada. *Molecular Ecology* **18**:4366-4379.
- Leimu, R., and M. Fischer. 2008. A Meta-analysis of local adaptation in plants. *PLoS ONE* **3**:e4010.
- Lenormand, T. 2002. Gene flow and the limits to natural selection. *Trends in Ecology & Evolution* **17**:183-189.
- Levene, H. 1953. Genetic equilibrium when more than one ecological niche is available. *The American Naturalist* **87**:331-333.
- Levins, R. 1962. Theory of fitness in a heterogeneous environment. I. The fitness set and adaptive function. *The American Naturalist* **96**:361-373.
- Levins, R. 1963. Theory of fitness in a heterogeneous environment. II. Developmental flexibility and niche selection. *The American Naturalist* **97**:75-90.
- Linhart, Y. B., and M. C. Grant. 1996. Evolutionary significance of local genetic differentiation in plants. *Annual Review of Ecology and Systematics* **27**:237-277.
- Lopez, S., F. Rousset, F. H. Shaw, R. G. Shaw, and O. Ronce. 2008. Migration load in plants: role of pollen and seed dispersal in heterogeneous landscapes. *J Evol Biol* **21**:294-309.
- Lynch, M., M. Pfrender, K. Spitz, N. Lehman, J. Hicks, D. Allen, L. Latta, M. Ottene, F. Bogue, and J. Colbourne. 1999. The quantitative and molecular genetic architecture of a subdivided species. *Evolution*:100-110.
- Malcolm, J. R., A. Markham, R. P. Neilson, and M. Garaci. 2002. Estimated migration rates under scenarios of global climate change. *Journal of Biogeography* **29**:835-849.
- Malhi, Y., and O. L. Phillips. 2004. Tropical Forests and Global Atmospheric Change: A Synthesis. *Philosophical Transactions: Biological Sciences* **359**:549-555.
- Maximov, N. A., and R. Yapp. 1929. *The Plant in relation to water. A study of the physiological basis of drought resistance*. Alien & Unwin, London.
- Mendoza, B., V. García-Acosta, V. Velasco, E. Jáuregui, and R. Díaz-Sandoval. 2007. Frequency and duration of historical droughts from the 16th to the 19th centuries in the Mexican Maya lands, Yucatan Peninsula. *Climatic Change* **83**:151-168.
- Mercer, K. L., H. M. Alexander, and A. A. Snow. 2011. Selection on seedling emergence timing and size in an annual plant, *Helianthus annuus* (common sunflower, Asteraceae). *American Journal of Botany* **98**:975-985.
- Miller, R. E., and N. L. Fowler. 1994. Life history variation and local adaptation within two populations of *Bouteloua rigidiseta* (Texas Grama). *Journal of Ecology* **82**:855-864.

- Moeller, D. A., M. A. Geber, and P. Tiffin. 2011. Population genetics and the evolution of geographic range limits in an annual plant. *The American Naturalist* **178**:S44-S57.
- Moles, A. T., and M. Westoby. 2004. Seedling survival and seed size: a synthesis of the literature. *Journal of Ecology* **92**:372-383.
- Muir, G., A. J. Lowe, C. C. Fleming, and C. Vogl. 2004. High nuclear genetic diversity, high levels of outcrossing and low differentiation among remnant populations of *Quercus petraea* at the margin of its range in Ireland. *Annals of Botany* **93**:691-697.
- Mulkey, S. S., A. P. Smith, S. J. Wright, J. L. Machado, and R. Dudley. 1992. Contrasting leaf phenotypes control seasonal variation in water loss in a tropical forest shrub. *Proceedings of the National Academy of Sciences* **89**:9084-9088.
- Muller, C. H. 1961. The live oaks of the series *Virentes*. *American Midland Naturalist* **65**:17-39.
- Nageswara Rao, R. C., H. S. Talwar, and G. C. Wright. 2001. Rapid assessment of specific leaf area and leaf nitrogen in peanut (*Arachis hypogaea* L.) using a chlorophyll meter. *Journal of Agronomy and Crop Science* **186**:175-182.
- Nixon, K. C. 1985. A biosystematic study of *Quercus* series *Virentes* (the live oaks) with phylogenetic analyses of Fagales, Fagaceae and *Quercus*. University of Texas, Austin, TX.
- O'Leary, M. H., S. Madhavan, and P. Paneth. 1992. Physical and chemical basis of carbon isotope fractionation in plants. *Plant, Cell & Environment* **15**:1099-1104.
- Parmesan, C. 2006. Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics* **37**:637-669.
- Parolin, P. 2001. Seed germination and early establishment of 12 tree species from nutrient-rich and nutrient-poor Central Amazonian floodplains. *Aquatic Botany* **70**:89-103.
- Partanen, J., V. Koski, and H. Hänninen. 1998. Effects of photoperiod and temperature on the timing of bud burst in Norway spruce (*Picea abies*). *Tree Physiology* **18**:811-816.
- Pearson, T. R. H., D. F. R. P. Burslem, R. E. Goeriz, and J. W. Dalling. 2003. Regeneration niche partitioning in neotropical pioneers: effects of gap size, seasonal drought and herbivory on growth and survival. *Oecologia* **137**:456-465.
- Pearson, T. R. H., D. F. R. P. Burslem, C. E. Mullins, and J. W. Dalling. 2002. Germination ecology of neotropical pioneers: interacting effects of environmental conditions and seed size. *Ecology* **83**:2798-2807.
- Peguero-Pina, J. J., D. Sancho-Knapik, E. Barrón, J. J. Camarero, A. Vilagrosa, and E. Gil-Pelegrín. 2014. Morphological and physiological divergences within *Quercus ilex* support the existence of different ecotypes depending on climatic dryness. *Annals of Botany* **114**:301-313.
- Perry, C. A., and K. J. Hsu. 2000. Geophysical, archaeological, and historical evidence support a solar-output model for climate change. *Proceedings of the National Academy of Sciences* **97**:12433-12438.

- Petit, R. J., and A. Hampe. 2006. Some evolutionary consequences of being a tree. *Annual Review of Ecology, Evolution, and Systematics* **37**:187-214.
- Pierce, A., and S. King. 2007. The effects of flooding and sedimentation on seed germination of two bottomland hardwood tree species. *Wetlands* **27**:588-594.
- Pigliucci, M., and C. D. Schlichting. 1996. Reaction norms of *Arabidopsis*. IV. Relationships between plasticity and fitness. *Heredity* **76**:427-436.
- Pigliucci, M., J. Whitton, and C. D. Schlichting. 1995. Reaction norms of *Arabidopsis*. I. Plasticity of characters and correlations across water, nutrient and light gradients. *Journal of Evolutionary Biology* **8**:421-438.
- Piña-Rodrigues, F. C. M., and M. B. Figliolia. 2005. Embryo immaturity associated with delayed germination in recalcitrant seeds of *Virola surinamensis* (Rol.) Warb. (Myristicaceae). *Seed Science and Technology* **33**:375-386.
- Poorter, H., Ü. Niinemets, L. Poorter, I. J. Wright, and R. Villar. 2009. Causes and consequences of variation in leaf mass per area (LMA): a meta-analysis. *New Phytologist* **182**:565-588.
- Poorter, L., M. van de Plassche, S. Willems, and R. G. A. Boot. 2004. Leaf traits and herbivory rates of tropical Tree species differing in successional status. *Plant Biology* **6**:746-754.
- Portillo-Quintero, C. A., and G. A. Sanchez-Azofeifa. 2010. Extent and conservation of tropical dry forests in the Americas. *Biological Conservation* **143**:144-155.
- Powers, J. S., J. M. Becknell, J. Irving, and D. Perez-Aviles. 2009. Diversity and structure of regenerating tropical dry forests in Costa Rica: Geographic patterns and environmental drivers. *Forest Ecology and Management* **258**:959-970.
- Powers, J. S., and E. Veldkamp. 2005. Regional variation in soil carbon and $\delta^{13}C$ in forests and pastures of northeastern Costa Rica. *Biogeochemistry* **72**:315-336.
- Premoli, A. C., E. Raffaele, and P. Mathiasen. 2007. Morphological and phenological differences in *Nothofagus pumilio* from contrasting elevations: Evidence from a common garden. *Austral Ecology* **32**:515-523.
- Queenborough, S. A., and C. Porras. 2013. Expanding the coverage of plant trait databases – A comparison of specific leaf area derived from fresh and dried leaves. *Plant Ecology & Diversity* **7**:383-388.
- Ramírez-Valiente, J. A., K. Koehler, and J. Cavender-Bares. 2015. Climatic origins predict variation in photoprotective leaf pigments in response to drought and low temperatures in live oaks (*Quercus* series *Virentes*). *Tree Physiology*.
- Ramírez-Valiente, J. A., D. Sánchez-Gómez, I. Aranda, and F. Valladares. 2010. Phenotypic plasticity and local adaptation in leaf ecophysiological traits of 13 contrasting cork oak populations under different water availabilities. *Tree Physiology* **30**:618-627.
- Ramírez-Valiente, J. A., F. Valladares, L. Gil, and I. Aranda. 2009. Population differences in juvenile survival under increasing drought are mediated by seed size in cork oak (*Quercus suber* L.). *Forest Ecology and Management* **257**:1676-1683.
- Rehfeldt, G., W. Wykoff, and C. Ying. 2001. Physiologic plasticity, evolution, and impacts of a changing climate on *Pinus contorta*. *Climatic Change* **50**:355-376.

- Rehfeldt, G. E. 1999. Systematics and genetic structure of Ponderosae taxa (Pinaceae) inhabiting the mountain islands of the Southwest. *American Journal of Botany* **86**:741.
- Rehfeldt, G. E., N. M. Tchebakova, Y. I. Parfenova, W. R. Wykoff, N. A. Kuzmina, and L. I. Milyutin. 2002. Intraspecific responses to climate in *Pinus sylvestris*. *Global Change Biology* **8**:912-929.
- Rehfeldt, G. E., C. C. Ying, D. L. Spittlehouse, and D. A. Hamilton. 1999. Genetic responses to climate in *Pinus contorta*: niche breadth, climate change, and reforestation *Ecological Monographs* **69**:375-407.
- Reich, P. B. 1995. Phenology of tropical forests: patterns, causes and consequences. *Canadian Journal of Botany* **73**:164-165.
- Reich, P. B., and R. Borchert. 1982. Phenology and ecophysiology of the tropical tree, *Tabebuia neochrysantha* (Bignoniaceae). *Ecology* **63**:294-299.
- Robakowski, P., Y. Li, and P. Reich. 2012. Local ecotypic and species range-related adaptation influence photosynthetic temperature optima in deciduous broadleaved trees. *Plant Ecology* **213**:113-125.
- Rozendaal, D. M. A., V. H. Hurtado, and L. Poorter. 2006. Plasticity in leaf traits of 38 tropical tree species in response to light; relationships with light demand and adult stature. *Functional Ecology* **20**:207-216.
- Sack, L., P. D. Cowan, N. Jaikumar, and N. M. Holbrook. 2003. The 'hydrology' of leaves: co-ordination of structure and function in temperate woody species. *Plant, Cell & Environment* **26**:1343-1356.
- Sack, L., P. J. Melcher, W. H. Liu, E. Middleton, and T. Pardee. 2006. How strong is intracopy leaf plasticity in temperate deciduous trees? *American Journal of Botany* **93**:829-839.
- Sack, L., M. T. Tyree, and N. M. Holbrook. 2005. Leaf hydraulic architecture correlates with regeneration irradiance in tropical rainforest trees. *New Phytologist* **167**:403-413.
- Savage, J. A., and J. Cavender-Bares. 2012. Habitat specialization and the role of trait lability in structuring diverse willow (genus *Salix*) communities. *Ecology* **93**:S138-S150.
- Savolainen, O., T. Pyhäjärvi, and T. Knürr. 2007. Gene flow and local adaptation in trees. *Annual Review of Ecology, Evolution, and Systematics* **38**:595-619.
- Scheepens, J. F., and J. Stöcklin. 2013. Flowering phenology and reproductive fitness along a mountain slope: maladaptive responses to transplantation to a warmer climate in *Campanula thyrsoidea*. *Oecologia* **171**:679-691.
- Schemske, D. W. 1984. Population structure and local selection in *Impatiens pallida* (Balsaminaceae), a selfing annual. *Evolution* **38**:817-832.
- Schlichting, C. D. 1986. The evolution of phenotypic plasticity in plants. *Annual Review of Ecology and Systematics* **17**:667-693.
- Schlichting, C. D., and D. A. Levin. 1990. Phenotypic plasticity in Phlox. III. Variation among natural populations of *P. drummondii*. *Journal of Evolutionary Biology* **3**:411-428.

- Schlichting, C. D., and M. Pigliucci. 1998. Phenotypic evolution: a reaction norm perspective. Sinauer Associates Incorporated.
- Schmid, B. 1985. Clonal growth in grassland perennials. III. Genetics variation and plasticity between and within populations of *Bellis perennis* and *Prunella vulgaris*. *Journal of Ecology* **73**:819-830.
- Seiwa, K. 2000. Effects of seed size and emergence time on tree seedling establishment: importance of developmental constraints. *Oecologia* **123**:208-215.
- Shaw, R. G., and C. J. Geyer. 2010. Inferring fitness landscapes. *Evolution* **64**:2510-2520.
- Shaw, R. G., C. J. Geyer, S. Wagenius, H. H. Hangelbroek, and J. R. Etterson. 2008. Unifying life history analyses for inference of fitness and population growth. *The American Naturalist* **172**:35-47.
- Shields, L. 1950. Leaf xeromorphy as related to physiological and structural influences. *The Botanical Review* **16**:399-447.
- Shimono, Y., and G. Kudo. 2003. Intraspecific variations in seedling emergence and survival of *Potentilla matsumurae* (Rosaceae) between alpine fellfield and snowbed habitats. *Annals of Botany* **91**:21-29.
- Silander, J. A., and J. Antonovics. 1979. The genetic basis of the ecological amplitude of *Spartina patens*. I. Morphometric and physiological traits. *Evolution*:1114-1127.
- Simons, A. M., and M. O. Johnston. 2000. Variation in seed traits of *Lobelia inflata* (Campanulaceae): sources and fitness consequences. *American Journal of Botany* **87**:124-132.
- Slatkin, M. 1985. Gene flow in natural populations. *Annual Review of Ecology and Systematics*:393-430.
- Slatkin, M. 1987. Gene flow and the geographic structure of natural populations. *Science* **236**:787-792.
- Stanton, M. L. 1984. Seed variation in wild radish: effect of seed size on components of seedling and adult fitness. *Ecology* **65**:1105-1112.
- Stinson, K. A. 2004. Natural selection favors rapid reproductive phenology in *Potentilla pulcherrima* (Rosaceae) at opposite ends of a subalpine snowmelt gradient. *American Journal of Botany* **91**:531-539.
- Storz, J. F. 2002. Contrasting patterns of divergence in quantitative traits and neutral DNA markers: analysis of clinal variation. *Molecular Ecology* **11**:2537-2551.
- Stratton, D. A. 1992. Life-cycle components of selection in *Erigeron annuus*: II. genetic variation. *Evolution* **46**:107-120.
- Sultan, S. E. 1987. Evolutionary implications of phenotypic plasticity in plants. Pages 127-178 in M. Hecht, B. Wallace, and G. Prance, editors. *Evolutionary Biology*. Springer US.
- Sultan, S. E., A. M. Wilczek, S. D. Hann, and B. J. Brosi. 1998. Contrasting ecological breadth of co-occurring annual *Polygonum* species. *Journal of Ecology* **86**:363-383.
- ten Brink, D.-J., H. P. Hendriksma, and H. H. Bruun. 2013. Habitat specialization through germination cueing: a comparative study of herbs from forests and open habitats. *Annals of Botany* **111**:283-292.

- Thomas, F. M., R. Blank, and G. Hartmann. 2002. Abiotic and biotic factors and their interactions as causes of oak decline in Central Europe. *Forest Pathology* **32**:277-307.
- Travisano, M., J. Mongold, A. Bennett, and R. Lenski. 1995. Experimental tests of the roles of adaptation, chance, and history in evolution. *Science* **267**:87-90.
- Turesson, G. 1922. The genotypical response of the plant species to the habitat. *Hereditas* **3**:211-350.
- Vaartaja, O. 1959. Evidence of photoperiodic ecotypes in trees. *Ecological Monographs* **29**:92-111.
- Valladares, F., E. Gianoli, and J. M. Gomez. 2007. Ecological limits to plant phenotypic plasticity. *New Phytologist* **176**:749-763.
- Vazquez-Yanes, C., and A. Orozco-Segovia. 1993. Patterns of seed longevity and germination in the tropical rainforest. *Annual Review of Ecology and Systematics* **24**:69-87.
- Vázquez-Yanes, C., and H. Smith. 1982. Phytochrome control of seed germination in the tropical rain forest pioneer trees *Cecropia obtusifolia* and *Piper auritum* and its ecological significance *New Phytologist* **92**:477-485.
- Veenendaal, E., M. Swaine, D. Newbery, H. Prins, and N. Brown. 1998. Limits to tree species distributions in lowland tropical rainforest. Pages 163-191 *in* Dynamics of tropical communities: the 37th symposium of the British Ecological Society, Cambridge University, 1996. Blackwell Science Ltd.
- Verdú, M., and A. Traveset. 2005. Early emergence enhances plant fitness: a phylogenetically controlled meta-analysis. *Ecology* **86**:1385-1394.
- Via, S., and R. Lande. 1985. Genotype-environment interaction and the evolution of phenotypic plasticity. *Evolution* **39**:505-522.
- Wagner, M., and N. Mitschunas. 2008. Fungal effects on seed bank persistence and potential applications in weed biocontrol: A review. *Basic and Applied Ecology* **9**:191-203.
- Walsh, B., and M. W. Blows. 2009. Abundant genetic variation + strong selection = multivariate genetic constraints: a geometric view of adaptation. *Annual Review of Ecology, Evolution, and Systematics* **40**:41-59.
- Walters, M. B., and P. B. Reich. 2000. Seed size, nitrogen supply, and growth rate affect tree seedling survival in deep shade. *Ecology* **81**:1887-1901.
- Weiher, E., A. van der Werf, K. Thompson, M. Roderick, E. Garnier, and O. Eriksson. 1999. Challenging Theophrastus: A common core list of plant traits for functional ecology. *Journal of Vegetation Science* **10**:609-620.
- Weinig, C. 2000. Plasticity versus canalization: population differences in the timing of shade-avoidance responses. *Evolution* **54**:441-451.
- Willis, C. G., C. C. Baskin, J. M. Baskin, J. R. Auld, D. L. Venable, J. Cavender-Bares, K. Donohue, and R. R. d. Casas. 2014. The evolution of seed dormancy: environmental cues, evolutionary hubs, and diversification of the seed plants. *New Phytologist* **203**:300-309.
- Wright, I. J., and K. Cannon. 2001. Relationships between leaf lifespan and structural defences in a low-nutrient, sclerophyll flora. *Functional Ecology* **15**:351-359.

- Wright, I. J., P. B. Reich, M. Westoby, D. D. Ackerly, Z. Baruch, F. Bongers, J. Cavender-Bares, T. Chapin, J. H. Cornelissen, M. Diemer, J. Flexas, E. Garnier, P. K. Groom, J. Gulias, K. Hikosaka, B. B. Lamont, T. Lee, W. Lee, C. Lusk, J. J. Midgley, M. L. Navas, U. Niinemets, J. Oleksyn, N. Osada, H. Poorter, P. Poot, L. Prior, V. I. Pyankov, C. Roumet, S. C. Thomas, M. G. Tjoelker, E. J. Veneklaas, and R. Villar. 2004. The worldwide leaf economics spectrum. *Nature* **428**:821-827.
- Wright, J. 2007. Local adaptation to serpentine soils in *Pinus ponderosa*. *Plant and Soil* **293**:209-217.
- Wulff, R. D. 1986. Seed size variation in *Desmodium paniculatum* II. Effects on seedling growth and physiological performance. *Ecology* **74**:99-114.
- Zangerl, A. R., and F. A. Bazzaz. 1984. Effects of short-term selection along environmental gradients on variation in populations of *Amaranthus retroflexus* and *Abutilon theophrasti*. *Ecology* **65**:207-217.
- Zhang, J., and B. M. Cregg. 2005. Growth and physiological responses to varied environments among populations of *Pinus ponderosa*. *Forest Ecology and Management* **219**:1-12.
- Zohar, Y., Y. Waisel, and R. Karschon. 1975. Effects of Light, Temperature and Osmotic Stress on Seed Germination of *Eucalyptus occidentalis*. *Australian Journal of Botany* **23**:391-397.

Appendix 1- Supplemental Material for Chapter 1

Effect	Germination			DTG			Survival			Fitness			
	Est	SE	Z	Est	SE	T	Est	SE	Z	Effect	Est	SE	Z
Intercept (ADT)	-2.29	0.60	-3.81	106.88	16.54	6.46	3.34	1.37	2.44	Intercept	-1.78	0.12	-14.87
AWT	0.67	0.45	1.51	10.19	12.74	0.80	-1.26	0.92	-1.38	Germination	-6.59	0.36	-18.13
SWT	0.02	0.47	0.05	37.53	13.70	2.74	1.96	1.45	1.36	Survival	3.68	0.17	21.41
LE Pop	-1.21	0.68	-1.78	-37.07	13.13	-2.82	-1.28	0.98	-1.31	LE Pop	-0.40	0.11	-3.75
LC	0.81	0.43	1.89	46.24	21.75	2.13	-0.70	0.92	-0.76	LC	0.14	0.04	3.60
AWT x LC	-0.07	0.53	-0.13	-6.17	4.29	-1.43	-0.40	0.98	0.42	ADT	0.07	0.08	0.89
SWT x LC	0.46	0.56	0.83	-38.72	28.51	-1.36	-0.83	1.41	-1.05	AWT	-0.72	0.13	-5.49
AWT x LE Pop	-0.31	0.80	-0.39	-46.53	26.40	-1.76	0.35	0.79	-1.66	AWT x LC	0.26	0.11	2.44
SWT x LE Pop	0.85	0.76	1.11	7.40	17.07	0.43	0.08	1.11	-0.22	SWT x LC	0.25	0.06	4.44
LE Pop x LC	1.95	0.72	2.71	-25.79	17.83	-1.45	1.29	0.89	2.23	AWT x LE Pop	0.15	0.26	0.56
AWT x LE Pop x LC	0.59	0.92	0.64	-47.08	23.65	-1.99	--	--	--	SWT x LE Pop	0.44	0.11	3.92
SWT x LE Pop x LC	-0.41	0.89	-0.46	28.91	31.49	0.92	--	--	--	Low Pop x LC	0.33	0.10	3.20
Seed Size	0.03	0.15	0.19	41.13	29.53	1.39	-0.21	0.31	-0.66	AWT x LE Pop x LC	-0.04	0.27	-0.14
DTG	--	--	--	--	--	--	-0.01	0.00	-1.77	SWT x LE Pop x LC	-0.45	0.12	-3.76
										Seed Size	0.01	0.00	22.93
										DTG	0.10	0.02	5.72

Table S1.1- Summary of model effect estimates for germination, days to germination (DTG), survival, and fitness for *Q. oleoides* on progeny from early- and late-cohort (EC or LC) *Quercus oleoides* seeds sampled from a high-elevation and low-elevation populations

and reciprocally planted into three watering treatments in NW Costa Rica: ambient dry treatment (ADT) and supplemental water treatment (SWT) at low-elevation site, ambient wet treatment (AWT) at high-elevation site.

Effect	DF	Height		Leaf Number		Basal Diameter		Longest Leaf Length	
		χ^2		χ^2		χ^2		χ^2	
Population (P)	12,13	2.69		6.90	**	3.00	+	9.30	**
Cohort (C)	12,13	3.02	+	0.01		14.64	***	7.39	**
Treatment (T)	11,13	22.16	***	24.86	***	21.89	***	34.34	***
Time	11,13	540.42	***	165.59	***	601.67	***	29.38	***
Time x P	19,21	2.99		4.90	+	6.17	**	0.41	
Time x C	19,21	0.59		0.63		1.94		0.15	
Time x T	17,21	230.00	***	216.10	***	119.92	***	137.53	***
P x C	25,26	0.65		6.87	**	0.02		0.13	
P x T	24,26	0.41		1.24		1.03		2.25	
C x T	24,26	8.80	*	3.03		6.23	*	10.21	**
Time x P x T	32,36	3.41		0.95		4.20		2.72	
Time x C x T	32,36	2.78		6.56		0.75		0.72	
Time x P x C	34,36	2.91		7.22	*	2.60		1.19	
P x C x T	36,38	1.63		0.49		0.11		2.72	
Days to germination (DTG)	41,42	4.81	*	2.88	+	9.84	**	3.72	*
Time x P x C x T	38,44	4.73		7.76		7.87	*	8.75	
Time x DTG	42,44	0.04		4.98	+	12.51		4.78	+
Seed Mass	43,44	4.05	**	4.83	**	2.07		0.39	

Table S1.2- Repeated measures analysis of traits measured for three seasons on progeny from early- and late-cohort *Quercus oleoides* seeds sampled from a high-elevation and low-elevation populations and reciprocally planted into three watering treatments in NW Costa Rica: ambient dry treatment (ADT) and supplemental water treatment (SWT) at low-elevation site, ambient wet treatment (AWT) at high-elevation site. Degrees of freedom shown are for nested models for all traits. +0.10 \geq P>0.05; * P \leq 0.05, ** P \leq 0.01; ***<0.001

Effect	Stem Height			Leaf Number ⁺			Basal Diameter ⁺			Length of Longest Leaf		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Time 1 (T1)	2.54	0.45	5.63	1.74	0.46	3.78	1.33	0.12	11.20	2.23	0.21	10.56
Time 2 (T2)	4.92	0.46	10.73	3.17	0.47	6.75	1.77	0.12	14.69	2.58	0.22	11.95
Time 3 (T3)	5.72	0.46	12.46	3.54	0.47	7.53	2.17	0.12	18.01	2.63	0.22	12.16
AWT	0.08	0.41	0.20	0.03	0.42	0.08	-0.03	0.10	-0.34	-0.21	0.19	-1.09
SWT	1.26	0.43	2.93	1.20	0.44	2.70	0.34	0.11	3.12	0.36	0.20	1.78
LE Pop	0.35	0.57	0.62	0.64	0.61	1.06	0.22	0.16	1.41	0.24	0.31	0.78
Late Cohort (LC)	0.42	0.37	1.15	0.50	0.39	1.28	-0.10	0.10	-0.99	-0.32	0.20	-1.63
Days to germination (DTG)	0.00	0.00	-1.86	0.00	0.00	-2.40	0.00	0.00	-4.21	0.00	0.00	-2.64
Seed size	0.19	0.09	2.03	0.21	0.09	2.22	0.04	0.02	1.45	0.03	0.04	0.63
T2 x AWT	-1.80	0.39	-4.65	-1.08	0.44	-2.46	-0.40	0.11	-3.60	-0.44	0.25	-1.72
T3 x AWT	-2.90	0.38	-7.55	-2.97	0.43	-6.85	-0.57	0.11	-5.26	-1.46	0.25	-5.80
T2 x SWT	-0.56	0.39	-1.43	-0.48	0.44	-1.09	-0.33	0.11	-2.94	-0.29	0.26	-1.12
T3 x SWT	-0.48	0.39	-1.22	-0.85	0.44	-1.91	-0.29	0.11	-2.56	-0.50	0.26	-1.91
T2 x LE Pop	-0.35	0.73	-0.49	-0.99	0.82	-1.20	-0.25	0.21	-1.20	-0.15	0.47	-0.32
T3 x LE Pop	-0.98	0.65	-1.51	-1.32	0.73	-1.81	-0.58	0.18	-3.18	-0.44	0.42	-1.05
AWT x LE Pop	-0.94	0.83	-1.13	-0.98	0.88	-1.12	-0.35	0.23	-1.53	-0.19	0.45	-0.41
SWT x LE Pop	-0.51	0.69	-0.74	-0.74	0.73	-1.01	-0.43	0.19	-2.31	-0.17	0.37	-0.45
T2 x LC	-0.37	0.40	-0.93	0.13	0.45	0.29	0.05	0.11	0.44	0.02	0.26	0.06
T3 x LC	-0.54	0.40	-1.36	-0.24	0.45	-0.54	-0.08	0.11	-0.68	0.05	0.26	0.21
AWT x LC	-0.63	0.47	-1.35	-0.45	0.50	-0.90	-0.01	0.13	-0.09	0.35	0.25	1.38
SWT x LC	-1.18	0.48	-2.46	-1.09	0.51	-2.14	-0.35	0.13	-2.64	-0.21	0.26	-0.83
LE Pop x LC	-0.51	0.64	-0.80	-1.04	0.67	-1.54	-0.20	0.17	-1.18	-0.02	0.34	-0.05
T2 x DTG	0.00	0.00	0.13	0.00	0.00	0.75	0.00	0.00	2.66	0.00	0.00	0.94
T3 x DTG	0.00	0.00	0.18	0.00	0.00	2.21	0.00	0.00	2.10	0.00	0.00	2.19
T2 x AWT x LE Pop	0.18	0.98	0.18	0.90	1.11	0.81	0.31	0.28	1.10	0.15	0.64	0.24

T3 x AWT x LE Pop	1.40	0.92	1.52	2.81	1.04	2.69	0.52	0.26	1.99	1.38	0.61	2.28
T2 x SWT x LE Pop	0.46	0.86	0.53	1.36	0.97	1.40	0.47	0.24	1.93	0.27	0.56	0.49
T3 x SWT x LE Pop	1.67	0.78	2.13	2.18	0.88	2.47	0.88	0.22	3.98	0.59	0.51	1.16
T2 x AWT x LC	0.46	0.53	0.87	-0.07	0.60	-0.11	0.04	0.15	0.25	0.13	0.35	0.39
T3 x AWT x LC	0.98	0.54	1.82	0.67	0.61	1.10	0.14	0.15	0.90	0.31	0.35	0.89
T2 x SWT x LC	0.37	0.52	0.71	0.23	0.59	0.40	0.28	0.15	1.89	0.23	0.34	0.67
T3 x SWT x LC	1.03	0.52	2.00	1.71	0.58	2.93	0.34	0.15	2.35	0.26	0.34	0.77
T2 x LE Pop x LC	0.09	0.79	0.12	0.80	0.89	0.90	0.13	0.22	0.60	0.12	0.51	0.24
T3 x LE Pop x LC	0.40	0.72	0.56	0.80	0.81	0.99	0.42	0.20	2.06	0.21	0.47	0.46
AWT x LE Pop x LC	1.04	0.91	1.14	1.18	0.96	1.22	0.26	0.25	1.07	-0.02	0.49	-0.04
SWT x LE Pop x LC	0.50	0.78	0.64	0.95	0.83	1.15	0.47	0.21	2.20	0.17	0.42	0.40
T2 x AWT x LE Pop x LC	-0.13	1.07	-0.12	-0.98	1.20	-0.81	-0.21	0.30	-0.71	-0.12	0.70	-0.18
T3 x AWT x LE Pop x LC	-0.91	1.02	-0.89	-2.42	1.15	-2.10	-0.43	0.29	-1.49	-1.29	0.67	-1.93
T2 x SWT x LE Pop x LC	-0.33	0.95	-0.35	-1.53	1.07	-1.44	-0.49	0.27	-1.84	-0.34	0.61	-0.55
T3 x SWT x LE Pop x LC	-1.49	0.88	-1.70	-2.48	0.99	-2.51	-0.86	0.25	-3.46	-0.29	0.57	-0.51

Table S1.3- Summary of repeated measures model estimates for growth traits (stem height, leaf number, basal diameter, and length of longest leaf) measured for at the end of each season (three time points). Traits measured were measured for three seasons (times) on progeny from early- and late-cohort *Quercus oleoides* seeds sampled from a high-elevation and low-elevation populations (CRH and CRL respectively) and reciprocally planted into three watering treatments in NW Costa Rica: ambient dry treatment (ADT) and supplemental water treatment (SWT) at low-elevation site, ambient wet treatment (AWT) at high-elevation site.

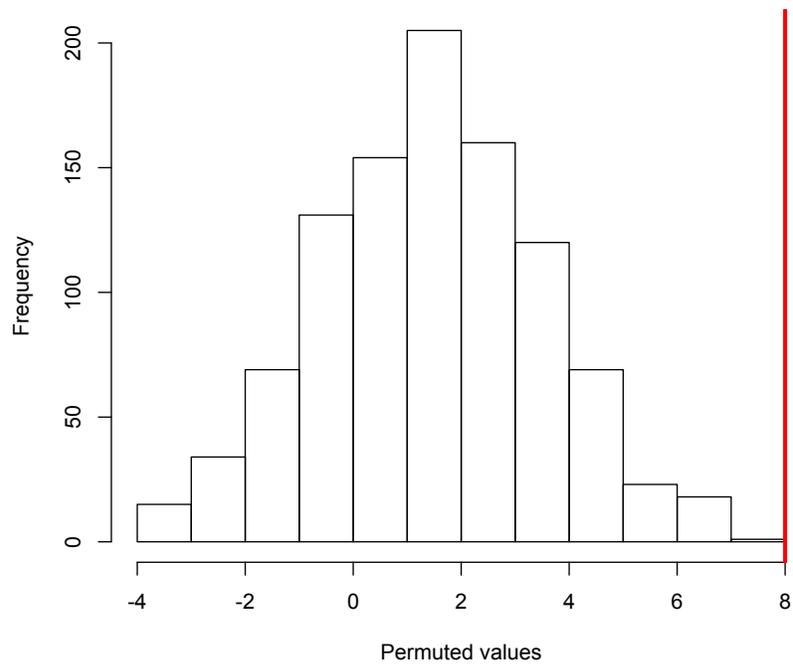


Figure S1.1- Histogram of a null model generated from 999 permutations from observed phenology differences of maternal *Quercus oleoides* trees monitored for seed production timing.

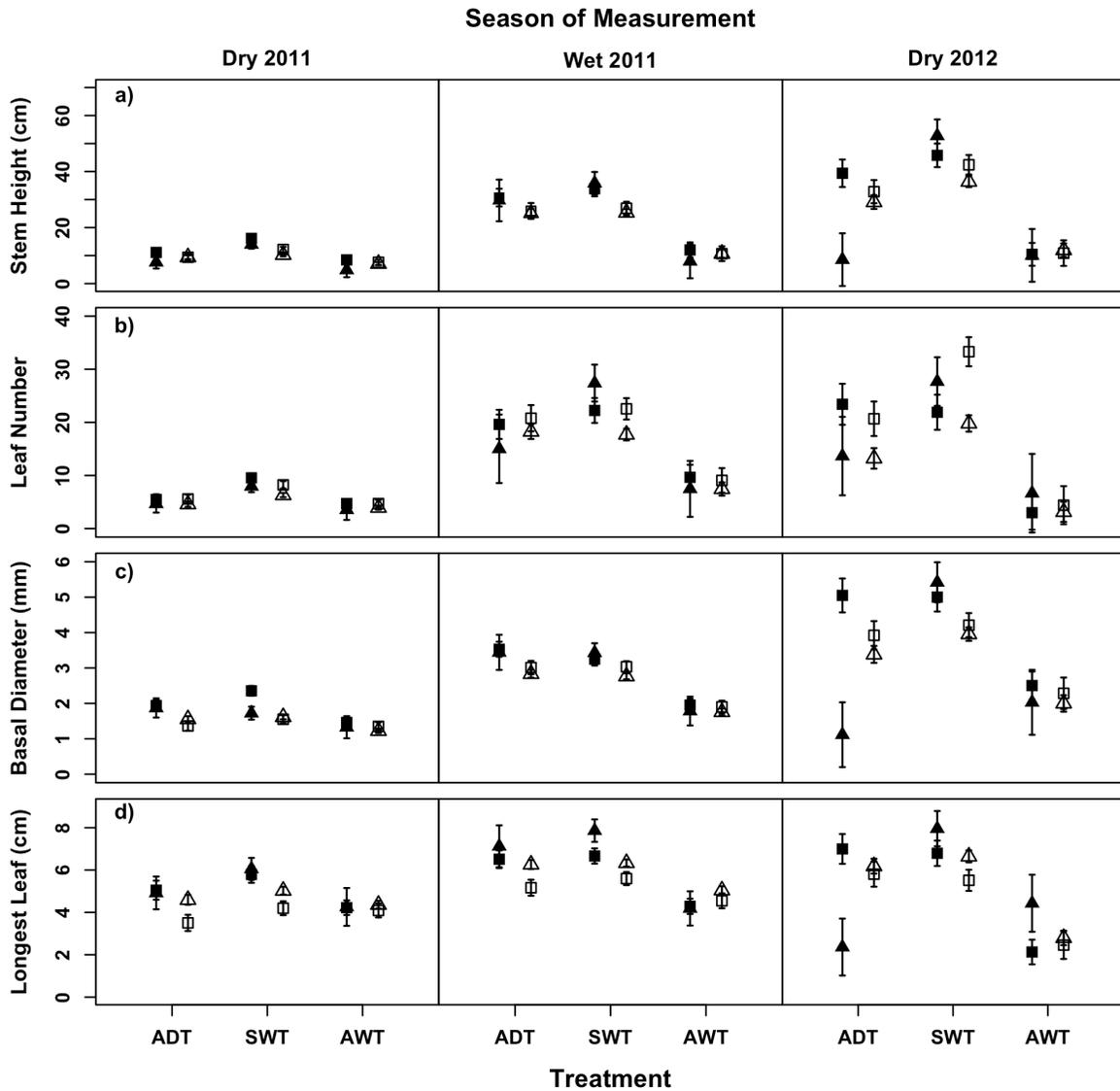


Figure S1.2- Predicted means (SE) of traits measured for three seasons on progeny from early- and late-cohort *Quercus oleoides* seeds sampled from a high-elevation and low-elevation population and reciprocally planted into three watering treatments: ambient dry site at low elevation (ADT), supplemental water at low elevation (SWT) and ambient wet at high elevation (AWT).

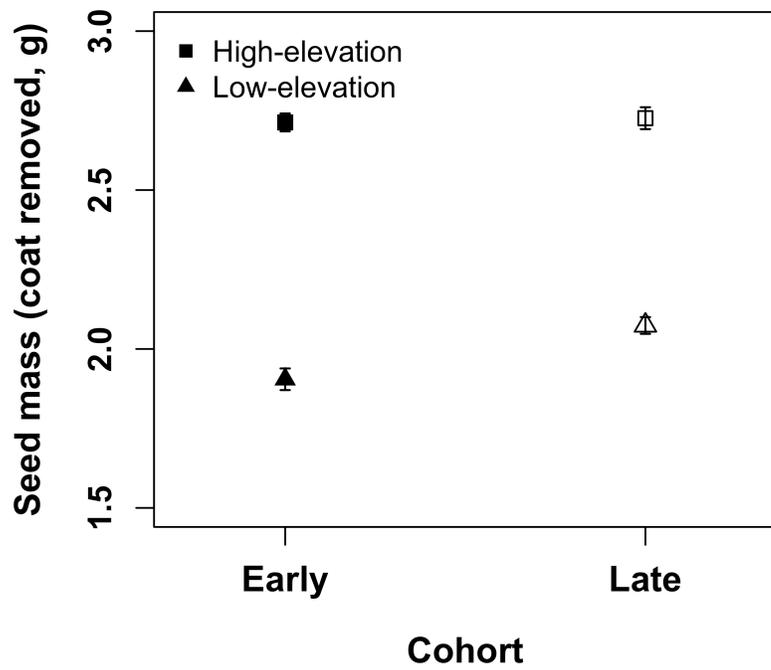


Figure S1.3- Least squares seed mass means (SE) of seeds collected from high- and low-elevation populations of *Quercus oleoides* trees in NW Costa Rica. Seeds were collected early (closed symbols) and late (open symbols) in the wet season of 2010.

Appendix 2- Supplemental Material for Chapter 2

Planting Cohort & Garden	Population			
	BZ	HN	CRH	CRL
2010T				
DG	249	272	262	165
IG	124	96	132	485
WG	61	55	60	226
2011T				
DG	167	219	104	687
IG	42	57	158	124
WG	22	28	80	62
2010DP				
DG	1417	1584	2255	4857
IG	653	1060	1664	2878
WG	326	530	832	1438
2011DP				
DG	778	1136	564	2536
IG	808	681	475	3270
WG	403	341	237	1635

Table S2.1- Summary of the number of seeds collected from four natural populations of *Q. oleoides* (Belize, BZ; Honduras, HZ, and Costa Rica high- and low- elevations, CRH and CRL respectively) and planted into the Dry (DG, Honduras), Intermediate (IG, Costa Rica low-elevation), and Wet (WG, Costa Rica high-elevation) gardens. Seeds for the 2010T and 2011T (transplant) cohorts were germinated in shadehouses and well watered until transplanted into gardens. Seeds for the 2010DP and 2011 DP (direct plantings) were stored in refrigerators until planted directly into gardens.

Effect	DS 2011		DS 2012	
	DF	X ²	X ²	
Garden (G)	2	1.167	7.148	*
Population (P)	3	1.357	1.391	
G x P	6	--	5.972	
Seed Mass	1	0.334	1.198	
Size	1	5.361	*	13.421 ***
MF (P)	2	0.000	0.000	
Block (G)	2	59.921	***	119.110 ***

Table S2.2- Summary of effect significance using nested model comparison of survivorship of *Q. oleoides* seed collected from natural populations throughout Central America and germinated into shadehouses in at Zamorano University (Honduras) and Sector Santa Rosa in the Guanacaste Conservation Area in NW Costa and transplanted into common gardens in Honduras (dry garden) and NW Costa Rica (intermediate and wet gardens) in 2010. Covariates of seed mass and size of plant at transplanting (size) were included in analyses. Degrees of freedom shown is the difference between nested models. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ****P<0.001

Effect	DS 2011			DS 2012		
	Est	SE	Z	Est	SE	Z
Intercept (IG)	2.31	0.92	2.52	0.94	0.71	1.32
WG	-0.19	0.75	-0.26	-1.51	0.81	-1.85
DG	-0.66	0.62	-1.06	-0.57	0.69	-0.83
HN	-0.37	0.49	-0.76	0.08	0.57	0.14
CRH	-0.14	0.48	-0.28	0.82	0.57	1.45
CRL	0.07	0.45	0.15	0.44	0.44	1.01
Seed Mass	0.15	0.26	0.59	-0.19	0.17	-1.10
Size	0.07	0.03	2.29	0.07	0.02	3.59
WG x HN	--	--	--	-0.90	0.83	-1.08
DG x HN	--	--	--	-0.18	0.71	-0.25
WG x CRH	--	--	--	-0.51	0.78	-0.66
DG x CRH	--	--	--	-1.17	0.70	-1.67
WG x CRL	--	--	--	-0.37	0.59	-0.62
DG x CRL	--	--	--	-0.73	0.66	-1.11

Table S2.3- GLMM summary of 2010 transplant survivorship of *Q. oleoides* seedlings transplanted into common gardens in Honduras- dry garden (DG), and NW Costa Rica- intermediate (IG) and wet (WG) gardens. Seeds collected from four natural populations of *Q. oleoides* (Belize, BZ; Honduras, HZ; Costa Rica high- and low- elevations, CRH and CRL respectively). Covariates of seed mass and size of plant at transplanting (size) were included in analyses. Degrees of freedom shown are for nested models for all traits. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***P<0.001

DS 2011									
Effect	Height			Diameter		Leaves		Biomass	
	DF	X ²		X ²	X ²	X ²	X ²		
Garden (G)	2	5.15 +		5.44 +		5.25 +		4.81 +	
Population (P)	2	8.79 *		2.46		7.53 +		3.81	
Seed Mass	1	0.15		1.35		0.00		0.29	
Size	1	96.04 ***		108.57 ***		118.77 ***		120.72 ***	
G x P	6	3.83		4.28		4.01		10.83 +	
MF (P)	2	2.05		0.51		0.00		0.00	
Block (G)	2	124.93 ***		172.61 ***		62.98 ***		201.24 ***	
DS 2012									
Effect	Height			Diameter		Leaves		Biomass	
	DF	X ²		X ²	X ²	X ²	X ²		
Garden (G)	2	10.28 *		9.06 *		9.07 *		9.50 *	
Population (P)	2	1.18		4.45		2.55		2.05	
Seed Mass	1	0.42		0.06		0.04		0.02	
Size	1	42.77 ***		36.26 ***		57.51 ***		42.79 ***	
G x P	6	6.58		6.42		6.35		6.88	
MF (P)	2	0.01		0.00		0.00		0.00	
Block (G)	2	215.28 ***		191.87 ***		151.99 ***		11.48 **	

Table S2.4- Summary of nested model comparisons to test effect significance of linear mixed effects models for growth traits (stem height, basal diameter, leaf number, and aboveground biomass) of 2010 transplant cohort. Degrees of freedom are for the nested models compared and are the same for all traits. Covariates of seed mass and size of plant at transplanting (size) were included in analyses. Degrees of freedom shown for all traits is the difference between nested models. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***P<0.001.

DS 2011

Effect	Height			Diameter ⁺			Leaves ⁺			Biomass		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (DG)	9.76	3.36	2.91	1.42	0.46	3.09	-0.74	4.08	-0.18	43.86	11.87	3.70
IG	1.34	2.84	0.47	0.42	0.47	0.89	0.83	4.70	0.18	4.46	12.82	0.35
WG	2.67	4.37	0.61	-0.42	0.58	-0.72	-5.20	5.69	-0.91	-6.18	15.74	-0.39
HN	5.47	2.96	1.85	-0.10	0.33	-0.29	-0.18	2.79	-0.07	-6.63	8.11	-0.82
CRH	1.35	2.90	0.46	0.00	0.32	-0.01	1.00	2.68	0.38	-3.56	7.79	-0.46
CRL	0.03	3.36	0.01	0.35	0.37	0.94	4.29	3.15	1.36	7.44	9.17	0.81
Seed Mass	1.33	0.87	1.53	0.13	0.10	1.21	0.12	0.88	0.13	1.97	2.55	0.77
Size	-5.02	3.04	-1.65	0.12	0.01	11.06	1.22	0.10	12.77	3.26	0.28	11.73
IG x HN	0.76	3.49	0.22	0.74	0.42	1.74	6.08	3.67	1.66	29.31	10.67	2.75
IG x CHR	0.90	3.23	0.28	0.33	0.40	0.82	0.73	4.39	0.17	12.20	12.77	0.96
IG x CRL	2.11	3.55	0.59	0.11	0.42	0.27	8.41	3.46	2.43	21.57	10.08	2.14
WG x HN	-0.22	6.48	-0.03	0.35	0.51	0.69	-1.92	4.15	-0.46	3.80	12.08	0.32
WG x CRH	-2.27	4.78	-0.47	0.14	0.48	0.30	5.10	3.59	1.42	11.69	10.44	1.12
WG x CRL	1.81	4.52	0.40	-0.24	0.47	-0.51	-3.76	4.02	-0.94	-7.86	11.68	-0.67

DS 2012

Effect	Height			Diameter ⁼			Leaf Number ⁼			Biomass ⁺		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (DG)	21.15	9.77	2.16	1.26	0.45	2.79	3.69	1.40	2.63	7.21	2.19	3.29
IG	7.13	11.19	0.64	0.34	0.49	0.69	-0.22	1.56	-0.14	0.83	2.41	0.34
WG	-27.89	13.63	-2.05	-1.07	0.60	-1.79	-4.44	1.89	-2.35	-6.71	2.94	-2.28
HN	-1.58	6.47	-0.24	0.04	0.31	0.12	-0.96	0.99	-0.98	-1.40	1.52	-0.92
CRH	-6.61	6.22	-1.06	0.01	0.30	0.03	-0.53	0.95	-0.56	-1.22	1.46	-0.84
CRL	-7.43	7.32	-1.02	-0.14	0.35	-0.39	-0.77	1.12	-0.68	-2.00	1.72	-1.16
Seed Mass	1.27	2.04	0.62	-0.02	0.10	-0.24	-0.07	0.31	-0.21	-0.07	0.48	-0.15
Size	1.47	0.22	6.64	0.06	0.01	6.09	0.26	0.03	7.73	0.35	0.05	6.63
IG x HN	12.72	8.49	1.50	0.35	0.40	0.87	1.77	1.30	1.36	2.72	2.00	1.36
IG x CHR	15.83	8.02	1.97	0.63	0.38	1.66	0.72	1.56	0.46	3.89	1.89	2.06
IG x CRL	18.88	8.32	2.27	0.80	0.40	2.01	2.15	1.23	1.75	4.48	1.96	2.29
WG x HN	-1.50	10.16	-0.15	-0.15	0.48	-0.31	0.79	1.48	0.53	0.93	2.39	0.39
WG x CRH	5.28	9.62	0.55	0.30	0.46	0.65	2.53	1.28	1.99	2.48	2.26	1.10
WG x CRL	5.24	9.31	0.56	0.22	0.44	0.50	0.54	1.43	0.38	2.22	2.19	1.02

⁼Estimates on log transformed scale

Table S2.5- Summary of linear mixed models of growth traits (stem height, basal diameter, leaf number, and aboveground biomass) of *Q. oleoides* seeds collected from four populations (Belize, BZ; Honduras, HN; and two populations in Costa Rica- high-elevation, CRH; low-elevation, CRL) and planted into shadehouses in Honduras and NW Costa Rica in 2010. Seedlings were transplanted into common gardens in Honduras (DG, dry garden), and in two gardens in Costa Rica intermediate garden (IG) and wet garden (WG).

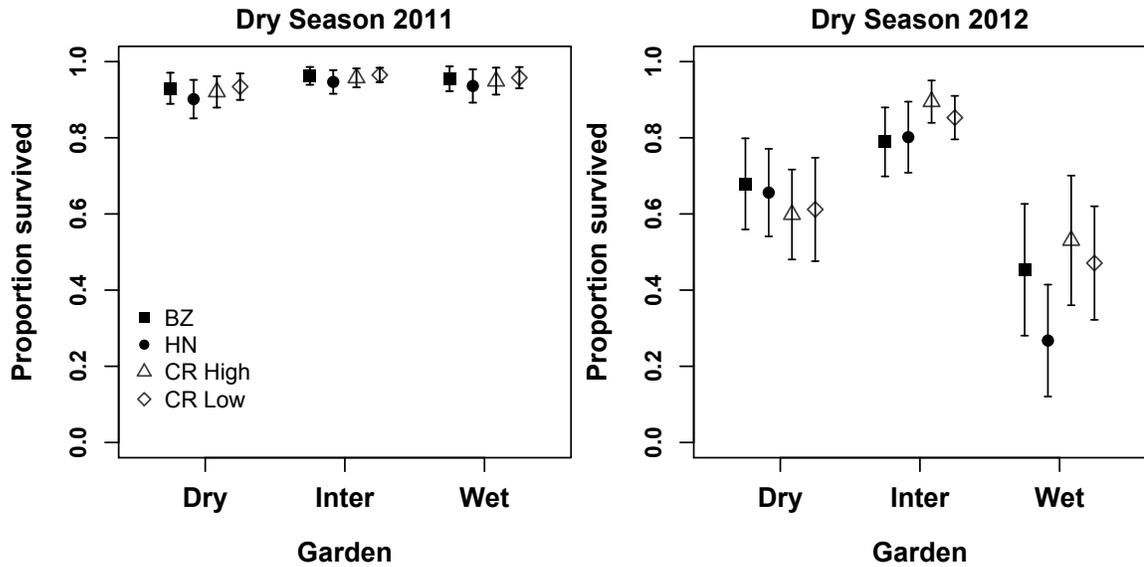


Figure S2.1. GLMM predicted survivorship of 2010 transplants in ambient rainfall plots at the dry (Honduras, intermediate (Inter, CR low-elevation) and Wet (CR high-elevation) gardens. Seeds were collected from four natural populations of *Q. oleoides* (Belize, BZ; Honduras, HZ, and Costa Rica high- and low- elevations, CRH and CRL respectively) and germinated in shadehouses and well watered until transplanted into gardens.

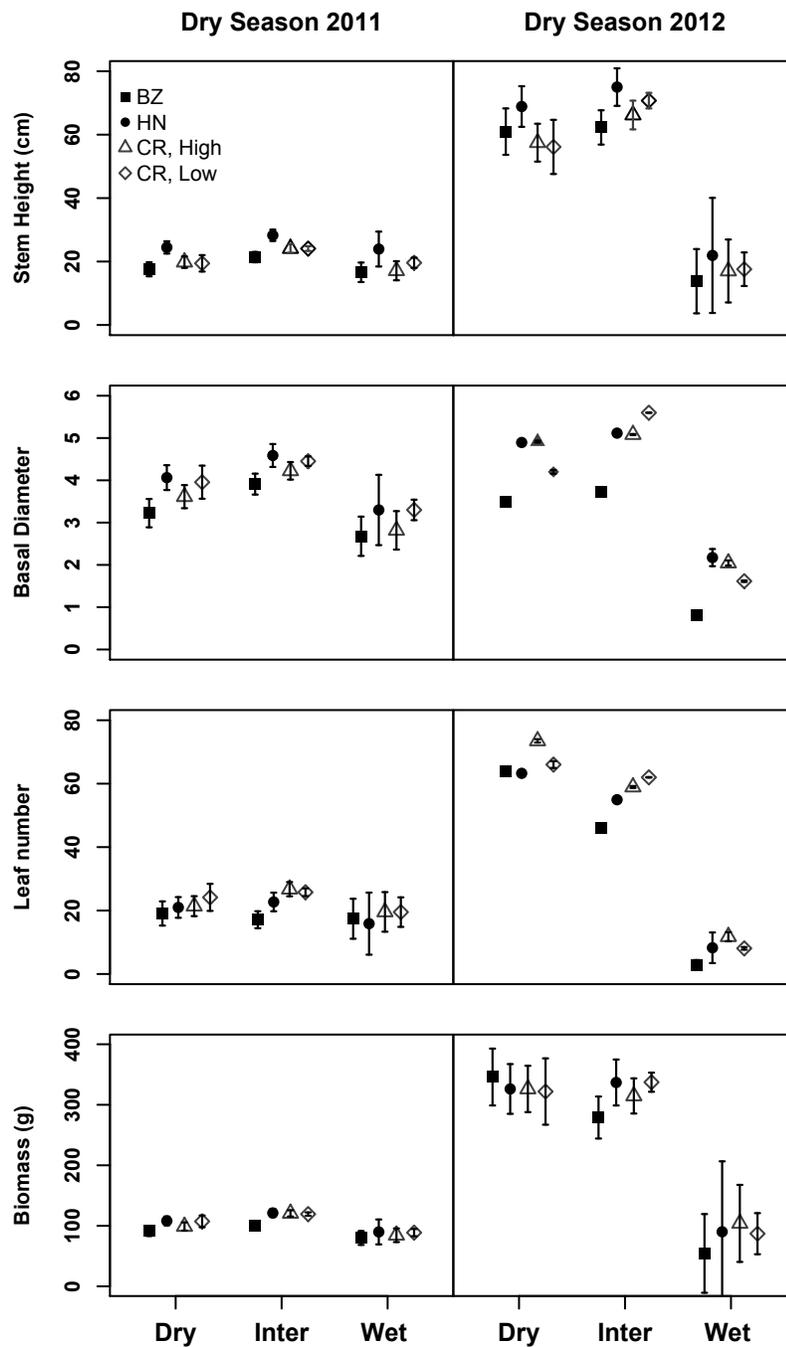


Figure S2.2- LMM predicted growth trait means of *Q. oleoides* seeds collected from four populations in Central America (Belize, BZ; Honduras, HZ, and Costa Rica high- and low- elevations, CRH and CRL respectively). Seedlings were transplanted in ambient rainfall blocks at dry (Honduras), intermediate (Inter, Costa Rica, low-elevation), and wet (Costa Rica high-elevation) gardens in 2010.

Effect	DF	WS2012		DS 2013		WS 2013		DS 2014	
		Dev		Dev		Dev		Dev	
Garden (G)	2	4.71	+	12.28	*	5.99	*	6.69	*
Population (P)	3	11.43	*	5.56	+	8.39	*	4.87	
Seed Mass	1	4.98	*	6.07	*	1.25		19.70	*
							**		
Size	1	21.91	***	23.00	***	21.97	*	16.78	***
Cut	1	10.11	***	11.20	**	11.48	**	9.92	**
G x P	6	6.59		7.67		5.93		8.34	

Table S2.6- Summary of effect significance using nested model comparison of survivorship of *Q. oleoides* seeds collected from natural populations through Central American and germinated in shadehouses and then transplanted into common gardens in Honduras (dry garden), and in two gardens in Costa Rica- intermediate and wet gardens in 2011. Covariates of seed mass and size of plant at transplanting (size) were included in analyses. Degrees of freedom shown for all traits is the difference in nested models. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***P<0.001

Effect	WS 2012			DS 2013			WS 2013			DS 2014		
	Est	SE	Z									
Intercept (DG)	-0.58	0.87	-0.67	-0.41	0.88	-0.47	-0.49	0.86	-0.57	-0.53	0.85	-0.63
WG	-1.25	1.01	-1.24	-1.24	1.05	-1.19	-1.49	1.03	-1.44	-1.57	1.01	-1.55
IG	-0.86	0.97	-0.89	-0.75	1.00	-0.75	-0.40	0.98	-0.41	-0.64	0.96	-0.67
HN	-0.02	0.83	-0.02	0.00	0.82	0.00	-0.01	0.78	-0.01	0.00	0.79	0.00
CRH	-0.59	1.17	-0.51	-0.64	1.16	-0.55	-1.22	1.12	-1.10	-1.19	1.13	-1.06
CRL	0.53	0.76	0.70	0.28	0.74	0.37	0.35	0.72	0.49	-0.26	0.71	-0.37
Seed Mass	0.47	0.21	2.22	0.38	0.21	1.83	0.23	0.21	1.12	0.34	0.21	1.67
Size	0.13	0.03	4.53	0.13	0.03	4.47	0.13	0.03	4.54	0.11	0.03	4.00
Cut	-2.09	0.80	-2.62	-2.25	0.81	-2.80	-2.23	0.79	-2.82	-2.06	0.78	-2.64
DG x HN	0.69	1.11	0.63	-0.04	1.12	-0.03	0.48	1.11	0.43	0.30	1.10	0.27
DG x CRH	0.87	0.94	0.93	0.71	0.93	0.77	0.53	0.90	0.59	0.65	0.91	0.72
DG x CRL	0.48	1.55	0.31	0.48	1.55	0.31	1.59	1.53	1.04	1.76	1.52	1.16
WG x HN	0.28	1.31	0.22	0.25	1.30	0.19	0.72	1.26	0.57	0.92	1.27	0.73
WG x CRH	-0.70	0.97	-0.72	-0.81	0.98	-0.83	-0.56	0.97	-0.58	-0.19	0.95	-0.20
WG x CRL	0.60	0.84	0.72	0.77	0.82	0.94	0.49	0.80	0.62	1.15	0.79	1.46

Table S2.7- GLMM summary of 2011 transplant survivorship of *Q. oleoides* seedlings transplanted into common gardens in Honduras- dry garden, and NW Costa Rica- intermediate (IG) and wet (WG) gardens. Seeds collected from four natural populations of *Q. oleoides* (Belize, BZ; Honduras, HZ, and Costa Rica high- and low- elevations, CRH and CRL respectively). Covariates of seed mass and size of plant at transplanting (size) were included in analyses.

WS 2012									
Effect	DF	Height		Diameter		Leaves		Biomass	
		X²		X²		X²		X²	
Garden (G)	2	36.51	***	33.85	***	13.09	***	25.77	***
Population (P)	3	16.73	***	7.21	+	6.01		11.73	*
Seed Mass	1	2.21		1.69		1.15		2.97	+
Size	1	11.06	***	3.70	*	5.91	*	9.65	***
Cut	1	0.92		0.34		1.82		2.15	
G x P	6	4.92		6.11		3.82		2.94	
MF (P)	2	0.94		0.37		0.13		0.00	
Block (G)	2	22.46	***	22.57	***	27.21	***	52.50	+
DS 2013									
Effect	DF	X²		X²		X²		X²	
Garden (G)	2	32.33	***	13.31	***	11.87	***	20.26	***
Population (P)	3	15.52	**	4.83		6.20	+	9.64	*
Seed Mass	1	0.70		0.44		0.18		0.00	
Size	1	15.77	***	8.22	***	18.85	***	21.28	*
Cut	1	0.36		0.73		0.39		0.01	
G x P	6	3.98		8.80		6.93		5.82	
MF (P)	2	0.00		2.69		0.00		2.23	
Block (G)	2	11.88	**	31.81	*	9.12	*	9.04	*
WS 2013									
Effect	DF	X²		X²		X²		X²	
Garden (G)	2	27.80	***	36.85	***	10.86	**	14.99	*
Population (P)	3	13.56	**	12.65	*	5.96		7.77	*
Seed Mass	1	0.00		0.28		0.05		0.18	
Size	1	1.43		3.00	+	6.21	*	6.51	*
Cut	1	0.44		1.45		2.06		0.53	
G x P	6	3.63		3.11		4.14		3.28	
MF (P)	2	0.18		2.69		0.00		2.23	
Block (G)	2	9.17	*	7.57	*	41.37	***	34.40	+
DS 2014									
Effect	DF	X²		X²		X²		X²	
Garden (G)	2	26.99	***	18.52	***	8.93	**	13.61	**
Population (P)	3	25.00	***	4.38		10.37	*	9.94	*
Seed Mass	1	1.95		0.36		0.31		0.02	
Size	1	6.44	*	2.10		14.63	***	9.96	**

Table S2.8- Summary of nested linear mixed model comparisons to test effects of factors on growth traits (stem height, basal diameter, leaf number, and aboveground biomass) of 2011 transplant cohort. Degrees of freedom shown for all traits is the difference between nested models. +0.10≥P>0.05; * P≤0.05, ** P≤0.01; ***P<0.001

WS 2012

Effect	Stem Height ⁺			Basal Diameter			Leaf Number ⁺			Biomass		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (DG)	6.84	0.85	8.05	3.36	0.44	7.72	7.25	1.39	5.23	15.26	1.53	9.98
WG	-3.60	0.87	-4.16	-1.98	0.46	-4.28	-5.36	1.61	-3.33	-7.52	1.71	-4.41
IG	-2.95	0.72	-4.12	-1.68	0.39	-4.29	-3.47	1.47	-2.37	-6.08	1.54	-3.95
HN	2.08	0.74	2.83	0.88	0.37	2.36	1.98	1.08	1.83	2.84	1.24	2.29
CRH	1.08	1.21	0.89	0.29	0.61	0.47	1.90	1.79	1.06	1.94	2.05	0.95
CRL	0.72	0.68	1.07	0.56	0.34	1.63	1.31	0.98	1.33	1.32	1.13	1.17
Seed Mass	0.17	0.26	0.67	0.11	0.13	0.89	0.34	0.38	0.91	0.35	0.43	0.81
Size	0.11	0.03	3.21	0.03	0.02	1.74	0.11	0.05	2.21	0.15	0.06	2.69
Cut	-0.71	0.39	-1.81	-0.11	0.24	-0.45	-0.96	0.89	-1.08	-0.76	0.96	-0.79
DG x HN	-0.66	0.91	-0.72	-0.44	0.46	-0.95	-0.99	1.33	-0.75	-0.84	1.51	-0.55
DG x CRH	-0.27	1.45	-0.19	-0.11	0.73	-0.16	-1.10	2.12	-0.52	-0.85	2.42	-0.35
Dig CRL	-0.60	0.81	-0.75	-0.44	0.41	-1.07	-0.53	1.18	-0.45	-0.37	1.34	-0.28
WG x HN	-0.97	1.15	-0.84	-0.48	0.59	-0.81	1.75	1.72	1.02	0.69	1.94	0.35
WG x CRH	-2.26	1.58	-1.44	-0.52	0.81	-0.64	2.33	2.37	0.98	1.28	2.66	0.48
WG x CRL	-0.87	1.02	-0.85	-0.23	0.52	-0.43	0.92	1.53	0.60	0.55	1.72	0.32

⁺Estimates on square root transformed scale

DS 2013

Effect	Stem Height			Basal Diameter ⁺			Leaf Number ⁺			Biomass		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (DG)	63.14	12.50	5.05	3.62	0.57	6.31	8.21	1.67	4.91	15.95	1.86	8.58
WG	-67.25	13.16	-5.11	-2.34	0.63	-3.69	-7.23	1.89	-3.82	-9.35	2.05	-4.56
IG	-61.04	10.98	-5.56	-2.27	0.57	-4.01	-4.68	1.64	-2.85	-7.48	1.75	-4.28
HN	20.68	10.20	2.03	-0.25	0.42	-0.59	0.45	1.36	0.33	1.01	1.53	0.66
CRH	-25.93	16.82	-1.54	-1.52	0.70	-2.18	-4.50	2.23	-2.02	-5.21	2.52	-2.07
CRL	6.10	9.39	0.65	0.05	0.39	0.13	-0.35	1.24	-0.28	-0.06	1.40	-0.04
Seed Mass	2.99	3.55	0.84	0.10	0.15	0.67	-0.21	0.47	-0.44	-0.02	0.53	-0.03
Size	2.02	0.49	4.10	0.06	0.02	2.93	0.29	0.07	4.47	0.35	0.07	4.78
Cut	4.92	7.15	0.69	0.32	0.36	0.89	-0.78	1.05	-0.75	-0.14	1.13	-0.13
DG x HN	-4.89	12.85	-0.38	0.84	0.53	1.59	0.59	1.70	0.35	0.90	1.92	0.47
DG x CRH	31.54	20.27	1.56	1.89	0.84	2.26	4.29	2.69	1.60	5.68	3.03	1.88
DG x CRL	-2.47	11.35	-0.22	0.19	0.47	0.41	1.15	1.50	0.77	0.97	1.70	0.57
WG x HN	0.72	16.72	0.04	1.17	0.70	1.68	4.13	2.23	1.85	3.87	2.51	1.54
WG x CRH	17.11	23.16	0.74	1.19	0.97	1.23	6.73	3.10	2.17	6.10	3.48	1.75
WG x CRL	1.82	14.81	0.12	0.53	0.62	0.86	2.62	1.98	1.33	2.22	2.22	1.00

⁺ Estimates on square root transformed scale

WS 2013

Effect	Stem Height			Basal Diameter ⁺			Leaf Number ⁺			Biomass ⁺		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (DG)	103.78	20.61	5.04	4.40	0.64	6.85	11.00	2.68	4.11	3.36	0.44	7.72
WG	-97.43	22.60	-4.31	-3.37	0.69	-4.89	-11.64	3.18	-3.66	-1.98	0.46	-4.28
IG	-51.53	19.07	-2.70	-1.76	0.57	-3.08	-1.84	2.89	-0.64	-1.68	0.39	-4.29
HN	53.31	17.34	3.07	1.01	0.54	1.87	1.93	1.97	0.98	0.88	0.37	2.36
CRH	4.48	28.60	0.16	0.45	0.89	0.50	-0.68	3.25	-0.21	0.29	0.61	0.47
CRL	18.65	15.94	1.17	0.47	0.50	0.94	2.11	1.81	1.17	0.56	0.34	1.63
Seed Mass	-0.30	6.04	-0.05	-0.10	0.19	-0.53	-0.22	0.69	-0.32	0.11	0.13	0.89
Size	1.13	0.83	1.36	0.05	0.03	1.77	0.25	0.10	2.58	0.03	0.02	1.74
Cut	-5.91	11.89	-0.50	0.47	0.35	1.32	-2.88	1.73	-1.66	-0.11	0.24	-0.45
DG x HN	-33.18	21.77	-1.52	-0.64	0.68	-0.94	0.74	2.48	0.30	-0.44	0.46	-0.95
DG x CRH	-14.19	34.44	-0.41	-0.41	1.07	-0.38	1.87	3.91	0.48	-0.11	0.73	-0.16
DG x CRL	-19.15	19.26	-0.99	-0.40	0.60	-0.66	-0.82	2.18	-0.38	-0.44	0.41	-1.07
WG x HN	-24.43	28.29	-0.86	0.00	0.88	0.00	3.83	3.28	1.17	-0.48	0.59	-0.81
WG x CRH	12.02	39.10	0.31	0.53	1.22	0.44	6.61	4.55	1.45	-0.52	0.81	-0.64
WG x CRL	8.93	25.06	0.36	0.75	0.78	0.96	3.80	2.90	1.31	-0.23	0.52	-0.43

DS 2014

Effect	Stem Height			Basal Diameter ⁺			Leaf Number ⁺			Biomass		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept												
(DG)	112.75	19.23	5.86	5.24	0.64	8.14	11.73	2.50	4.69	20.42	2.89	7.07
WG	-98.04	21.39	-4.58	-3.06	0.71	-4.33	-9.49	2.97	-3.19	-13.33	3.46	-3.85
IG	-75.26	18.90	-3.98	-2.26	0.62	-3.65	-3.97	2.70	-1.47	-5.15	3.16	-1.63
HN	50.01	15.15	3.30	0.57	0.51	1.12	2.63	1.88	1.40	2.72	2.09	1.30
CRH	-27.67	25.00	-1.11	-0.14	0.84	-0.17	-3.88	3.10	-1.25	0.63	3.44	0.18
CRL	21.33	13.86	1.54	0.40	0.46	0.85	0.30	1.72	0.18	2.70	1.91	1.41
Seed Mass	6.22	5.28	1.18	0.02	0.18	0.11	0.35	0.65	0.54	0.10	0.73	0.13
Size	1.81	0.73	2.49	0.04	0.02	1.45	0.35	0.09	3.89	0.32	0.10	3.20
Cut	-8.05	12.22	-0.66	0.06	0.41	0.15	-2.45	1.62	-1.51	-3.05	1.86	-1.64
DG x HN	-23.92	18.86	-1.27	-0.08	0.63	-0.13	0.69	2.35	0.29	1.46	2.62	0.56
DG x CRH	20.80	29.92	0.70	0.56	1.00	0.56	6.38	3.72	1.72	0.40	4.14	0.10
DG x CRL	-20.67	16.66	-1.24	-0.20	0.56	-0.35	1.14	2.07	0.55	-1.31	2.31	-0.57
WG x HN	-13.76	24.58	-0.56	0.45	0.82	0.55	1.65	3.09	0.53	3.17	3.47	0.91
WG x CRH	14.65	34.02	0.43	0.39	1.14	0.35	2.91	4.28	0.68	2.19	4.81	0.46
WG x CRL	-13.74	21.80	-0.63	1.08	0.73	1.48	0.69	2.74	0.25	1.92	3.07	0.63

Table S2.9- Summary of linear mixed models of growth traits (stem height, basal diameter, leaf number, and aboveground biomass) at the end of the wet season (WS) 2012, dry season (DS) 2013, WS 2013, and DS 2014 of *Q. oleoides* seeds collected from four populations (Belize, BZ; Honduras, HN; and two populations in Costa Rica-high-elevation, CRH and low-elevation CRL) and planted into shadehouses in Honduras and NW Costa Rica in 2011. Seedlings were transplanted into common gardens in Honduras, the dry garden (DG), and in two gardens in Costa Rica- intermediate garden (IG) and wet garden (WG). Covariates of seed mass and size of plant at transplanting (size) were included in analyses.

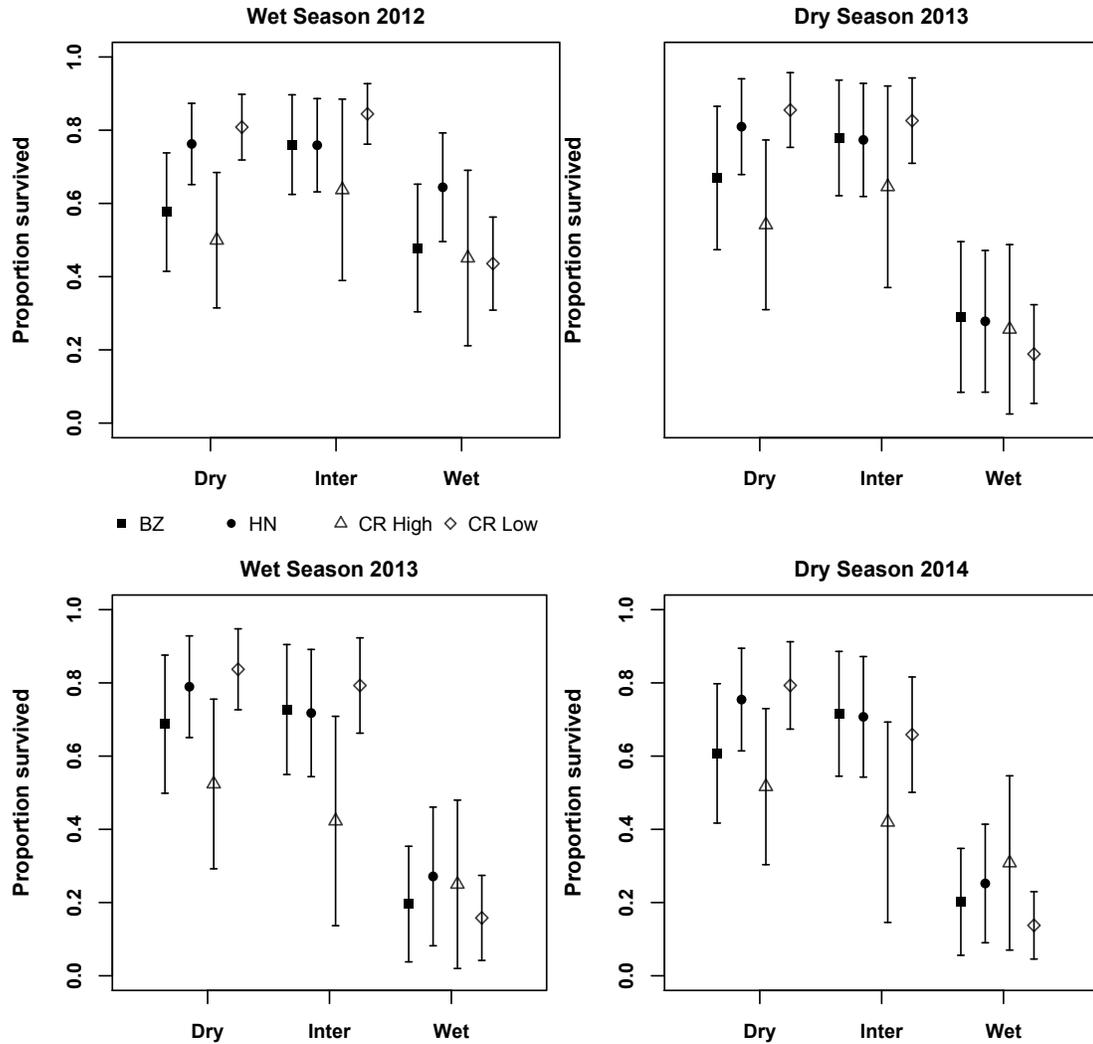


Figure S2.3- GLMM predicted survivorship of *Q. oleoides* seedlings from seeds collected from four populations throughout Central America (Belize, BZ; Honduras, HZ, and Costa Rica high- and low- elevations, CRH and CRL respectively) and planted into shadehouses in Honduras and Costa Rica. Seedlings were transplanted into common gardens at the dry (Honduras), intermediate (Inter, Costa Rica low-elevation) and wet (Costa Rica high-elevation) gardens in 2011.

DS 2011												
	Height			Diameter			Leaf Number			Longest Leaf		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (Dry Garden)	12.59	2.93	4.29	4.32	7.73	0.56	7.07	1.97	3.59	32.22	7.39	4.36
WG	-4.30	1.67	-2.58	-0.70	4.06	-0.17	-4.09	1.34	-3.07	-13.44	4.67	-2.88
IG	0.91	1.37	0.67	4.23	3.92	1.08	0.38	1.10	0.34	2.68	3.83	0.70
HN	0.01	3.21	0.00	-1.93	9.64	-0.20	-0.58	2.13	-0.27	-1.45	8.01	-0.18
CRH	1.29	2.21	0.58	-0.42	6.62	-0.06	-0.17	1.47	-0.12	1.63	5.53	0.30
CRL	1.79	1.99	0.90	1.32	5.95	0.22	0.98	1.34	0.74	4.48	5.00	0.90
Seed size	-0.52	1.17	-0.45	-2.25	3.28	-0.69	0.28	0.79	0.36	-0.68	2.96	-0.23

DS 2012												
	Height			Diameter			Leaf Number⁺			Biomass⁺		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (Dry Garden)	24.68	9.88	2.50	4.45	2.86	1.56	4.69	1.91	2.46	8.77	2.34	3.76
WG	-35.21	5.94	-5.92	-5.62	1.72	-3.27	-3.29	1.61	-2.05	-5.41	1.87	-2.89
IG	15.36	4.77	3.22	4.54	1.48	3.06	4.80	1.29	3.72	5.46	1.49	3.67
HN	11.98	8.35	1.44	-1.14	3.22	-0.36	1.50	1.80	0.83	1.98	2.10	0.94
CRH	10.92	5.43	2.01	2.07	2.09	0.99	1.02	1.18	0.87	1.72	1.37	1.26
CRL	9.08	5.02	1.81	2.64	1.91	1.38	1.14	1.09	1.04	1.66	1.27	1.31
Seed size	5.09	3.07	1.66	0.39	1.14	0.34	-0.32	0.67	-0.48	0.01	0.78	0.01

⁺On squareroot transformed scale

Table S2.13- Summary of linear mixed models of growth traits (stem height, basal diameter, leaf number, and aboveground biomass) of *Q. oleoides* seeds collected from four populations (Belize, BZ; Honduras, HN; and two populations in Costa Rica-high-elevation CRH and low-elevation CRL) and planted directly into common gardens in Honduras (DG, dry garden) and NW Costa Rica (intermediate-IG and wet-WG gardens) in 2010. Analyses were conducted at the end of the dry seasons in 2011 and 2012.

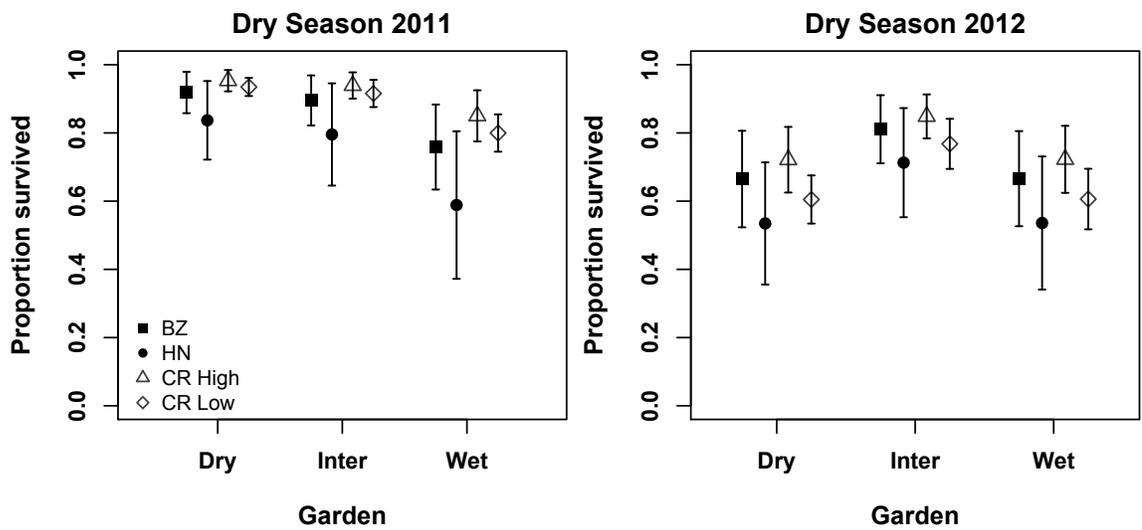


Figure S2.5- GLMM predicted survivorship of seedlings from seeds collected from four populations of *Q. oleoides* across Central America (Belize, BZ; Honduras, HZ, and Costa Rica high- and low- elevations, CR High and CR Low respectively) and planted directly into common gardens in dry (Honduras), intermediate (Inter, Costa Rica low-elevation) and wet (Costa Rica high-elevation) gardens in 2010.

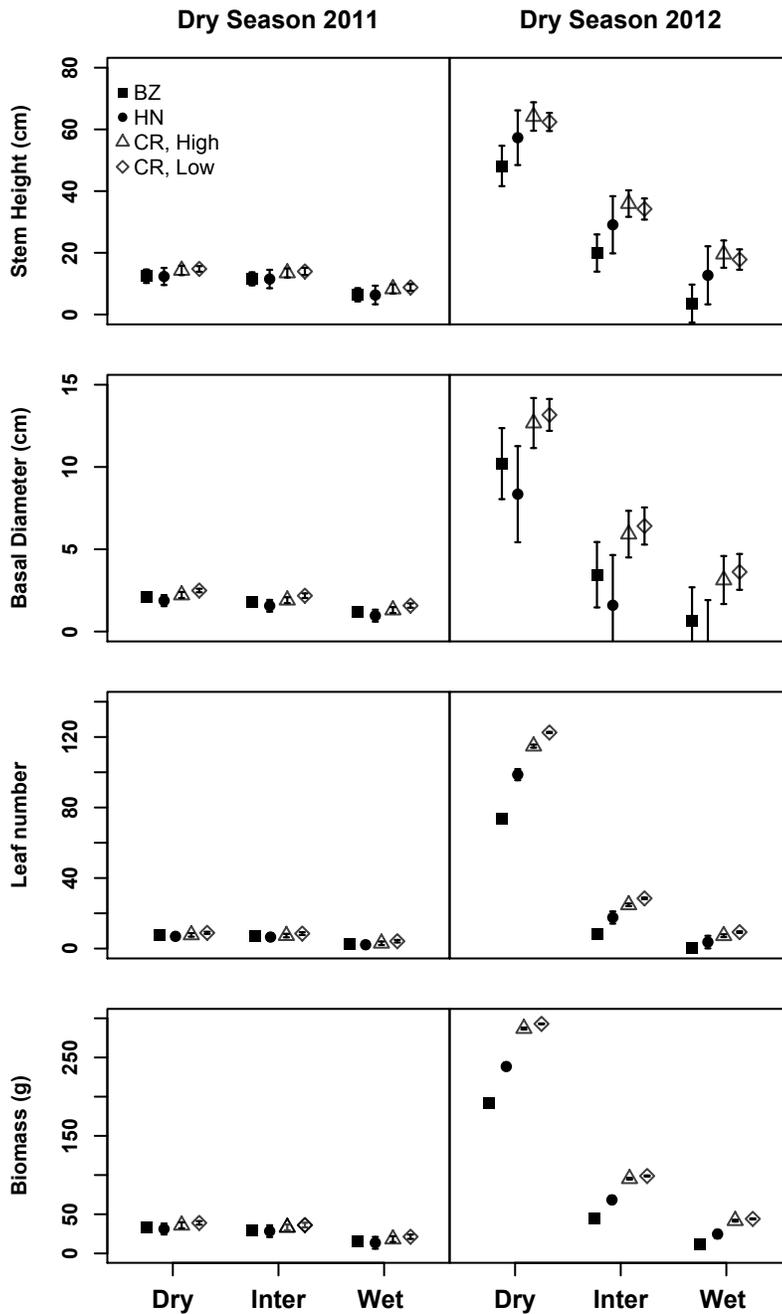


Figure S2.6 LMM predicted growth trait means of *Q. oleoides* seedlings in ambient rainfall blocks at dry (Honduras), intermediate (inter, Costa Rica, low-elevation), and wet (Costa Rica high-elevation) gardens. Seeds were collected from four populations in Central America (Belize, BZ; Honduras, HZ, and Costa Rica high- and low- elevations, CR High and CR Low respectively) and planted into common gardens in 2010.

Effect	DF	WS 2012		DS 2013		WS 2013		DS 2014	
		X ²		X ²		X ²		X ²	
Garden	2	24.25	***	23.72	***	22.46	***	24.03	***
Pop	3	0.90		0.67		1.15		5.54	
Seed Mass	1	3.81	*	3.84	*	5.34	*	5.80	*

Table S2.14- Summary of effect significance using nested model comparison of survivorship of *Q. oleoides* seeds collected from natural populations through Central America and reciprocally planted directly into common gardens in Honduras and NW Costa Rica in 2011. Degrees of freedom (DF) shown is the difference between nested models for each factor. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***P<0.001

Effect	WS 2012			DS 2013			WS 2013			DS 2014		
	Est	SE	Z									
Intercept (DG)	1.45	0.95	1.53	1.36	0.94	1.45	1.25	0.87	1.43	1.04	0.82	1.27
IG	-1.36	0.57	-2.38	-1.22	0.57	-2.15	-1.17	0.49	-2.38	-1.87	0.47	-3.96
WG	-4.28	0.61	-7.00	-4.13	0.60	-6.87	-3.58	0.53	-6.78	-3.58	0.51	-7.00
HN	-0.02	0.84	-0.03	0.01	0.84	0.01	-0.06	0.81	-0.08	0.16	0.78	0.20
CRH	0.37	0.69	0.53	0.36	0.69	0.53	-0.32	0.66	-0.49	-0.43	0.62	-0.71
CRL	0.46	0.68	0.68	0.41	0.67	0.61	0.01	0.64	0.02	0.29	0.61	0.48
Seed Mass	0.54	0.27	1.96	0.53	0.27	1.96	0.57	0.25	2.29	0.58	0.24	2.39

Table S2.15- GLMM summary of survivorship seedlings planted directly into common gardens in Honduras (DG, dry garden) and Costa Rica (intermediate and wet gardens, IG and WG respectively) in 2011. Seeds collected from four populations of *Q. oleoides* across Central America (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation CRL).

WS 2012									
		Height		Diameter		Leaves		Biomass	
Effect	DF	X²		X²		X²		X²	
Garden	2	27.18	***	25.26	***	39.58	***	30.20	***
Population	3	7.17	+	6.09		13.26	**	8.50	*
Cut	1	19.25	***	14.16	***	18.18	***	16.01	***
Seed Mass	1	0.14		0.00		1.79		0.35	
DS 2013									
		Height		Diameter		Leaves		Biomass	
Effect	DF	X²		X²		X²		X²	
Garden	2	12.42	**	19.01	**	14.91	**	13.94	**
Population	3	7.91	*	1.42		8.91	*	5.18	
Cut	1	16.32	***	0.07		10.59	**	16.36	***
Seed Mass	1	0.17		0.02		0.82		0.66	
WS 2013									
		Height		Diameter		Leaves		Biomass	
Effect	DF	X²		X²		X²		X²	
Garden	2	10.21	**	9.29	*	15.16	**	13.29	**
Population	3	18.68	***	8.45	*	10.42	*	11.56	**
Cut	1	10.08	**	8.00	**	11.34	**	12.05	**
Seed Mass	1	0.01		0.00		0.12		0.07	
DS 2014									
		Height		Diameter		Leaves		Biomass	
Effect	DF	X²		X²		X²		X²	
Garden	2	9.29	*	6.42	*	14.39	**	11.99	**
Population	3	12.49	**	17.88	***	9.72	*	10.02	*
Cut	1	2.66		9.38	**	12.86	**	8.14	**
Seed Mass	1	0.09				0.27		0.31	

Table S2.16- Summary of nested linear mixed model comparisons to test effects of factors on seedling growth traits (stem height, basal diameter, leaf number, and aboveground biomass) of seeds planted directly into common gardens in Honduras (DG, dry garden) and Costa Rica (intermediate and wet gardens, IG and WG respectively) in 2011. Degrees of freedom (DF) shown is the difference between nested models for each factor. +0.10≥P>0.05; * P≤0.05, ** P≤0.01; ***P<0.001

WS 2012

	Height			Diameter			Leaf Number ⁺			Biomass ⁺		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (DG)	32.51	6.93	4.69	0.48	0.11	4.46	2.74	0.89	3.08	98.60	23.57	4.18
WG	-33.85	5.49	-6.16	-0.55	0.08	-7.09	-4.17	0.54	-7.69	-83.06	14.29	-5.81
IG	5.27	4.23	1.25	-0.08	0.06	-1.42	1.77	0.37	4.84	39.10	9.63	4.06
HN	9.87	5.73	1.72	0.12	0.09	1.42	0.20	0.77	0.26	11.99	20.68	0.58
CRH	-0.65	4.96	-0.13	0.05	0.08	0.66	0.30	0.66	0.46	1.35	17.80	0.08
CRL	4.19	4.73	0.89	0.13	0.07	1.84	1.39	0.64	2.19	27.94	17.04	1.64
Cut	-30.64	6.86	-4.47	-0.40	0.11	-3.81	-3.99	0.92	-4.34	-100.72	24.67	-4.08
Seed Mass	-0.79	2.13	-0.37	0.00	0.03	-0.02	0.38	0.28	1.36	4.68	7.55	0.62

DS 2013

	Height			Diameter			Leaf Number ⁺			DS2013		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (DG)	31.94	9.06	3.53	0.62	0.12	5.07	2.62	1.21	2.17	9.66	1.28	7.56
WG	-36.21	10.09	-3.59	-0.66	0.14	-4.75	-3.78	1.12	-3.39	-4.52	1.31	-3.45
IG	2.15	8.78	0.25	0.09	0.12	0.74	1.67	0.92	1.82	1.35	1.11	1.22
HN	12.57	6.00	2.09	0.09	0.08	1.19	0.10	0.83	0.12	0.79	0.88	0.90
CRH	0.56	5.22	0.11	0.05	0.07	0.79	0.55	0.73	0.76	0.35	0.76	0.46
CRL	3.77	4.96	0.76	0.06	0.06	0.92	1.34	0.69	1.95	1.16	0.72	1.60
Cut	-29.47	7.18	-4.10	0.02	0.09	0.26	-3.29	1.00	-3.29	-4.31	1.05	-4.11
Seed Mass	0.94	2.24	0.42	0.00	0.03	-0.15	0.28	0.31	0.91	0.27	0.33	0.82
Residual	325.40	18.04		0.05	0.23		6.31	2.51		6.93	2.63	

WS 2013

	Height			Diameter			Leaf Number ⁺			WS 2013		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (DG)	56.23	13.20	4.26	0.94	0.25	3.70	6.44	1.92	3.35	13.34	2.18	6.13
IG	-40.07	11.80	-3.40	-0.74	0.22	-3.33	-4.77	1.39	-3.43	-5.52	1.64	-3.36
WG	-5.31	9.50	-0.56	-0.21	0.18	-1.20	1.57	1.03	1.53	1.17	1.24	0.94
HN	26.00	9.89	2.63	0.30	0.19	1.57	1.90	1.50	1.27	2.89	1.69	1.71
CRH	-3.62	8.58	-0.42	0.05	0.17	0.31	0.84	1.30	0.64	0.69	1.46	0.47
CRL	10.64	8.17	1.30	0.28	0.16	1.76	2.83	1.24	2.27	3.08	1.39	2.21
Cut	-37.98	11.84	-3.21	-0.65	0.23	-2.85	-6.14	1.80	-3.41	-7.11	2.02	-3.52
Seed Mass	-0.33	3.69	-0.09	0.00	0.07	0.02	0.20	0.56	0.35	0.17	0.63	0.27

DS 2014

	Height			Diameter			Leaf Number ⁺			DS 2014		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (DG)	6.87	0.79	8.73	0.86	0.12	7.38	4.42	1.70	2.60	11.62	1.91	6.09
IG	-2.04	0.64	-3.17	-0.25	0.10	-2.59	-1.32	1.48	-0.90	-2.64	1.63	-1.62
WG	-0.42	0.50	-0.84	-0.07	0.07	-0.89	4.25	1.18	3.61	3.26	1.29	2.52
HN	2.10	0.64	3.29	0.24	0.09	2.52	1.68	1.36	1.24	2.94	1.53	1.92
CRH	0.80	0.55	1.45	0.12	0.08	1.41	0.92	1.18	0.78	1.33	1.33	1.00
CRL	1.18	0.53	2.24	0.26	0.08	3.36	2.58	1.12	2.30	3.09	1.26	2.45
Cut	-1.25	0.77	-1.64	-0.35	0.11	-3.10	-5.92	1.62	-3.64	-5.29	1.83	-2.88
Seed Mass	0.07	0.24	0.30	0.02	0.04	0.65	0.26	0.50	0.52	0.32	0.57	0.56

⁺ Estimates on square root transformed scale

Table S2.17- Summary of linear mixed models of growth traits (stem height, basal diameter, leaf number, and aboveground biomass) at the end of the wet season (WS) 2012, dry season (DS) 2013, WS 2013, and DS 2014 of *Q. oleoides* seeds collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH and Costa Rica low-elevation, CRL) and planted directly into common gardens in Honduras (DG, dry garden) and NW Costa Rica (intermediate and wet gardens, IG and WG respectively) in 2011.

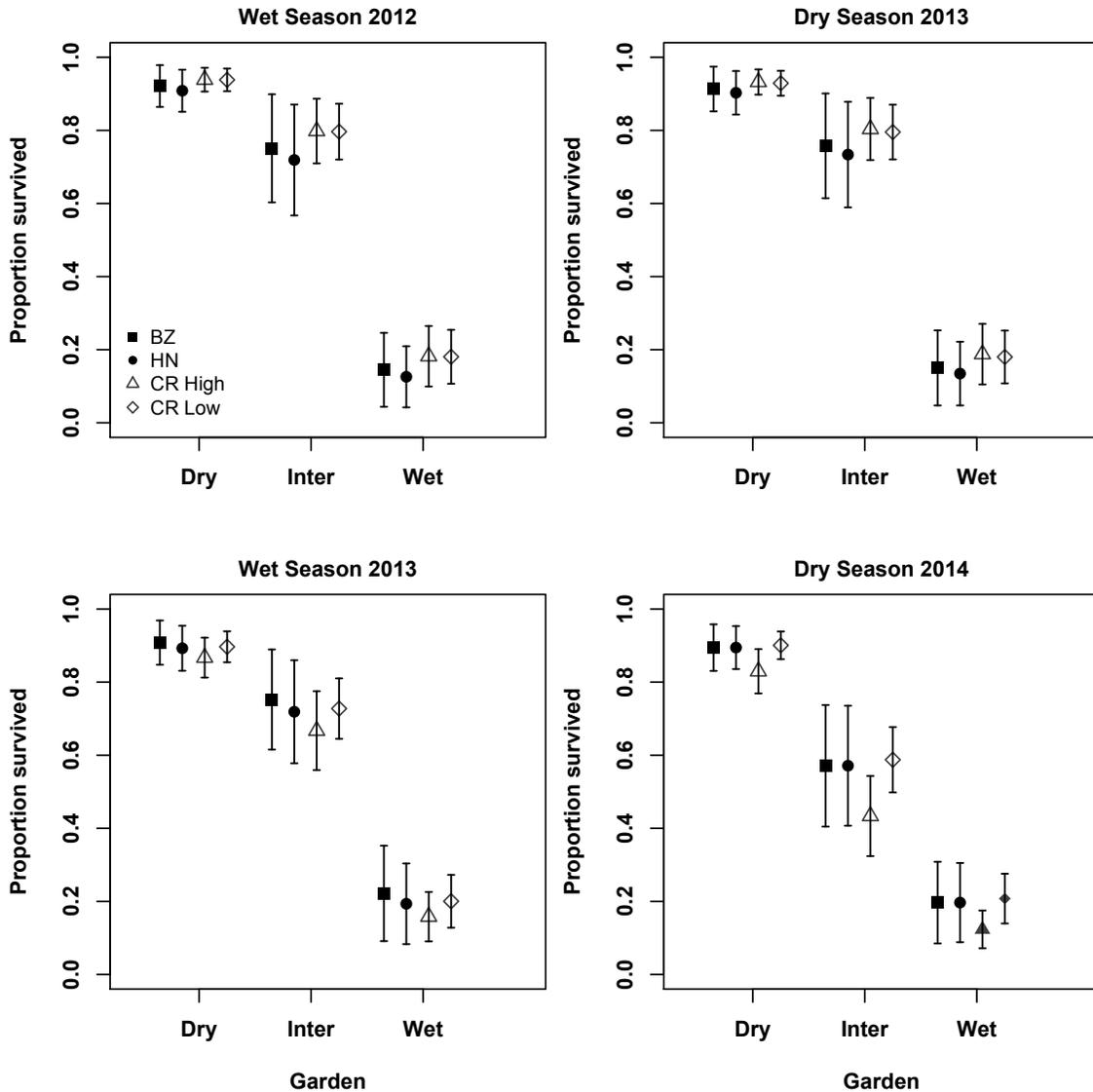


Figure S2.7- GLMM predicted survivorship of *Q. oleoides* seedlings from seeds collected from four populations throughout Central America (Belize, BZ; Honduras, HZ, and Costa Rica high- and low- elevations, CR High and CR Low respectively) and planted into common gardens at the dry (Honduras), intermediate (Inter, Costa Rica low-elevation) and wet (Costa Rica high-elevation) gardens in 2011.

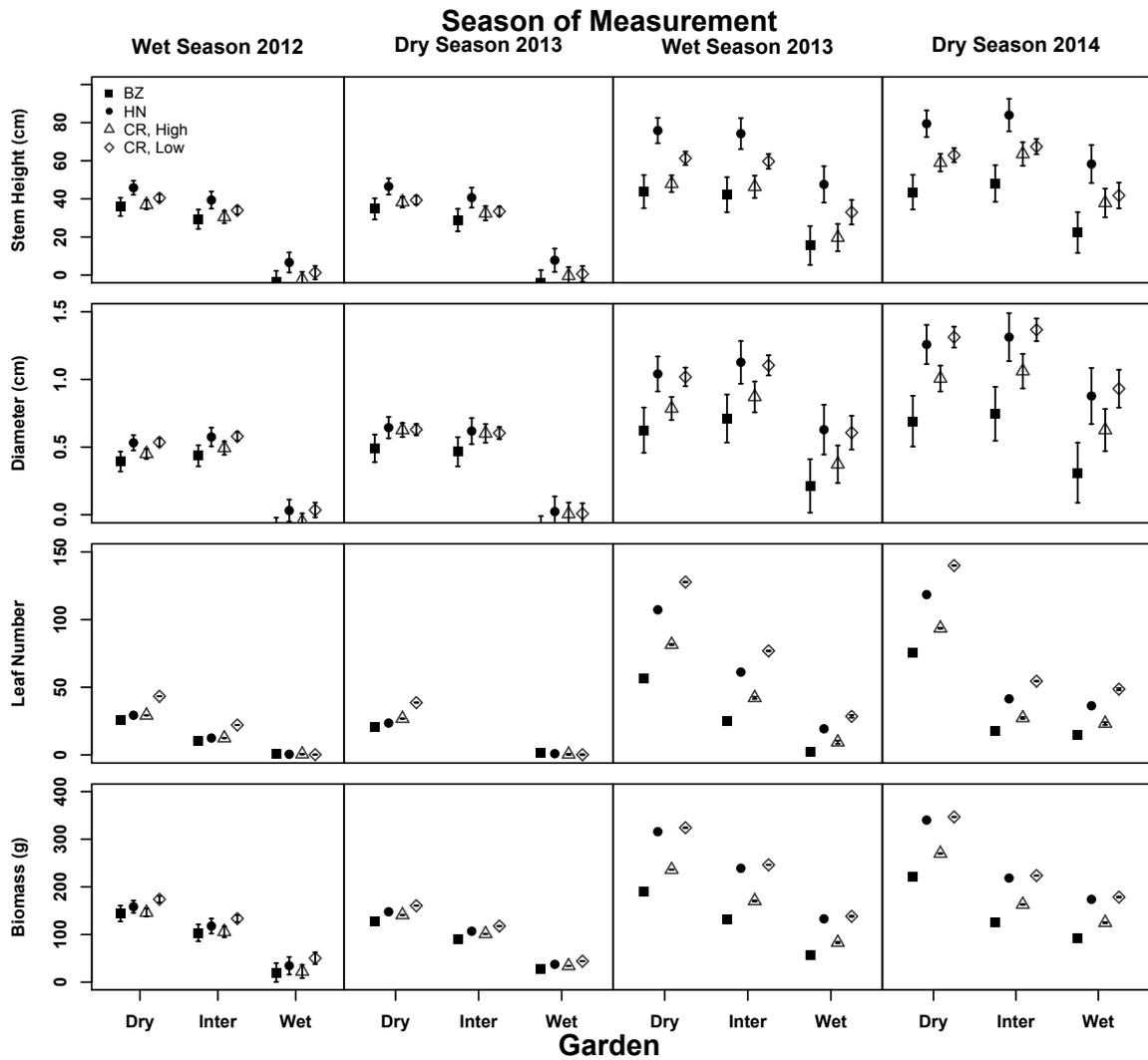


Figure S2.8- LMM predicted growth trait means of *Q. oleoides* seedlings from seeds collected from four populations in Central America (Belize, BZ; Honduras, HZ, and Costa Rica high- and low- elevations, CR High and CR Low respectively). Seeds were planted directly into in ambient rainfall blocks at dry (Honduras), intermediate (Inter, Costa Rica, low-elevation), and wet (Costa Rica high-elevation) gardens in 2011.

		DS 2011	DS 2012
Fixed Effects	DF	X²	X²
Treatment (T)	3	5.37	5.48
Population (P)	3	4.22	2.48
Seed Mass	1	1.20	0.68
Size at Planting	1	0.19	4.89 *
Herbivory	1	0.34	8.17 **
T x P	9	7.00	4.07

Table S2.18- Summary generalized linear mixed model nested model comparison to test effects of factors on survivorship of *Q. oleoides* seedlings from seeds collected from natural populations through Central America (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH and Costa Rica low-elevation, CRL) and germinated in a shadehouses at Zamorano University and transplanted into dry garden in 2010. Degrees of freedom shown is the difference in nested models for each factor tested. +0.10 \geq P>0.05; * P \leq 0.05, ** P \leq 0.01; ***P<0.001

Fixed Effects	DS 2011			DS 2012		
	Est	SE	Z	Est	SE	Z
BS Water	1.23	0.63	1.94	0.19	0.53	0.36
DS Water	0.75	0.66	1.14	0.22	0.52	0.42
Ambient Water	0.19	0.63	0.31	-0.25	0.54	-0.45
WS Water	-0.14	0.59	-0.24	-0.37	0.53	-0.69
HN	0.07	0.54	0.13	0.10	0.46	0.21
CRH	0.10	0.53	0.18	0.48	0.46	1.03
CRL	0.23	0.64	0.37	0.19	0.53	0.36
Seed Mass	0.20	0.19	1.08	0.12	0.14	0.83
Size at Planting	-0.02	0.04	-0.44	0.06	0.03	2.20
Herbivory	-0.18	0.31	-0.60	-0.96	0.29	-3.32
DS Water x HN	0.88	1.02	0.86	0.59	0.65	0.90
DS Water x CRH	0.24	0.88	0.27	0.32	0.65	0.49
DS Water x CRL	-0.27	1.00	-0.27	0.02	0.73	0.02
Ambient Water x HN	-0.19	0.78	-0.24	0.09	0.63	0.14
Ambient Water x CRH	-0.05	0.77	-0.07	-0.56	0.62	-0.90
Ambient Water x CRL	0.80	1.07	0.75	-0.22	0.73	-0.31
WS Water x HN	0.58	0.77	0.76	0.27	0.62	0.43
WS Water x CRH	0.26	0.74	0.35	-0.09	0.62	-0.15
WS Water x CRL	2.05	1.27	1.62	0.47	0.71	0.66

Table S2.19- GLMM summary of 2010 transplant survivorship of *Q. oleoides* seedlings from seeds collected from natural populations through Central America (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH and Costa Rica low-elevation, CRL) and germinated in a shadehouses at Zamorano University and transplanted into dry garden in 2010.

		DS 2011							
		Height		Diameter		Leaves		Biomass	
Effect	DF	X ²		X ²		X ²		X ²	
Treatment (T)	3	11.93	**	20.54	***	18.62	***	13.51	**
Population (P)	3	15.85	**	11.59	**	21.56	***	13.80	**
Seed mass	1	2.03		3.10	+	0.00		1.56	
Size	1	53.72	***	66.34	***	84.60	***	71.92	***
Herbivory	1	4.97	*	3.88	*	12.36	***	5.48	*
T x P	9	10.70		18.74	*	13.28		12.86	*

		DS 2012							
		Height		Diameter		Leaves		Biomass	
Effect	DF	X ²		X ²		X ²		X ²	
Treatment (T)	3	2.11		4.29		1.36		3.42	
Population (P)	3	12.00	**	7.90	*	10.49	*	6.74	+
Seed mass	1	1.19		2.10		1.93		3.77	+
Size	1	31.28	***	18.82	***	41.89	***	32.87	***
Herbivory	1	8.23	**	10.21	**	10.57	**	13.80	***
T x P	9	12.33		9.93		10.59		13.07	

Table S2.20- Summary of nested linear mixed model comparisons to test effects of factors on growth traits (stem height, basal diameter, leaf number, and aboveground biomass) of 2010 transplant cohort at the dry garden site. Covariates of seed mass and size of plant at transplanting (size) were included in analyses. Degrees of freedom (DF) shown is the difference between nested models for each factor. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***P<0.001

DS 2011

	Stem Height			Diameter			Leaf Number			Biomass		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (Ambient)	4.52	3.53	1.28	1.06	0.48	2.20	1.72	4.24	0.41	41.42	11.95	3.47
DS Water	4.47	3.12	1.43	1.39	0.42	3.27	3.40	3.38	1.01	13.75	10.41	1.32
WS Water	5.10	3.65	1.40	0.94	0.50	1.89	0.49	3.85	0.13	12.13	11.99	1.01
Both Seasons	5.32	3.29	1.61	0.56	0.45	1.24	5.06	3.54	1.43	12.57	10.95	1.15
HN	6.47	3.36	1.92	0.83	0.46	1.82	-0.23	3.41	-0.07	12.81	10.79	1.19
CRH	1.13	3.25	0.35	0.26	0.44	0.60	1.05	3.28	0.32	4.34	10.39	0.42
CRL	1.25	3.87	0.32	0.70	0.53	1.34	4.36	3.90	1.12	13.02	12.33	1.06
Seed Mass	1.31	0.92	1.43	0.22	0.13	1.77	0.05	0.93	0.05	3.68	2.94	1.25
Size	1.59	0.21	7.57	0.24	0.03	8.49	2.11	0.21	9.90	5.96	0.67	8.85
Herbivory	-4.09	1.47	-2.79	-0.40	0.20	-1.99	-13.51	3.39	-3.99	-19.52	7.51	-2.60
DS Water x HN	-0.44	4.17	-0.11	-0.54	0.57	-0.94	5.91	4.22	1.40	8.06	13.35	0.60
WS water x HN	-5.22	4.68	-1.12	-0.77	0.64	-1.21	1.47	4.72	0.31	-9.67	14.94	-0.65
BS Water x HN	2.88	4.41	0.65	0.97	0.60	1.62	6.83	4.45	1.54	18.70	14.08	1.33
DS Water x CRH	2.14	4.05	0.53	0.05	0.55	0.10	11.43	4.10	2.79	21.12	12.97	1.63
WS water x CRH	-0.53	4.65	-0.11	-0.19	0.63	-0.30	7.28	4.68	1.56	9.15	14.83	0.62
BS Water x CRH	-0.15	4.23	-0.04	0.18	0.58	0.31	6.59	4.26	1.55	11.86	13.47	0.88
DS Water x CRL	5.69	4.94	1.15	0.05	0.67	0.08	5.33	4.98	1.07	16.32	15.77	1.03
WS water x CRL	-4.17	5.23	-0.80	-1.17	0.71	-1.64	-3.63	5.27	-0.69	-19.41	16.68	-1.16
BS Water x CRL	-2.34	4.98	-0.47	-0.43	0.68	-0.63	1.31	5.02	0.26	-3.06	15.88	-0.19

	DS 2012											
	Stem Height			Diameter			Leaf Number			Biomass		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (Ambient)	42.60	10.92	3.90	5.04	2.67	1.89	5.53	1.67	3.30	11.71	2.10	5.58
DS Water	1.51	10.64	0.14	1.50	2.45	0.61	-0.30	1.61	-0.19	-0.58	1.99	-0.29
WS Water	1.08	11.90	0.09	1.28	2.81	0.46	-0.40	1.81	-0.22	-0.57	2.25	-0.25
Both Seasons	-6.77	11.17	-0.61	1.55	2.58	0.60	-0.90	1.70	-0.53	-0.98	2.09	-0.47
HN	3.04	9.56	0.32	2.66	2.47	1.07	0.00	1.49	0.00	-0.76	1.90	-0.40
CRH	-6.92	9.18	-0.75	3.56	2.38	1.50	0.32	1.43	0.22	-0.32	1.82	-0.17
CRL	-11.56	10.88	-1.06	1.30	2.83	0.46	1.59	1.69	0.94	-1.99	2.16	-0.92
Seed Mass	2.82	2.59	1.09	0.97	0.67	1.45	0.56	0.40	1.39	1.00	0.51	1.95
Size	3.40	0.60	5.70	0.68	0.15	4.41	0.62	0.09	6.68	0.69	0.12	5.88
Herbivory	-42.60	6.45	-6.61	-7.42	1.30	-5.69	-5.49	0.96	-5.73	-7.87	1.14	-6.89
DS Water x HN	11.20	11.79	0.95	1.12	3.06	0.37	2.30	1.83	1.26	4.08	2.34	1.74
WS water x HN	0.78	13.23	0.06	-2.84	3.43	-0.83	0.72	2.05	0.35	1.30	2.62	0.50
BS Water x HN	22.30	12.44	1.79	3.73	3.23	1.16	4.16	1.93	2.16	5.74	2.47	2.33
DS Water x CRH	6.82	11.45	0.60	-2.42	2.97	-0.81	1.62	1.78	0.91	2.22	2.27	0.98
WS water x CRH	9.96	13.06	0.76	-2.91	3.40	-0.86	1.33	2.03	0.66	1.26	2.59	0.49
BS Water x CRH	9.45	11.88	0.80	-2.68	3.09	-0.87	1.39	1.85	0.75	1.79	2.36	0.76
DS Water x CRL	31.51	13.90	2.27	2.94	3.61	0.81	2.56	2.16	1.18	7.27	2.76	2.63
WS Water x CRL	5.62	14.72	0.38	-2.45	3.82	-0.64	0.30	2.29	0.13	2.52	2.92	0.86
BS Water x CRL	16.20	13.99	1.16	1.70	3.64	0.47	-0.03	2.17	-0.01	3.96	2.78	1.43

Table S2.21- Summary of linear mixed models of growth traits (stem height, basal diameter, leaf number, and aboveground biomass) of *Q. oleoides* seeds collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and planted into shadehouses in Honduras and transplanted into common garden in Honduras subjected to one of four watering treatments (Ambient; dry season water, DS Water; wet season water, WS Water; or watered both seasons, BS water). Covariates of seed mass and size of plant at transplanting (size) were included in analyses.

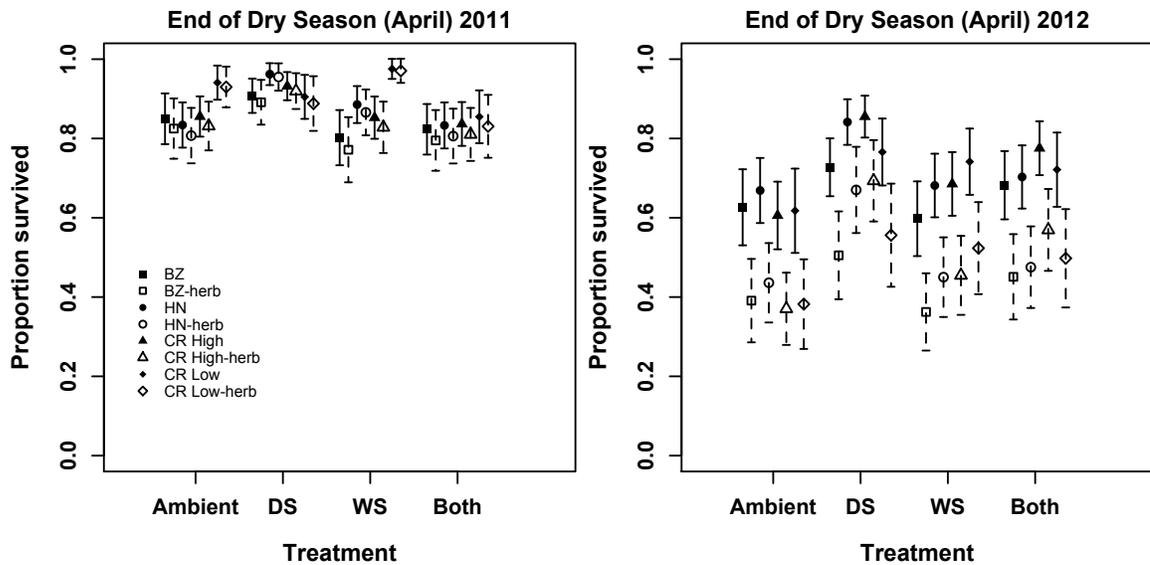


Figure S2.9- GLMM predicted survival of 2010 transplants at Dry Garden (Honduras) that were administered one of four watering treatments: Ambient, wet season water (WS Water), dry season water (DS water) and watered both seasons (Both). Herbivory index was included in analyses and estimates of survivorship are based on with (open symbols) and without (closed symbols) herbivore damage. Seeds were collected from four populations in Central America (Belize, BZ; Honduras, HZ, and Costa Rica high- and low- elevations, CR High and CR Low respectively).

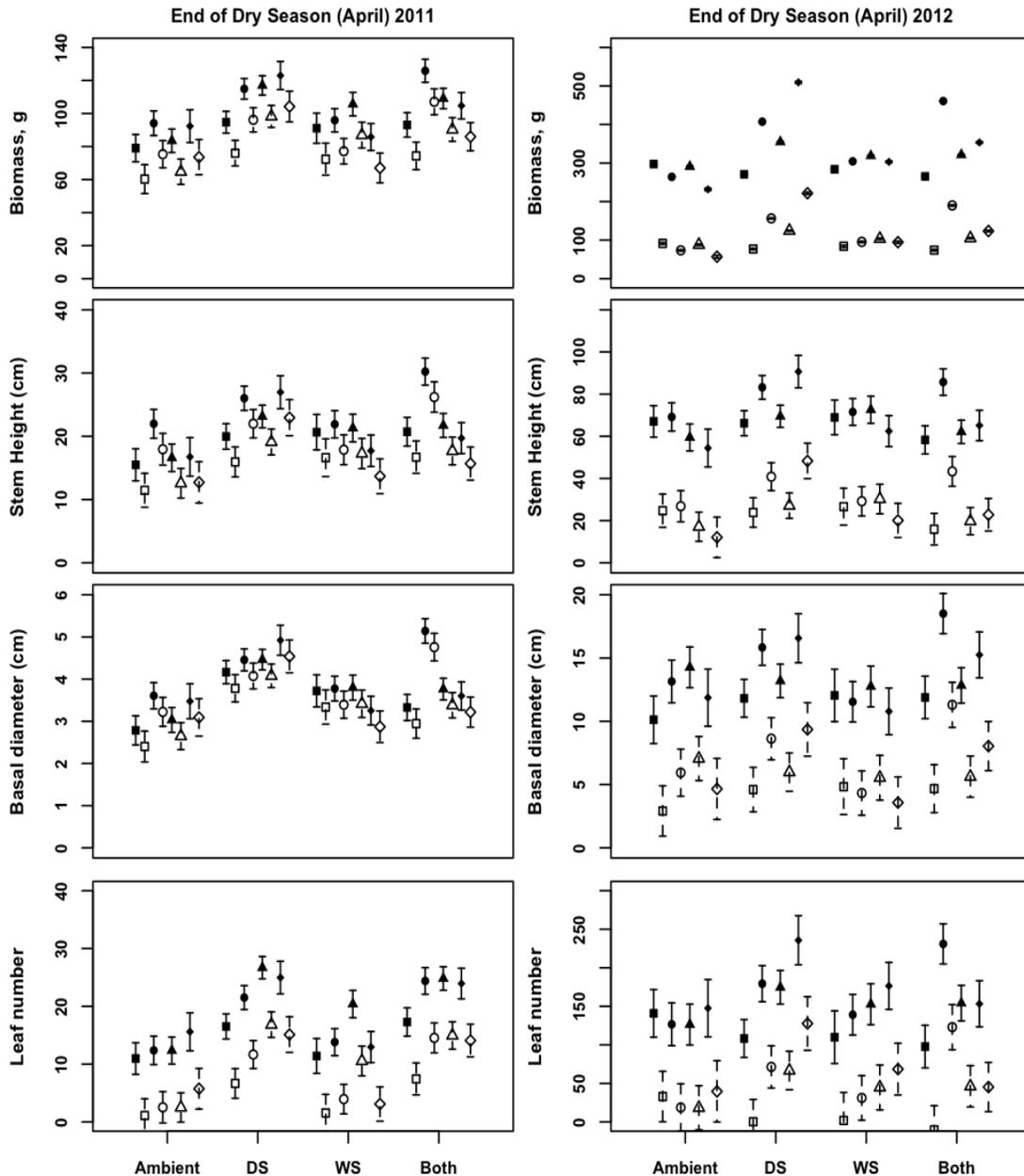


Figure S2.10- LMM predicted growth trait means (SE) for 2010 transplants at three measurement points in the treatments at the Dry Garden (Honduras). Herbivory index was included in analyses and estimates of growth traits are with (open symbols) and without (closed symbols) herbivore damage. Seedlings were subjected to one of four watering treatments: Ambient, wet season water (WS Water), dry season water (DS water) and watered both seasons (Both). Seeds were collected from four populations in Central America (Belize, BZ; Honduras, HZ, and Costa Rica high- and low- elevations, CR High and CR Low respectively).

Effect	DF	WS 2012		DS 2013		WS 2013		DS 2014	
		X ²	\`	X ²		X ²		X ²	
Treatment (T)	3	13.25	**	13.11	**	11.18	*	11.63	**
Population (P)	3	8.75	*	7.64	*	10.28	*	10.20	*
Seed Mass	1	0.00		0.00		0.00		0.00	
Size	1	82.70	***	72.37	***	60.99	***	57.80	***
Cut	1	24.34	***	22.40	***	14.38	***	10.04	**
Herbivory	1	22.136	***	72.37	***	10.36	**	9.47	**
T x P	9	9.96		4.94		0.00		0.00	

Table S2.22- Summary of effect significance using nested model comparison of survivorship of *Q. oleoides* seeds collected from natural populations through Central America and planted into shadehouses in Honduras and then transplanted into common garden in 2011 and subjected to one of four watering treatments (Ambient, dry season water-DS Water, wet season water- WS Water, or watered both seasons -BS water). Covariates of seed mass and size of plant at transplanting (size) were included in analyses. Degrees of freedom (DF) shown is the difference between nested models for each factor. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***P<0.001

Fixed Effects	WS 2012			DS 2013			WS 2013			DS 2014		
	Est	SE	Z									
Intercept (Both)	0.38	0.64	0.58	0.53	0.69	0.76	0.04	0.76	0.05	0.01	0.76	0.02
DS Water	-0.35	0.52	-0.67	-0.47	0.52	-0.90	-0.26	0.53	-0.50	-0.24	0.54	-0.45
Ambient	-1.26	0.54	-2.35	-1.27	0.54	-2.36	-0.74	0.55	-1.36	-0.83	0.56	-1.50
WS Water	-1.17	0.54	-2.17	-1.19	0.54	-2.20	-0.73	0.56	-1.31	-0.74	0.56	-1.31
HN	0.26	0.48	0.53	-0.02	0.49	-0.04	0.25	0.49	0.51	0.24	0.49	0.50
CRH	-0.17	0.60	-0.28	-0.15	0.60	-0.25	-0.28	0.61	-0.45	-0.29	0.61	-0.47
CRL	0.04	0.41	0.10	0.00	0.41	0.01	0.43	0.42	1.02	0.39	0.42	0.93
Seed Mass	0.01	0.14	0.07	0.01	0.14	0.09	0.05	0.14	0.35	0.03	0.14	0.18
Size at Planting	0.16	0.02	8.48	0.15	0.02	8.31	0.15	0.02	8.23	0.15	0.02	8.13
Cut	-1.87	0.40	-4.65	-2.13	0.42	-5.08	-2.34	0.47	-4.97	-2.22	0.47	-4.69
Herbivory	1.65	0.40	4.17	1.73	0.40	4.36	1.77	0.38	4.62	1.74	0.37	4.70
Ambient x HN	0.31	0.66	0.46	0.49	0.66	0.74	0.16	0.66	0.25	0.20	0.67	0.30
Ambient x CRH	-0.66	0.86	-0.77	-0.68	0.87	-0.79	-0.54	0.87	-0.62	-0.41	0.87	-0.47
Ambient x CRL	0.78	0.56	1.41	0.79	0.56	1.42	0.28	0.56	0.50	0.27	0.56	0.49
DS Water x HN	0.49	0.66	0.74	0.87	0.66	1.31	0.58	0.66	0.88	0.48	0.66	0.73
DS Water x CRH	0.16	0.81	0.20	0.07	0.81	0.08	0.35	0.81	0.44	0.36	0.81	0.44
DS Water x CRL	0.20	0.55	0.38	0.30	0.55	0.55	0.15	0.55	0.26	0.12	0.55	0.22
WS Water x HN	0.28	0.67	0.41	0.57	0.67	0.85	0.18	0.68	0.27	0.20	0.68	0.30
WS Water x CRH	0.52	0.82	0.64	0.53	0.82	0.64	0.54	0.83	0.64	0.15	0.84	0.18
WS Water x CRL	0.19	0.56	0.34	0.14	0.57	0.24	-0.44	0.58	-0.76	-0.48	0.58	-0.83

Table S2.23- GLMM summary of 2011 transplant cohort survivorship of *Q. oleoides* seedlings from seeds collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and germinated in a shadehouses at Zamorano University and transplanted into a common garden and administered one of four watering treatments: (Ambient, dry season water-DS Water, wet season water- WS Water, or watered both seasons -BS water).

WS2012		Height		Diameter		Leaf Number		Biomass	
Effect	DF	X²		X²		X²		X²	
Treatment (T)	3	4.14		18.06	**	5.26		5.29	
Population (P)	3	23.41	***	5.93		5.23		14.92	**
Seed Mass	1	0.06		0.44		0.30		0.15	
Size	1	14.45	***	0.68		51.87	***	60.01	***
Cut	1	3.27	+	1.21		11.83	***	9.16	**
Herbivory	1	2.33		0.02		0.49		0.00	
T x P	9	7.38		7.76		4.83		6.57	
MF (P)	2	1.09		0.00		6.86	*	3.44	
Block (T)	2	71.76	***	3.03		263.03	***	219.88	***
DS 2013		Height		Diameter		Leaves		Biomass	
Effect	DF	X²		X²		X²		X²	
T	3	3.57		5.39		6.07		4.03	
P	3	23.38	***	8.72	*	9.74	*	30.75	***
Seed Mass	1	0.00		0.09		0.22		0.05	
Size	1	19.26	**	0.05		54.29	***	16.53	***
Cut	1	1.83		0.25		6.67	*	1.74	
Herbivory	1	1.52		0.00		0.95		0.82	
T x P	9	3.97		13.64		8.93		8.38	
MF (P)	2	0.04		0.00		3.39		0.24	
Block (T)	2	79.90	***	1.40		232.81	***	150.04	***
WS 2013		Height		Diameter		Leaves		Biomass	
Effect	DF	X²		X²		X²		X²	
T	3	4.01		8.76	*	5.85		5.40	
P	3	42.02	***	9.15	*	19.30	***	17.02	**
Seed Mass	1	0.00		0.08		0.01		0.75	
Size	1	8.92	**	2.10		39.30		34.09	***
Cut	1	0.28		0.75		5.09	*	3.38	+
Herbivory	1	2.97	+	0.41		1.75		0.08	
T x P	9	8.14		9.19		9.71		8.71	
MF (P)	2	0.50		0.00		3.26		0.26	
Block (T)	2	91.31	***	3.03		207.69	***	76.26	***
DS 2014		Height		Diameter		Leaves		Biomass	
Effect	DF	X²		X²		X²		X²	
Treat	3	5.09		12.39	**	6.90	+	5.40	
Pop	3	42.64	***	1.33		9.90	*	17.02	**
Seed Mass	1	0.25		0.20		0.54		0.75	
Size	1	12.33	***	12.33	***	37.06	***	34.09	***
Cut	1	2.17		3.01	+	3.11	+	3.38	+
Herbivory	1	2.35		0.59		0.75		0.08	
T x P	9	12.80		16.92	*	8.61		8.71	
MF (P)	2	0.41		0.00		1.27		0.26	
Block (T)	2	76.45	***	0.99		110.66	***	76.26	***

Table S2.24- Summary of nested model comparisons to test effect significance of linear mixed effects models for growth traits (stem height, basal diameter, leaf number, and aboveground biomass) from seeds collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and germinated in a shadehouses at Zamorano University and transplanted into a common garden and administered one of four watering treatments: (Ambient, dry season water-DS Water, wet season water- WS Water, or watered both seasons -BS water) in 2010. Covariates of seed mass and size of plant at transplanting (size) were included in analyses. Degrees of freedom (DF) shown is the difference between nested models for each factor.
+0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***P<0.001

WS 2012

	Height			Diameter			Leaves ⁺			Biomass		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (Both)	25.01	6.31	3.97	94.47	13.39	7.05	3.58	1.13	3.18	3.58	1.13	3.18
DS Water	-5.07	6.54	-0.78	-23.20	14.75	-1.57	0.28	0.98	0.29	0.28	0.98	0.29
Ambient	-3.19	6.88	-0.46	-45.23	15.81	-2.86	-0.36	1.07	-0.33	-0.36	1.07	-0.33
WS Water	-6.69	7.06	-0.95	-28.72	16.10	-1.78	0.36	0.99	0.37	0.36	0.99	0.37
HN	12.57	5.22	2.41	-26.19	13.45	-1.95	1.13	0.75	1.52	1.13	0.75	1.52
CRH	-3.04	6.92	-0.44	-10.43	17.69	-0.59	0.84	1.12	0.75	0.84	1.12	0.75
CRL	3.89	4.49	0.87	-11.32	11.57	-0.98	0.77	0.65	1.18	0.77	0.65	1.18
Seed Mass	-0.37	1.54	-0.24	-2.57	3.87	-0.67	0.11	0.20	0.55	0.11	0.20	0.55
Size at Planting	0.80	0.21	3.83	0.44	0.53	0.83	0.19	0.03	7.35	0.19	0.03	7.35
Cut	-5.83	3.21	-1.82	4.19	3.81	1.10	-1.62	0.46	-3.53	-1.62	0.46	-3.53
Herbivory	-3.92	2.57	-1.53	0.89	6.35	0.14	0.23	0.33	0.70	0.23	0.33	0.70
DS Water x HN	2.27	7.21	0.32	22.20	18.70	1.19	-0.05	0.94	-0.06	-0.05	0.94	-0.06
Ambient x HN	2.88	7.64	0.38	25.26	19.84	1.27	-1.27	1.06	-1.19	-1.27	1.06	-1.19
WS Water x HN	-6.97	7.84	-0.89	13.73	20.23	0.68	-0.34	0.95	-0.36	-0.34	0.95	-0.36
DS Water x CRH	-1.55	9.18	-0.17	28.16	23.81	1.18	-1.20	1.31	-0.92	-1.20	1.31	-0.92
Ambient x CRH	11.52	10.67	1.08	21.01	27.81	0.76	-1.05	1.43	-0.73	-1.05	1.43	-0.73
WS Water x CRH	5.05	10.27	0.49	-10.50	26.52	-0.40	-0.63	1.34	-0.47	-0.63	1.34	-0.47
DS Water x CRL	-0.32	6.13	-0.05	10.32	15.96	0.65	0.18	0.81	0.22	0.18	0.81	0.22
Ambient x CRL	-1.27	6.55	-0.19	29.76	17.02	1.75	-0.97	0.94	-1.03	-0.97	0.94	-1.03
WS Water x CRL	-0.79	6.83	-0.12	8.57	17.63	0.49	-0.38	0.82	-0.46	-0.38	0.82	-0.46

DS 2013

	Height			Diameter			Leaves ⁺			Biomass		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (Both)	25.06	6.67	3.76	6.31	0.74	8.49	3.93	1.60	2.45	12.34	1.03	11.95
DS Water	-4.58	6.86	-0.67	-1.89	0.80	-2.35	0.17	1.35	0.13	-1.09	1.03	-1.06
Ambient	-2.86	7.21	-0.40	-1.08	0.86	-1.25	-0.54	1.49	-0.36	0.01	1.08	0.01
WS Water	-8.08	7.41	-1.09	-2.35	0.88	-2.68	0.16	1.36	0.12	-1.62	1.11	-1.46
HN	15.93	5.35	2.98	-2.56	0.73	-3.51	0.48	1.05	0.46	2.03	0.77	2.62
CRH	-0.44	7.08	-0.06	-2.16	0.96	-2.25	-0.27	1.57	-0.17	-0.59	1.03	-0.57
CRL	4.15	4.59	0.90	-1.65	0.63	-2.62	0.47	0.92	0.51	0.33	0.67	0.50
Seed Mass	-0.08	1.55	-0.05	0.06	0.21	0.31	-0.13	0.28	-0.47	0.07	0.23	0.30
Size at Planting	0.95	0.21	4.46	-0.01	0.03	-0.23	0.28	0.04	7.53	0.12	0.03	3.80
Cut	-4.65	3.43	-1.35	-0.18	0.28	-0.63	-1.72	0.65	-2.65	-0.89	0.52	-1.69
Herbivory	-3.28	2.65	-1.24	-0.01	0.35	-0.03	0.46	0.47	0.98	-0.63	0.38	-1.65
DS Water x HN	-3.48	7.45	-0.47	2.18	1.02	2.14	1.84	1.33	1.39	1.31	1.08	1.22
Ambient x HN	-4.58	7.89	-0.58	2.30	1.08	2.13	-0.23	1.51	-0.15	-0.61	1.14	-0.53
WS Water x HN	-7.22	8.12	-0.89	2.27	1.10	2.06	1.24	1.34	0.93	-0.40	1.18	-0.34
DS Water x CRH	-2.97	9.51	-0.31	2.46	1.30	1.90	0.26	1.86	0.14	0.09	1.38	0.07
Ambient x CRH	3.80	11.04	0.34	3.45	1.51	2.28	1.43	2.03	0.70	0.69	1.60	0.43
WS Water x CRH	4.31	10.64	0.41	3.15	1.44	2.19	1.63	1.90	0.86	0.47	1.54	0.31
DS Water x CRL	-0.24	6.34	-0.04	2.22	0.87	2.57	1.77	1.15	1.54	1.01	0.92	1.10
Ambient x CRL	-2.54	6.76	-0.38	1.38	0.93	1.49	-0.10	1.33	-0.07	-0.38	0.98	-0.39
WS Water x CRL	1.34	7.07	0.19	2.21	0.96	2.30	1.23	1.16	1.06	0.64	1.02	0.62

WS 2013

	Height			Diameter			Leaves ⁺			Biomass		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (Both)	48.55	14.10	3.44	2.09	0.20	10.54	7.52	2.76	2.73	7.52	2.76	2.73
DS Water	-13.69	14.30	-0.96	0.16	0.22	0.74	-0.85	2.41	-0.35	-0.85	2.41	-0.35
Ambient	1.85	15.01	0.12	-0.04	0.23	-0.16	0.04	2.52	0.02	0.04	2.52	0.02
WS Water	-16.63	15.41	-1.08	0.07	0.23	0.32	-1.50	2.57	-0.58	-1.50	2.57	-0.58
HN	30.23	11.10	2.72	-0.14	0.19	-0.71	6.22	1.76	3.54	6.22	1.76	3.54
CRH	-10.18	14.70	-0.69	0.22	0.26	0.86	3.48	2.34	1.49	3.48	2.34	1.49
CRL	4.73	9.54	0.50	-0.10	0.17	-0.62	3.68	1.51	2.43	3.68	1.51	2.43
Seed Mass	0.50	3.25	0.15	-0.02	0.06	-0.28	-0.10	0.52	-0.20	-0.10	0.52	-0.20
Size at Planting	1.36	0.44	3.07	-0.01	0.01	-1.45	0.42	0.07	6.04	0.42	0.07	6.04
Cut	-6.59	7.23	-0.91	-0.07	0.08	-0.97	-3.45	1.25	-2.75	-3.45	1.25	-2.75
Herbivory	-10.56	5.49	-1.93	0.06	0.09	0.65	0.48	0.86	0.56	0.48	0.86	0.56
DS Water x HN	24.17	15.40	1.57	-0.17	0.27	-0.64	0.32	2.41	0.13	0.32	2.41	0.13
Ambient x HN	-10.94	16.30	-0.67	0.05	0.29	0.17	-3.27	2.55	-1.28	-3.27	2.55	-1.28
WS Water x HN	-10.35	16.76	-0.62	0.23	0.29	0.78	-4.46	2.62	-1.70	-4.46	2.62	-1.70
DS Water x CRH	1.52	19.62	0.08	0.09	0.35	0.26	-3.09	3.07	-1.01	-3.09	3.07	-1.01
Ambient x CRH	4.22	22.80	0.19	0.19	0.40	0.47	-2.38	3.57	-0.67	-2.38	3.57	-0.67
WS Water x CRH	-0.85	21.96	-0.04	-0.29	0.38	-0.76	-3.53	3.43	-1.03	-3.53	3.43	-1.03
DS Water x CRL	13.62	13.09	1.04	0.05	0.23	0.20	0.91	2.05	0.44	0.91	2.05	0.44
Ambient x CRL	-5.24	13.97	-0.38	0.32	0.25	1.28	-2.41	2.19	-1.10	-2.41	2.19	-1.10
WS Water x CRL	2.80	14.59	0.19	0.23	0.26	0.90	-2.02	2.28	-0.88	-2.02	2.28	-0.88

	DS 2014											
	Height			Diameter*			Leaves ⁺			Biomass		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (Both)	65.88	14.84	4.44	1.92	0.17	11.23	9.75	2.93	3.33	16.64	3.24	5.14
DS Water	-17.87	15.10	-1.18	0.07	0.19	0.36	-1.00	2.80	-0.36	-1.66	3.16	-0.53
Ambient	-8.35	15.85	-0.53	0.40	0.20	1.99	-1.36	2.93	-0.46	-1.39	3.30	-0.42
WS Water	-9.77	16.27	-0.60	0.15	0.20	0.76	-1.69	3.00	-0.56	-1.66	3.39	-0.49
HN	33.13	11.70	2.83	0.13	0.17	0.75	4.82	2.07	2.33	5.80	2.36	2.45
CRH	-13.14	15.50	-0.85	-0.21	0.22	-0.95	2.02	2.74	0.74	1.58	3.13	0.51
CRL	3.43	10.06	0.34	0.05	0.14	0.32	2.28	1.78	1.29	2.37	2.03	1.17
Seed Mass	-1.73	3.43	-0.50	-0.02	0.05	-0.45	-0.48	0.61	-0.80	-0.60	0.69	-0.87
Size at Planting	1.65	0.47	3.54	-0.01	0.01	-1.59	0.51	0.08	6.17	0.56	0.09	5.94
Cut	-11.52	7.61	-1.51	-0.15	0.06	-2.40	-3.23	1.44	-2.24	-3.25	1.62	-2.00
Herbivory	-8.92	5.79	-1.54	-0.06	0.08	-0.78	-0.16	1.02	-0.16	-0.33	1.17	-0.28
DS Water x HN	22.77	16.24	1.40	-0.19	0.23	-0.81	0.73	2.86	0.26	1.83	3.28	0.56
Ambient x HN	-13.31	17.19	-0.77	-0.47	0.25	-1.88	-1.96	3.03	-0.65	-2.41	3.48	-0.69
WS Water x HN	-28.25	17.68	-1.60	0.03	0.25	0.13	-4.60	3.11	-1.48	-5.51	3.58	-1.54
DS Water x CRH	-3.22	20.70	-0.16	0.68	0.30	2.29	-2.33	3.64	-0.64	-2.39	4.19	-0.57
Ambient x CRH	1.87	24.05	0.08	-0.29	0.35	-0.83	-0.32	4.23	-0.08	-0.64	4.86	-0.13
WS Water x CRH	-12.32	23.16	-0.53	0.40	0.33	1.19	-4.20	4.08	-1.03	-4.96	4.69	-1.06
DS Water x CRL	9.99	13.81	0.72	0.03	0.20	0.17	1.82	2.43	0.75	2.23	2.79	0.80
Ambient x CRL	-8.00	14.73	-0.54	-0.22	0.21	-1.04	-1.41	2.59	-0.54	-1.83	2.98	-0.62
WS Water x CRL	-8.90	15.39	-0.58	0.18	0.22	0.80	-1.19	2.71	-0.44	-1.59	3.11	-0.51

Table S2.25- Summary of linear mixed models of growth traits (stem height, basal diameter, leaf number, and aboveground biomass) of *Q. oleoides* seedlings from seeds collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and germinated in a shadehouses at Zamorano University and transplanted into a common garden and administered one of four watering treatments: (Ambient, dry season water-DS Water, wet season water- WS Water, or watered both seasons -BS water) in 2010. Covariates of seed mass and size of plant at transplanting (size) were included in analyses.

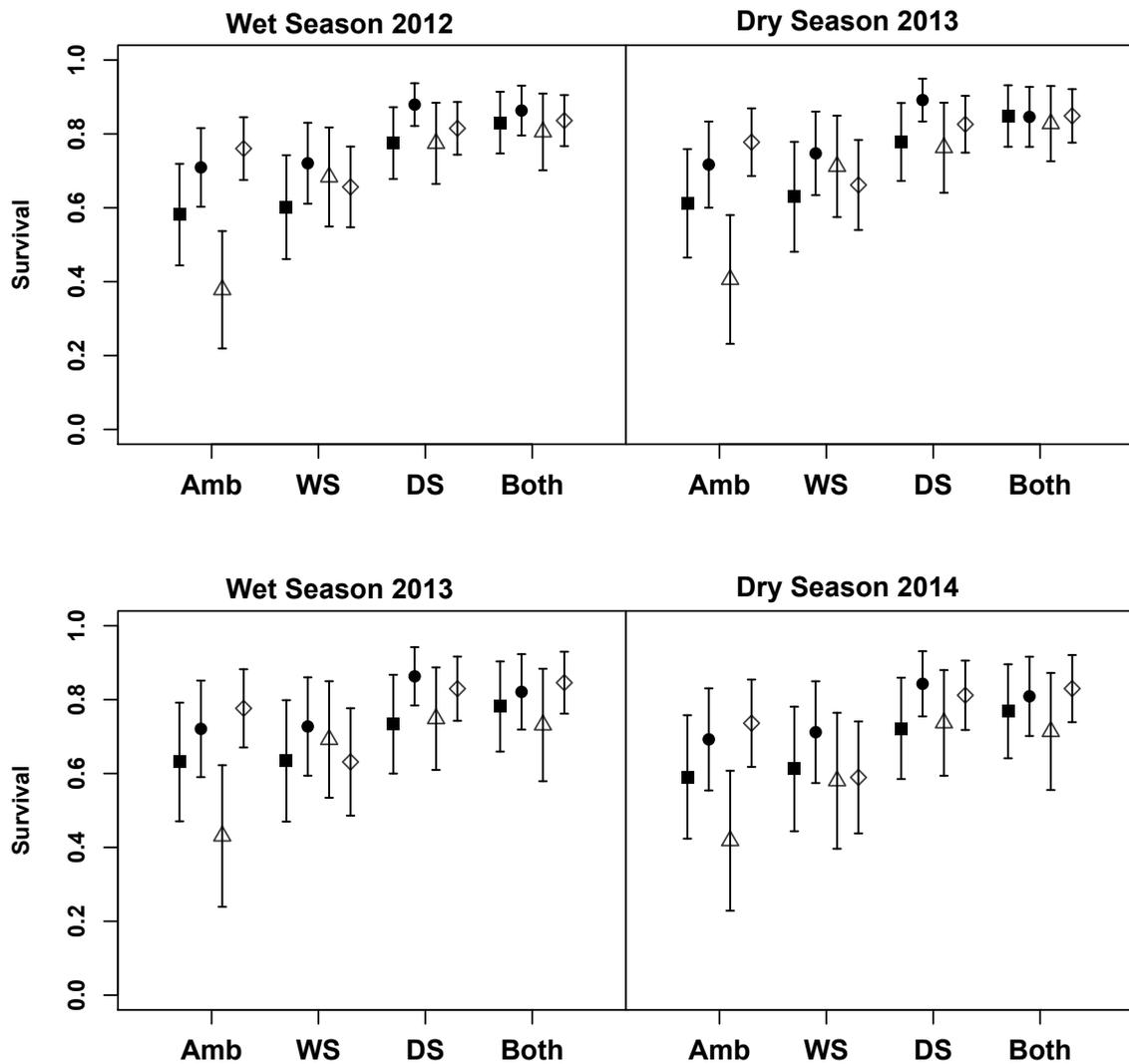


Figure S2.11- GLMM predicted survival of 2011 transplants at Dry Garden (Honduras) subjected to one of four watering treatments: Ambient, wet season water (WS Water), dry season water (DS water) and watered both seasons (Both). Seeds were collected from four populations in Central America (Belize, BZ; Honduras, HZ, and Costa Rica high- and low- elevations, CR High and CR Low respectively).

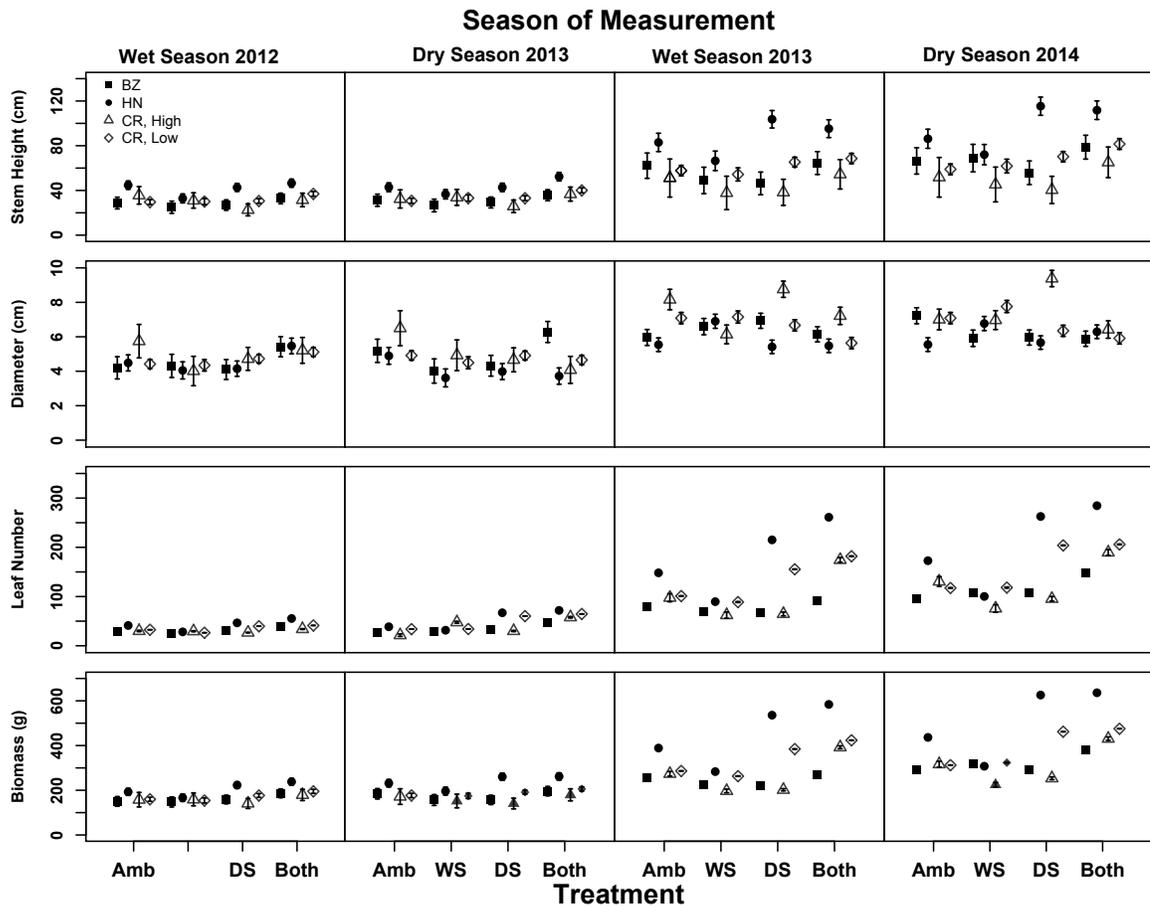


Figure S2.12- LMM predicted growth trait means for 2011 transplants at three measurement points in the treatments at the Dry Garden (Honduras). Seedlings were administered one of four watering treatments: Ambient, wet season water (WS Water), dry season water (DS water) and watered both seasons (Both). Seeds were collected from four populations in Central America (Belize, BZ; Honduras, HZ, and Costa Rica high- and low- elevations, CR High and CR Low respectively).

	DS 2011		DS 2012	
Effects	DF	Dev	Dev	
Treatment	3	2.95	10.96	*
Population	3	1.60	1.99	
Seed size	1	0.79	5.76	*
Germination Date	1	0.75	12.26	***

Table S2.26-Summary of effect significance using nested model comparison of survivorship of *Q. oleoides* seedlings from seeds collected from natural populations through Central America (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and planted into the dry garden and subjected to one of four watering (Ambient, dry season water-DS Water, wet season water- WS Water, or watered both seasons -BS water). Degrees of freedom (DF) shown is the difference between nested models for each factor. +0.10 \geq P>0.05; * P \leq 0.05, ** P \leq 0.01; ***P<0.001

Effects	DS 2011			DS 2012		
	Est	SE	Z	Est	SE	Z
Intercept (Both Water)	27.56	1617.00	0.02	19.01	5.54	3.43
DS Water	-0.64	0.94	-0.69	0.67	0.43	1.55
Ambient	-1.29	0.82	-1.56	-0.612	0.34	-1.82
WS Water	-0.73	0.93	-0.78	-0.16	0.38	-0.42
HN	-15.37	1617.00	-0.01	0.43	0.77	0.56
CRH	-14.67	1617.00	-0.01	0.80	0.72	1.11
CRL	-15.33	1617.00	-0.01	0.82	0.63	1.31
Seed size	0.48	0.58	0.84	0.65	0.28	2.26
Germination Date	-0.00	0.00	-0.91	-0.00	0.00	-3.53

Table S2.27- GLMM summary of seedling survivorship of the 2010 direct planting cohort from *Q. oleoides* seeds collected from four populations throughout Central America and planted into the DG (Honduras) and administered one of four watering treatments: (Ambient, dry season water-DS Water, wet season water- WS Water, or watered both seasons -BS water)

DS 2011									
		Stem Height		Diameter		Leaves		Biomass	
Effect	DF	Dev		Dev		Dev		Dev	
Treatment (T)	3	31.48	***	31.48	***	24.28	***	29.54	***
Population (P)	3	4.46		4.46		3.80		3.50	
Herbivory	1	0.75		0.75		0.28		0.69	
Seed Mass	1	0.09		0.09		1.61		0.39	
T x P	9	20.60	*	20.60	*	10.67		16.16	+

DS 2012									
		Stem Height		Diameter		Leaves		Biomass	
Effect	DF	Dev		Dev		Dev		Dev	
Treatment (T)	3	14.98	**	8.34	*	8.76	*	10.67	*
Population (P)	3	6.29	+	2.92		5.26		5.44	
Herbivory	1	0.08		1.50		0.04		0.04	
Seed Mass	1	0.88		0.06		2.03		1.78	
T x P	9	10.82		8.02		7.63		8.25	

Table S2.28- Summary of nested model comparisons to test effect significance of linear mixed effects models for growth traits (stem height, basal diameter, leaf number, and aboveground biomass) of 2010 direct planting cohort of seedlings at the dry garden. Seedlings were administered one of four watering treatments: Ambient, dry season water-DS Water, wet season water- WS Water, or watered both seasons -BS water. Degrees of freedom (DF) shown is the difference between nested models for each factor. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***P<0.001

	Stem Height			Diameter			Leaf Number			Biomass		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (Both)	23.69	5.64	4.21	3.56	0.64	5.57	12.63	4.87	2.60	59.61	15.32	3.89
DS Water	-8.15	9.08	-0.90	-1.38	1.04	-1.33	-3.76	7.60	-0.50	-19.10	24.20	-0.79
Ambient	-17.60	7.24	-2.43	-1.62	0.83	-1.95	-9.29	6.08	-1.53	-43.09	19.30	-2.23
WS Water	4.94	7.98	0.62	0.18	0.91	0.19	-1.59	6.70	-0.24	4.05	21.27	0.19
HN	14.08	6.76	2.08	0.94	0.76	1.23	2.88	5.63	0.51	26.12	18.00	1.45
CRH	6.09	5.65	1.08	0.14	0.64	0.21	4.62	4.73	0.98	15.31	15.06	1.02
CRL	3.61	4.92	0.73	0.22	0.56	0.40	6.68	4.11	1.63	14.80	13.10	1.13
Herbivory	-1.79	2.06	-0.87	-0.17	0.23	-0.75	-0.91	1.72	-0.53	-4.57	5.50	-0.83
Seed Mass	0.35	1.19	0.29	0.02	0.13	0.14	1.27	1.00	1.28	1.99	3.19	0.63
Ambient x HN	-8.17	9.74	-0.84	-0.96	1.10	-0.88	-1.33	8.10	-0.16	-14.39	25.95	-0.56
Ambient x CRH	-6.64	8.74	-0.76	-0.89	0.99	-0.91	-7.68	7.28	-1.06	-21.58	23.28	-0.93
Ambient x CRL	5.39	7.49	0.72	0.41	0.85	0.49	-2.76	6.25	-0.44	6.36	19.96	0.32
DS Water x HN	13.91	11.66	1.19	2.13	1.31	1.62	13.91	9.69	1.44	44.06	31.05	1.42
DS Water x CRH	9.72	10.42	0.93	1.69	1.18	1.44	8.50	8.68	0.98	29.35	27.76	1.06
DS Water x CRL	8.80	9.34	0.94	1.40	1.05	1.33	2.09	7.78	0.27	18.44	24.87	0.74
WS Water x HN	-24.63	10.53	-2.34	-1.73	1.19	-1.46	-5.89	8.78	-0.67	-46.15	28.05	-1.65
WS Water x CRH	-14.88	9.43	-1.58	-0.90	1.06	-0.85	-6.23	7.85	-0.79	-31.23	25.12	-1.24
WS Water x CRL	-13.27	8.23	-1.61	-0.89	0.93	-0.96	-6.77	6.86	-0.99	-29.45	21.94	-1.34

	DS 2012											
	Stem Height			Diameter [±]			Leaf Number [±]			Biomass [±]		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (Both)	83.72	20.91	4.00	4.40	1.05	4.20	12.60	5.05	2.49	19.45	5.70	3.41
DS Water	-57.61	27.32	-2.11	-1.42	1.43	-0.99	-10.71	6.61	-1.62	-13.11	7.32	-1.79
Ambient	-66.06	27.50	-2.40	-2.29	1.45	-1.58	-8.42	6.68	-1.26	-11.23	7.39	-1.52
WS Water	-29.68	24.67	-1.20	-0.83	1.31	-0.63	-6.47	6.02	-1.08	-7.28	6.66	-1.09
HN	0.04	24.24	0.00	0.45	1.22	0.37	6.23	5.73	1.09	7.30	6.35	1.15
CRH	-31.99	19.84	-1.61	-1.04	1.02	-1.02	0.56	4.76	0.12	-0.48	5.27	-0.09
CRL	-10.19	18.11	-0.56	-0.81	0.93	-0.87	0.58	4.32	0.13	0.50	4.79	0.11
Herbivory	-1.56	5.69	-0.28	-0.37	0.30	-1.24	0.27	1.37	0.20	-0.29	1.52	-0.19
Seed Mass	3.22	3.42	0.94	0.04	0.18	0.25	1.19	0.82	1.45	1.24	0.91	1.36
Ambient x HN	44.09	35.13	1.26	0.18	1.79	0.10	-2.61	8.36	-0.31	-1.84	9.26	-0.20
Ambient x CRH	63.44	31.22	2.03	2.03	1.59	1.27	2.89	7.45	0.39	5.23	8.25	0.63
Ambient x CRL	46.17	28.18	1.64	1.89	1.45	1.30	3.33	6.76	0.49	5.15	7.49	0.69
DS Water x HN	71.48	35.28	2.03	2.49	1.78	1.40	4.84	8.34	0.58	7.50	9.25	0.81
DS Water x CRH	82.91	30.82	2.69	1.98	1.57	1.26	12.80	7.34	1.74	16.55	8.14	2.04
DS Water x CRL	58.28	28.04	2.08	2.20	1.43	1.54	10.99	6.68	1.65	14.03	7.41	1.90
WS Water x HN	10.13	33.21	0.31	-0.45	1.69	-0.27	-5.95	7.91	-0.75	-6.07	8.77	-0.69
WS Water x CRH	39.04	31.42	1.24	0.73	1.60	0.46	9.34	7.48	1.25	10.83	8.30	1.31
WS Water x CRL	8.79	25.47	0.35	0.44	1.30	0.34	4.86	6.08	0.80	4.55	6.74	0.68

Table S2.29- Summary of linear mixed models of growth traits (stem height, basal diameter, leaf number, and aboveground biomass) of seedlings from the 2010 direct planting cohort at the end of the DS 2011 and 2012 of *Q. oleoides* seeds collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and planted directly into common gardens in Honduras in one of four watering treatments: Ambient, dry season water-DS Water, wet season water- WS Water, or watered both seasons -BS water.

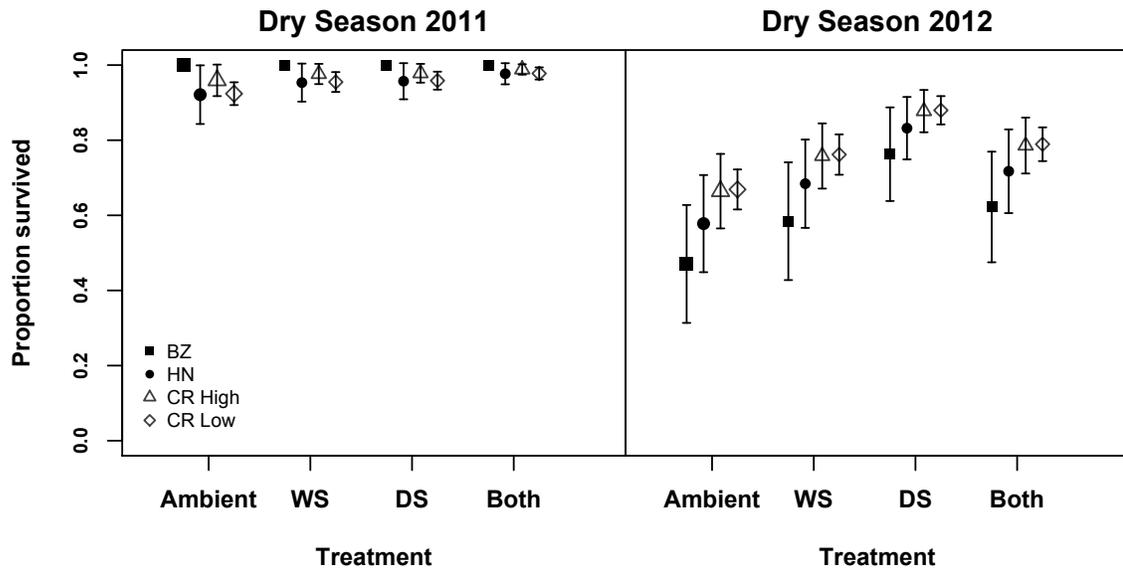


Figure S2.13- GLMM predicted survivorship of seedlings from 2010 direct planting cohort at the dry garden site. Seedlings were administered one of four watering treatments: Ambient, wet season water (WS Water), dry season water (DS water) and watered both seasons (Both). Seeds were collected from four populations in Central America (Belize, BZ; Honduras, HZ, and Costa Rica high- and low- elevations, CR High and CR Low respectively).

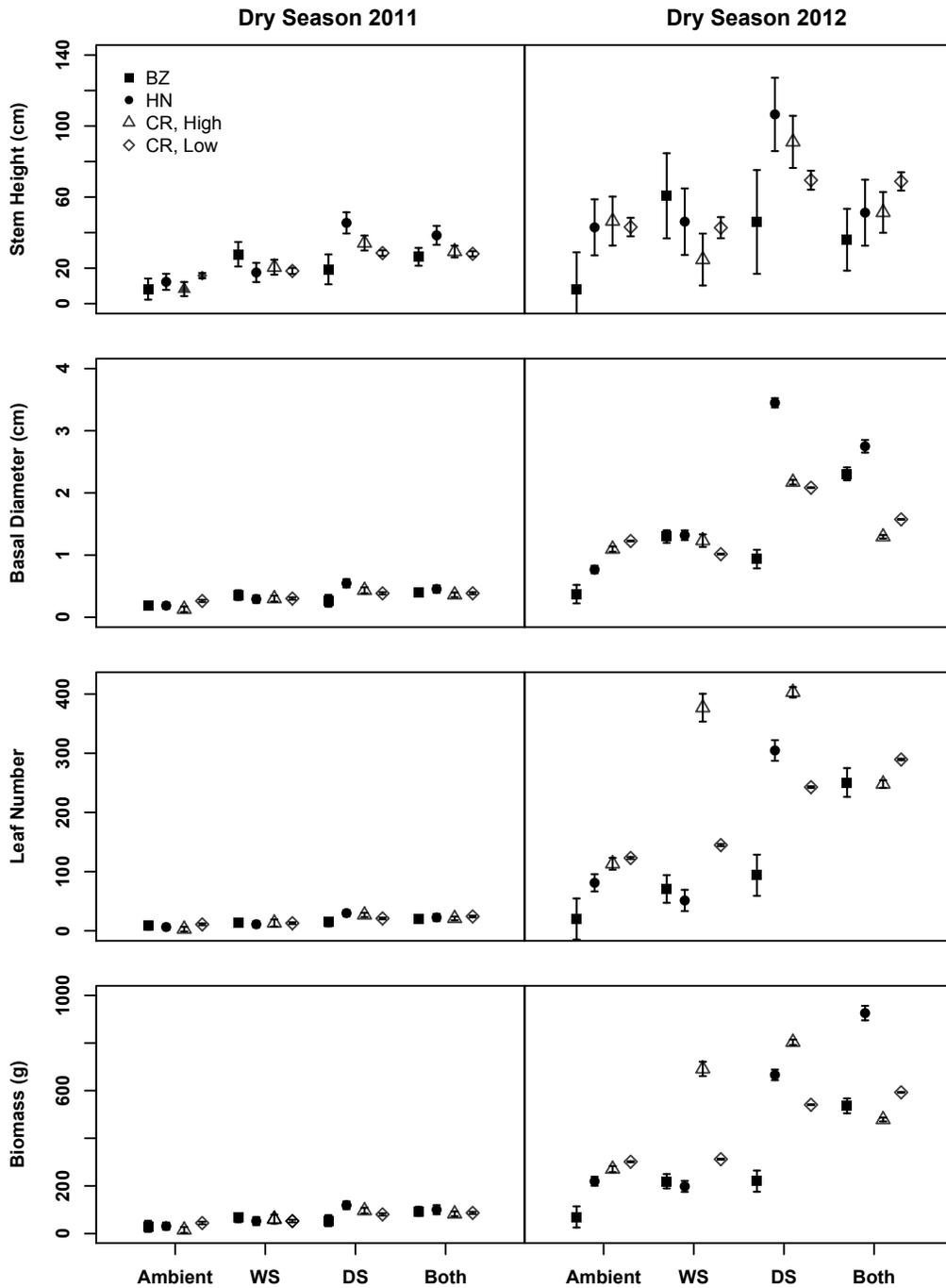


Figure S2.14-LMM predicted growth trait means of seedlings from 2010 direct planting cohort at the Dry Garden (Honduras). Seedlings were administered one of four watering treatments: Ambient, wet season water (WS Water), dry season water (DS water) and watered both seasons (Both). Seeds were collected from four populations in Central America (Belize, BZ; Honduras, HZ, and Costa Rica high- and low-elevations, CR High and CR Low respectively).

Effect	DF	WS 2012		DS 2013		WS 2013		DS 2014	
		X ²		X ²		X ²		X ²	
Treatment	3	7.46	+	7.19	+	6.98	+	6.22	+
Population	3	18.96	***	18.02	***	10.65	*	9.28	*
Seed Mass	1	0.17		0.29		0.51		0.91	
Cut	1	2.66		1.29		0.02		0.01	

Table S2.30-Summary of effect significance using nested model comparison of survivorship of *Q. oleoides* seedlings from seeds collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and planted directly into the dry garden 2011. Seedlings were administered one of four watering (Ambient, dry season water-DS Water, wet season water- WS Water, or watered both seasons -BS water). Degrees of freedom (DF) shown is the difference between nested models for each factor. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***P<0.001

	WS 2012			DS 2013			WS 2013			DS 2014		
	Est	SE	Z									
Intercept (Ambient)	1.75	0.56	3.11	1.61	0.63	2.55	1.20	0.59	2.03	1.03	0.59	1.74
DS Water	-0.80	0.49	-1.62	-0.74	0.48	-1.55	-0.54	0.51	-1.07	-0.61	0.53	-1.15
WS Water	-1.40	0.49	-2.85	-1.35	0.48	-2.82	-1.37	0.50	-2.74	-1.36	0.53	-2.57
Both Water	-0.76	0.49	-1.57	-0.72	0.48	-1.52	-0.41	0.50	-0.82	-0.37	0.53	-0.71
HN	1.12	0.44	2.54	1.05	0.43	2.41	1.01	0.42	2.44	0.95	0.41	2.33
CRH	1.47	0.42	3.50	1.38	0.42	3.32	1.01	0.39	2.62	1.01	0.38	2.65
CRL	0.56	0.38	1.47	0.50	0.38	1.31	0.52	0.37	1.43	0.57	0.36	1.58
Seed Mass	0.01	0.05	0.22	0.06	0.19	0.30	0.10	0.18	0.56	0.15	0.17	0.85
Cut	1.09	0.75	1.45	0.68	0.63	1.07	-0.07	0.46	-0.15	0.05	0.46	0.10

Table S2.31- GLMM summary of *Q. oleoides* seedling survivorship from the 2011 direct planting cohort. Seeds were from natural populations through Central America (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and planted directly into dry garden site in Honduras. Seedlings were administered one of four watering (Ambient, dry season water- DS Water, wet season water- WS Water, or watered both seasons -BS water).

WS 2012									
Effect	DF	Height X ²		Diameter X ²		Leaves X ²		Biomass X ²	
Treat	2	35.76	***	52.94	***	35.90	***	39.44	***
Pop	3	4.42		6.95	+	3.86		4.14	
Seed Mass	1	7.01	**	1.37		0.29		1.72	

DS 2013									
Effect	DF	Height X ²		Diameter X ²		Leaves X ²		Longest Leaf X ²	
Treat	2	8.40	*	8.03	*	8.35	*	8.52	*
Pop	3	4.58		5.85		4.00		4.52	
Seed Mass	1	0.24		0.54		0.23		0.23	

WS 2013									
Effect	DF	Height X ²		Diameter X ²		Leaves X ²		Longest Leaf X ²	
Treat	2	12.49	**	10.61	**	11.95	**	13.57	**
Pop	3	2.74		1.32		1.02		2.01	
Seed Mass	1	0.15		0.00		0.03		0.00	

DS 2014									
Effect	DF	Height X ²		Diameter X ²		Leaves X ²		Longest Leaf X ²	
Treat	2	9.38	**	4.74	+	9.25	*	10.28	**
Pop	3	6.96	+	6.66	+	4.87		6.80	+
Seed Mass	1	0.03		0.17		0.48		0.27	

Table S2.32- Summary of nested model comparisons to test effect significance of linear mixed effects models for growth traits (stem height, basal diameter, leaf number, and aboveground biomass) of 2011 direct planting cohort of seedlings at the DG (Honduras). Seedlings were administered one of four watering treatments: Ambient, dry season water- DS Water, wet season water- WS Water, or watered both seasons -BS water. Degrees of freedom (DF) shown is the difference between nested models for each factor. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***P<0.001

	WS 2012											
	Height			Diameter			Leaf Number⁺			Biomass⁺		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (IG-Amb)	43.13	8.98	4.80	0.63	0.11	5.66	3.26	0.95	3.43	3.26	0.95	3.43
WG-Amb	-32.58	4.68	-6.96	-0.66	0.06	-11.01	-3.88	0.54	-7.22	-3.88	0.54	-7.22
IG-DS Water	16.31	3.17	5.15	0.18	0.04	4.48	1.11	0.36	3.08	1.11	0.36	3.08
HN	-23.20	21.42	-1.08	-0.55	0.30	-1.83	0.72	2.52	0.29	0.72	2.52	0.29
CRH	9.89	6.48	1.53	0.12	0.08	1.43	1.06	0.70	1.51	1.06	0.70	1.51
CRL	4.87	5.93	0.82	0.10	0.08	1.28	1.29	0.65	1.97	1.29	0.65	1.97
Seed Mass	-8.72	3.25	-2.68	-0.05	0.04	-1.17	-0.18	0.33	-0.54	-0.18	0.33	-0.54
	DS 2013											
	Height			Diameter			Leaf Number⁺			Biomass⁺		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (IG-Amb)	-25.86	10.42	-2.48	0.27	0.20	1.30	3.26	0.95	3.43	3.26	0.95	3.43
WG-Amb	5.57	8.82	0.63	-0.42	0.17	-2.52	-3.88	0.54	-7.22	-3.88	0.54	-7.22
IG-DS Water	9.98	23.51	0.42	0.05	0.14	0.39	1.11	0.36	3.08	1.11	0.36	3.08
HN	13.52	6.48	2.09	0.18	0.40	0.46	0.72	2.52	0.29	0.72	2.52	0.29
CRH	11.95	6.05	1.98	0.19	0.11	1.71	1.06	0.70	1.51	1.06	0.70	1.51
CRL	1.51	3.09	0.49	0.25	0.10	2.41	1.29	0.65	1.97	1.29	0.65	1.97
Seed Mass	-8.72	3.25	-2.68	0.04	0.05	0.73	-0.18	0.33	-0.54	-0.18	0.33	-0.54

	WS 2013											
	Height			Diameter			Leaf Number ⁺			Biomass ⁺		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (IG-Amb)	47.03	15.69	3.00	0.87	0.31	2.76	7.25	2.10	3.45	7.25	2.10	3.45
WG-Amb	-24.06	8.42	-2.86	-0.48	0.18	-2.59	-2.93	0.92	-3.20	-2.93	0.92	-3.20
IG-DS Water	9.61	5.82	1.65	0.15	0.13	1.17	0.43	0.58	0.73	0.43	0.58	0.73
HN	34.47	35.79	0.96	0.43	0.73	0.59	2.19	4.38	0.50	2.19	4.38	0.50
CRH	15.21	9.87	1.54	0.17	0.20	0.86	1.09	1.21	0.90	1.09	1.21	0.90
CRL	12.86	9.24	1.39	0.21	0.19	1.10	1.07	1.13	0.94	1.07	1.13	0.94
Seed Mass	-1.84	4.73	-0.39	-0.01	0.10	-0.06	0.10	0.58	0.17	0.10	0.58	0.17
	DS 2014											
	Height			Diameter			Leaf Number ⁺			Biomass ⁺		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (IG-Amb)	23.48	15.39	1.53	0.48	0.32	1.51	2.27	1.65	1.38	2.27	1.65	1.38
WG-Amb	-8.55	8.33	-1.03	-0.09	0.17	-0.54	1.29	0.89	1.45	1.29	0.89	1.45
IG-DS Water	15.62	5.34	2.92	0.19	0.11	1.79	2.25	0.57	3.93	2.25	0.57	3.93
HN	62.54	40.56	1.54	0.96	0.82	1.17	4.28	4.33	0.99	4.28	4.33	0.99
CRH	22.98	11.24	2.04	0.30	0.23	1.30	1.79	1.20	1.49	1.79	1.20	1.49
CRL	26.01	10.53	2.47	0.50	0.21	2.34	2.40	1.13	2.13	2.40	1.13	2.13
Seed Mass	0.96	5.37	0.18	0.04	0.11	0.41	0.40	0.57	0.69	0.40	0.57	0.69

Table S2.33- Summary of linear mixed models of growth traits (stem height, basal diameter, leaf number, and aboveground biomass) of seedlings from the 2011 direct planting cohort of *Q. oleoides* seeds collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and planted directly into dry garden in Honduras in one of four watering treatments: Ambient, dry season water-DS Water, wet season water- WS Water, or watered both seasons -BS water.

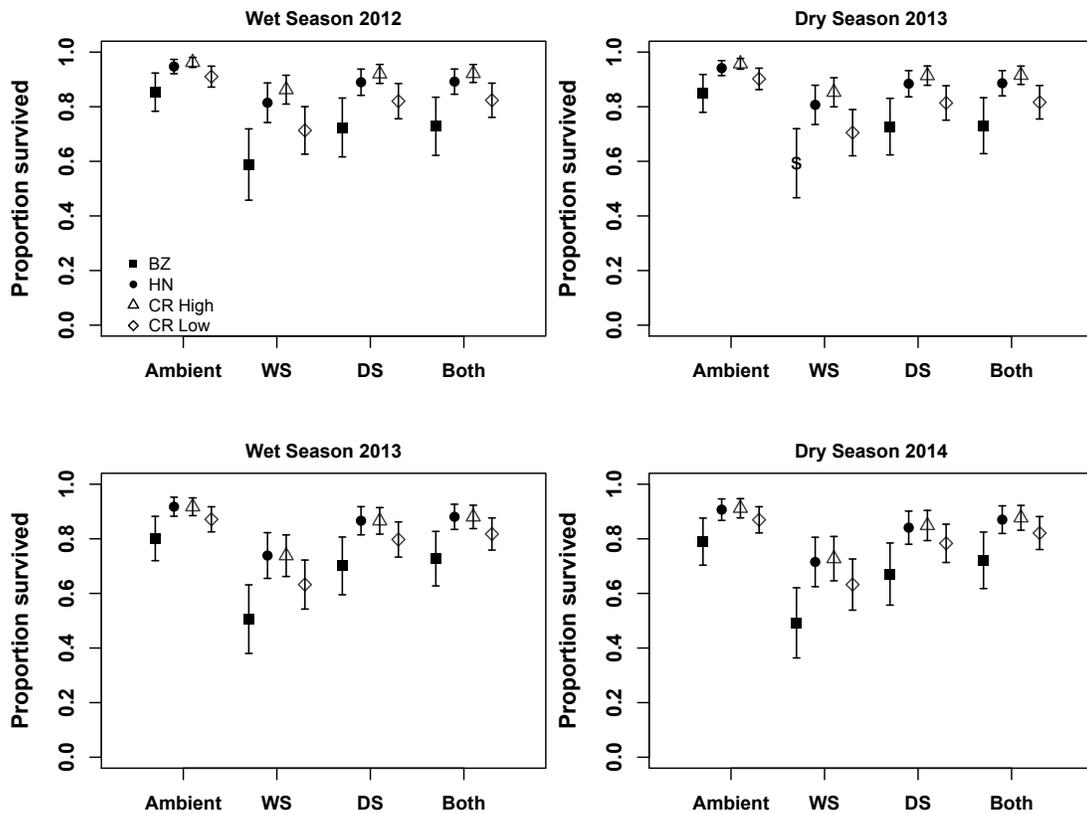


Figure S2.15- GLMM predicted survivorship of seedlings from direct planting in 2011. Seedlings were administered one of four watering treatments: Ambient, wet season water (WS Water), dry season water (DS water) and watered both seasons (Both). Seeds were collected from four populations in Central America (Belize, BZ; Honduras, HZ, and Costa Rica high- and low- elevations, CR High and CR Low respectively).

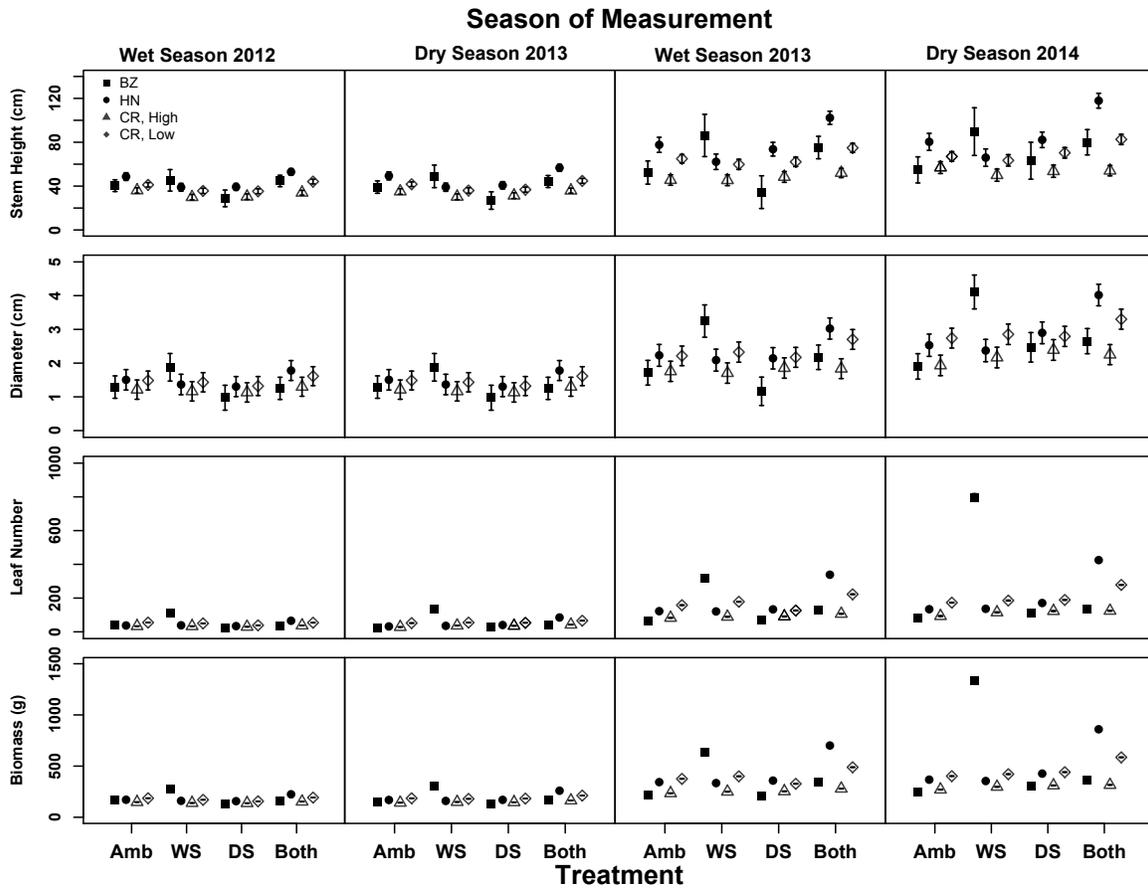


Figure S2.16- LMM predicted growth trait means of seedlings from 2011 direct planting cohort at the Dry Garden (Honduras). Seedlings were administered one of four watering treatments: Ambient, wet season water (WS Water), dry season water (DS water) and watered both seasons (Both). Seeds were collected from four populations in Central America (Belize, BZ; Honduras, HZ, and Costa Rica high- and low-elevations, CR High and CR Low respectively).

Effect	DF	DS 2011		DS 2012	
		X ²		X ²	
Treatment (T)	2	4.64	+	4.81	+
Population (P)	3	6.03		4.55	
Seed mass	1	0.72		0.02	
Size at planting	1	24.61	***	11.37	**
T x P	6	4.60		4.07	

Table S2.34- Summary of effect significance using nested model comparison of survivorship of *Q. oleoides* seedlings the 2010 transplant cohort at the end of the DS 2011 and 2012. Seeds were collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and into shadehouses and then transplanted into the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DS Water); all seedlings at wet garden experienced ambient rainfall (WG-Amb). Degrees of freedom (DF) shown is the difference between nested models for each factor. +0.10≥P>0.05; * P≤0.05, ** P≤0.01; ***P<0.001

	DS 2011		Z	DS 2012		
	Est	SE		Est	SE	Z
Intercept (IG- Amb)	3.11	1.05	2.96	0.78	0.79	0.99
IG- DS Water	0.54	0.65	0.84	-0.75	0.70	-1.07
WG- Ambient	-0.97	0.53	-1.85	0.11	0.60	0.18
HN	-0.65	0.45	-1.45	0.10	0.57	0.17
CRH	-0.34	0.45	-0.75	0.87	0.58	1.50
CRL	0.00	0.40	0.00	0.47	0.44	1.07
Seed Mass	-0.03	0.23	-0.13	-0.14	0.17	-0.86
Size at Planting	0.07	0.02	3.31	0.08	0.02	4.82
IG-DSW x HN	--	--	--	-0.91	0.84	-1.08
IG DSW x CRH	--	--	--	-0.54	0.79	-0.68
IG DSW x CRL	--	--	--	-0.38	0.60	-0.64
WG Amb x HN	--	--	--	-0.41	0.75	-0.55
WG Amb x CRH	--	--	--	-1.10	0.73	-1.50
WG Amb x CRL	--	--	--	-0.11	0.56	-0.20

Table S2.35- Summary generalized linear mixed model of survivorship of *Q. oleoides* seedlings the 2010 transplant cohort at the end of the DS 2011 and 2012. Seeds were collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and into shadehouses and then transplanted into the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DSW); all seedlings at wet garden experienced ambient rainfall (WG-Amb).

Effect	DS 2011								
	DF	Stem Height		Diameter		Leaves		Biomass	
		X ²		X ²		X ²		X ²	
Treatment (T)	2	20.42	***	9.91	**	3.15		2.64	
Population (P)	3	4.59		5.83		24.22	***	13.89	**
Seed M	1	0.00		0.00		1.22		0.00	
Size	1	45.38	***	45.81	***	159.20	***	166.54	***
T x P	6	2.37		4.90		4.40		3.68	

Effect	DS 2012								
	DF	Stem Height		Diameter		Leaves		Biomass	
		X ²		X ²		X ²		X ²	
Treatment (T)	2	20.06	***	20.41	***	9.51	**	20.94	***
Population (P)	3	6.06		12.41	**	5.11		5.59	
Seed M	1	0.01		0.00		1.69		0.26	
Size	1	31.00	***	21.94	***	55.16	***	32.21	***
T x P	6	2.09		0.88		5.08		1.67	

Table S2.36 Summary of effect significance using nested model comparison of growth traits of *Q. oleoides* seedlings the 2010 transplant cohort at the end of the DS 2011 and 2012. Seeds were collected from four populations of *Q. oleoides* (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and into shadehouses and then transplanted into the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DSW); all seedlings at wet garden experienced ambient rainfall (WG-Amb). Degrees of freedom are for the nested models compared and are the same for all traits. Covariates of seed mass and size of plant at transplanting (size) were included in analyses. Degrees of freedom (DF) shown is the difference between nested models for each factor. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***P<0.001

DS 2011

	Height ⁺			Diameter			Leaves ⁺			Biomass		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
IG-Amb	6.30	0.67	9.46	0.58	0.24	2.38	2.39	0.58	4.11	60.01	12.60	4.76
IG-DSW	-0.34	0.60	-0.57	0.20	0.21	0.94	-0.24	0.62	-0.38	-3.99	13.17	-0.30
WG-Amb	-3.78	0.89	-4.26	-0.47	0.32	-1.48	-0.64	0.85	-0.75	-8.87	18.46	-0.48
HN Pop	0.37	0.52	0.71	0.42	0.18	2.27	0.50	0.38	1.31	20.31	9.22	2.20
CRH Pop	0.27	0.46	0.60	0.23	0.16	1.45	0.84	0.34	2.51	17.45	8.09	2.16
CRL Pop	0.43	0.39	1.10	0.40	0.14	2.94	0.80	0.29	2.78	16.01	6.89	2.32
Seed Size	0.01	0.16	0.03	0.00	0.06	-0.03	-0.13	0.12	-1.10	-0.09	2.82	-0.03
Leaves at Planting	0.10	0.02	6.86	0.04	0.01	6.89	0.15	0.01	13.42	3.71	0.27	13.76
IG-DSW x HN Pop	0.78	0.69	1.12	-0.36	0.25	-1.49	0.12	0.51	0.24	-2.01	12.29	-0.16
IG-DSW x CRH Pop	0.03	0.62	0.05	-0.08	0.22	-0.35	0.56	0.45	1.23	10.31	10.94	0.94
IG-DSW x CRL Pop	-0.05	0.50	-0.10	-0.27	0.18	-1.53	0.37	0.36	1.02	4.53	8.78	0.52
WG-Amb x HN Pop	0.31	1.46	0.21	-0.46	0.52	-0.89	-0.72	1.08	-0.67	-22.56	25.89	-0.87
WG-Amb x CRH Pop	-0.05	1.02	-0.05	-0.19	0.36	-0.52	-0.80	0.75	-1.06	-19.58	18.09	-1.08
WG-Amb x CRL Pop	-0.35	0.82	-0.43	-0.41	0.29	-1.43	-0.61	0.61	-1.01	-15.50	14.55	-1.07

	DS 2012											
	Height ⁺			Diameter			Leaves ⁺			Biomass		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
IG-Amb	9.34	0.91	10.29	1.12	0.12	8.98	7.07	1.59	4.45	158.92	86.06	1.85
IG-DSW	-1.81	0.74	-2.45	-0.12	0.11	-1.06	-2.48	1.45	-1.71	-72.02	85.94	-0.84
WG-Amb	-4.81	1.12	-4.28	-0.62	0.16	-3.78	-5.36	2.12	-2.53	-169.18	123.02	-1.38
HN Pop	0.51	0.69	0.73	0.11	0.10	1.08	0.28	1.18	0.24	48.41	65.50	0.74
CRH Pop	-0.32	0.61	-0.52	0.10	0.09	1.16	-0.10	1.04	-0.10	13.42	57.50	0.23
CRL Pop	0.02	0.52	0.05	0.17	0.08	2.19	0.45	0.88	0.51	35.97	48.96	0.74
Seed Size	0.02	0.21	0.11	0.00	0.03	0.07	-0.47	0.36	-1.30	-7.13	20.03	-0.36
Leaves at Planting	0.11	0.02	5.64	0.01	0.00	4.73	0.26	0.03	7.59	12.77	1.92	6.67
IG-DSW x HN Pop	0.83	0.92	0.90	0.02	0.14	0.13	0.27	1.57	0.17	50.46	87.33	0.58
IG-DSW x CRH Pop	0.37	0.82	0.45	0.08	0.12	0.64	2.53	1.40	1.81	97.86	77.74	1.26
IG-DSW x CRL Pop	0.72	0.66	1.09	0.05	0.10	0.55	1.68	1.12	1.50	65.39	62.36	1.05
WG-Amb x HN Pop	-0.84	1.94	-0.43	-0.08	0.29	-0.28	-0.73	3.31	-0.22	-80.21	183.86	-0.44
WG-Amb x CRH Pop	0.17	1.36	0.12	-0.04	0.20	-0.21	0.91	2.32	0.39	-8.56	128.48	-0.07
WG-Amb x CRL Pop	-0.10	1.09	-0.09	-0.06	0.16	-0.39	-0.37	1.86	-0.20	-51.39	103.36	-0.50

Table S2.37- Summary of linear mixed models of growth traits (stem height, basal diameter, leaf number, and aboveground biomass) of seedlings from *Q. oleoides* seeds collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and germinated in shadehouses and later transplanted into the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DSW); all seedlings at wet garden experienced ambient rainfall (WG-Amb). Covariates of seed mass and size of plant at transplanting (size) were included in analyses.

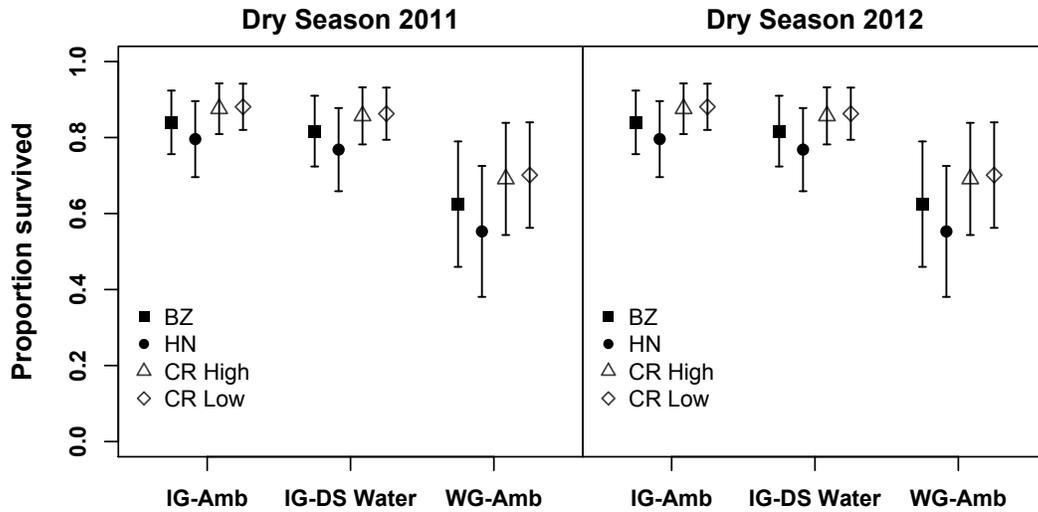


Figure S2.17- GLMM predicted survival of seedlings from 2010 transplant cohort at the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DS Water); all seedlings at wet garden experienced ambient rainfall (WG-Amb).

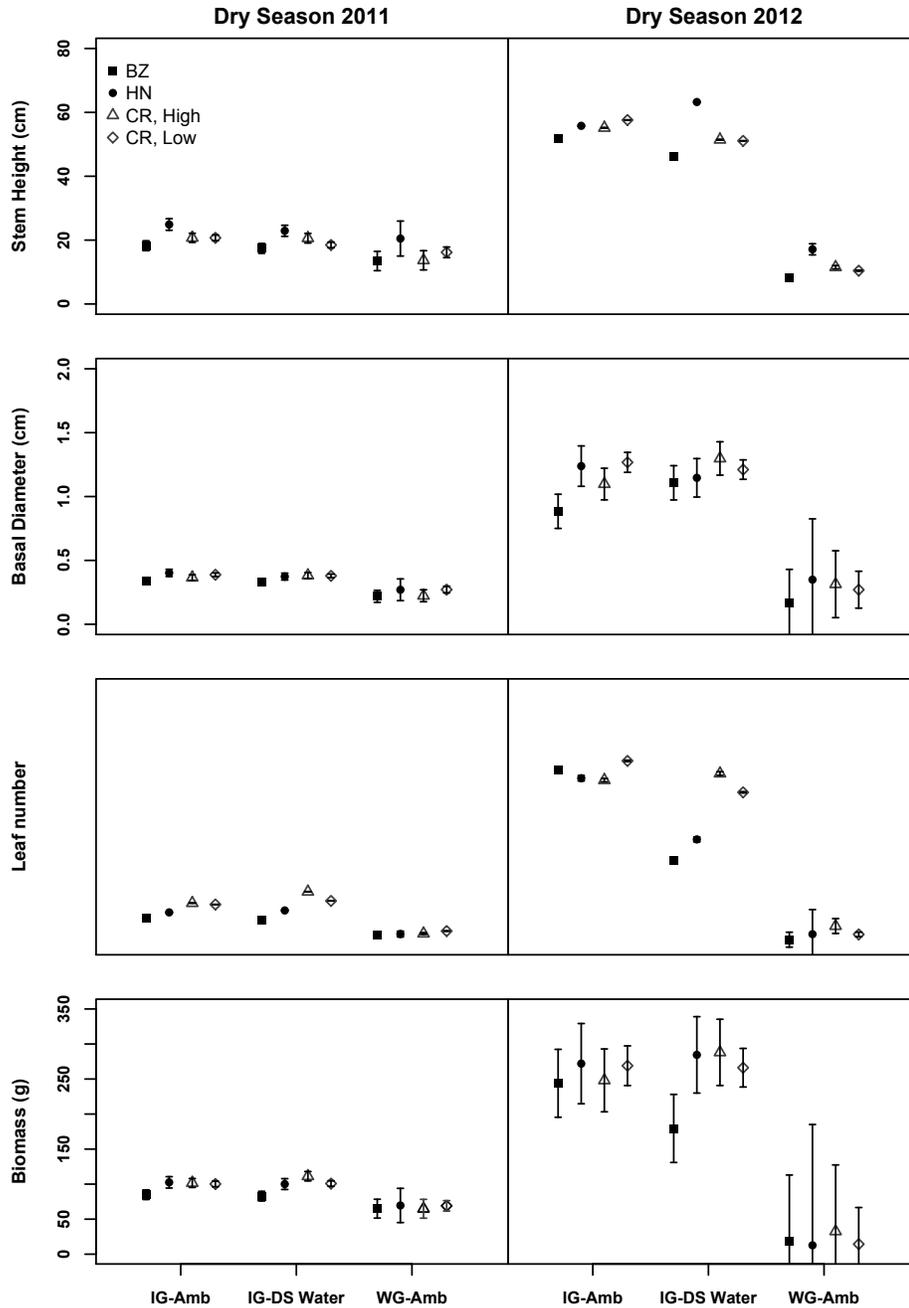


Figure S2.18- LMM predicted growth trait means of seedlings from 2010 transplant cohort the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DS Water); all seedlings at wet garden experienced ambient rainfall (WG-Amb).

Effect	DF	WS 2012		DS 2013		WS 2013		DS 2014	
		X ²		X ²		X ²		X ²	
Treatment (T)	2	13.72	**	14.86	**	14.92	**	18.28	***
Population	3	3.10		1.38		2.50		2.34	
Seed Mass	1	6.10	*	3.18	+	1.36		3.59	+
Size	1	5.34	*	4.08	*	4.84	*	1.89	
T x P	6	6.53		6.02		7.28		9.00	

Table S2.38- Summary of effect significance using nested model comparison of survivorship of *Q. oleoides* seedlings the 2011 transplant cohort at the end of the DS 2011 and 2012. Seeds were collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and into shadehouses and then transplanted into the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DSW); all seedlings at wet garden experienced ambient rainfall (WG-Amb). Covariates of seed mass and size of plant at transplanting (size) were included in analyses. Degrees of freedom (DF) shown is the difference between nested models for each factor. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***P<0.001

	WS 2012			DS 2013			WS 2013			DS 2014		
	Est	SE	Z									
Intercept IG-Amb)	-1.07	1.01	-1.06	-0.51	1.01	-0.51	-0.52	1.00	-0.52	-0.67	0.96	-0.70
WG-Amb	-1.20	0.88	-1.36	-1.22	0.89	-1.38	-1.47	0.91	-1.61	-1.49	0.84	-1.78
IG-DSW	2.24	1.31	1.70	2.15	1.34	1.61	2.36	1.31	1.80	1.70	1.04	1.64
HN	0.27	0.84	0.32	0.21	0.83	0.26	0.14	0.80	0.17	0.29	0.80	0.37
CRH	-0.23	1.21	-0.19	-0.34	1.19	-0.28	-1.05	1.16	-0.91	-0.80	1.15	-0.70
CRL	0.84	0.79	1.05	0.53	0.77	0.69	0.54	0.76	0.72	0.08	0.73	0.10
Seed Mass	0.81	0.34	2.41	0.58	0.33	1.78	0.38	0.33	1.16	0.59	0.31	1.88
Size	0.10	0.04	2.29	0.09	0.04	2.02	0.09	0.04	2.17	0.06	0.04	1.38
IG-DSW x HN	0.04	1.72	0.02	0.12	1.76	0.07	0.18	1.71	0.11	-0.01	1.37	-0.01
IG-DSW x CRH	-2.83	1.91	-1.48	-2.66	1.90	-1.40	-1.95	1.87	-1.05	-2.23	1.75	-1.28
IG-DSW x CRL	-1.40	1.43	-0.98	-1.10	1.45	-0.76	-1.16	1.41	-0.82	-0.05	1.17	-0.04
WG-Amb x HN	0.65	1.12	0.58	-0.11	1.11	-0.10	0.43	1.11	0.39	0.19	1.09	0.18
WG-Amb x CRH	0.54	1.56	0.35	0.60	1.54	0.39	1.74	1.54	1.13	1.88	1.51	1.25
WG-Amb x CRL	-0.69	0.98	-0.71	-0.81	0.97	-0.84	-0.57	0.97	-0.58	-0.20	0.94	-0.21

Table S2.39- Summary generalized linear mixed model of survivorship of *Q. oleoides* seedlings the 2011 transplant cohort. *Quercus oleoides* seeds were collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and into shadehouses and then transplanted into the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DSW); all seedlings at wet garden experienced ambient rainfall (WG-Amb).

WS 2012							
		Height		Diameter		Leaves	Biomass
Effect	DF	X ²		X ²		X ²	X ²
Treatment (T)	2	28.45	***	18.09	***	7.51	* 13.85 **
Population (P)	3	15.39	**	1.53		8.49	* 8.19 *
Seed Mass	1	0.05		0.11		1.80	1.32
Size	1	6.84	**	0.00		8.49	** 5.77 *
T x P	6	1.91		5.63		4.35	4.20
DS 2013							
		Height		Diameter		Leaves	Biomass
Effect	DF	X ²		X ²		X ²	X ²
Treatment (T)	2	29.55	***	11.75	**	14.59	** 34.67 ***
Population (P)	3	10.95	*	5.92		4.88	10.27 *
Seed Mass	1	0.18		0.34		0.44	0.40
Size	1	11.37	**	0.70		13.89	*** 8.39 **
T x P	6	1.41		11.34	+	6.47	1.52
WS 2013							
		Height		Diameter		Leaves	Biomass
Effect	DF	X ²		X ²		X ²	X ²
Treatment (T)	2	30.34	***	1.96		19.08	*** 23.20 *
Population (P)	3	5.22		1.22		0.91	1.88
Seed Mass	1	1.24		3.52	+	4.66	* 4.24 *
Size	1	3.27	+	0.43		0.18	0.98
T x P	6	2.91		10.23		4.45	3.38
DS 2014							
		Height		Diameter		Leaves	Biomass
Effect	DF	X ²		X ²		X ²	X ²
Treatment (T)	2	26.91	***	4.96	+	14.01	** 18.42 ***
Population (P)	3	19.91	***	3.28		10.66	* 15.02 **
Seed Mass	1	0.12		1.27		0.09	0.00
Size	1	4.41	*	0.06		6.01	* 7.08 **
T x P	6	1.40		17.69	**	2.28	1.70

Table S2.40- Summary of effect significance using nested model comparison of growth traits of *Q. oleoides* seedlings the 2011 transplant cohort. Seeds were collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and into shadehouses and then transplanted into the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DS Water); all seedlings at wet garden experienced ambient rainfall (WG-Amb). Covariates of seed mass and size of plant at transplanting (size) were included in analyses. Degrees of freedom (DF) shown is the difference between nested models for each factor. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***P<0.001

WS 2012

	Height			Diameter			Leaf Number			Biomass		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept IG-Amb)	63.96	15.37	4.16	1.69	0.27	6.37	59.64	33.66	1.77	299.23	72.20	4.14
WG-Amb	-57.31	15.27	-3.75	0.33	0.26	1.29	-67.44	33.29	-2.03	-222.13	72.00	-3.09
IG-DSW	-13.35	12.54	-1.06	-0.02	0.20	-0.11	-25.30	27.95	-0.91	-102.43	60.56	-1.69
HN Pop	26.43	11.67	2.26	0.06	0.21	0.27	33.88	25.84	1.31	45.03	54.86	0.82
CRH Pop	0.34	19.14	0.02	0.38	0.35	1.07	17.66	42.23	0.42	-9.54	89.74	-0.11
CRL Pop	7.70	10.85	0.71	-0.01	0.20	-0.07	26.01	23.88	1.09	1.58	50.74	0.03
Seed Mass	-1.13	5.00	-0.23	0.03	0.09	0.34	-5.17	11.11	-0.47	-12.44	23.63	-0.53
Size at Planting	1.75	0.61	2.89	0.00	0.01	-0.02	3.41	1.30	2.63	6.25	2.78	2.25
WG-Amb x HN Pop	-14.74	18.74	-0.79	0.34	0.34	1.00	19.60	39.29	0.50	56.47	84.37	0.67
IG-DSW x HN Pop	0.83	14.95	0.06	-0.13	0.27	-0.46	20.61	31.73	0.65	77.39	67.92	1.14
WG-Amb x CRH Pop	-16.12	25.92	-0.62	-0.42	0.47	-0.89	41.24	54.03	0.76	73.24	116.16	0.63
IG-DSW x CRH Pop	-19.13	27.79	-0.69	0.10	0.51	0.20	-21.64	57.86	-0.37	-21.55	124.22	-0.17
WG-Amb x CRL Pop	-8.36	16.58	-0.50	0.21	0.30	0.69	1.22	34.94	0.04	27.94	74.97	0.37
IG-DSW x CRL Pop	5.98	12.97	0.46	-0.10	0.24	-0.40	11.22	27.44	0.41	71.81	58.72	1.22

DS 2013

	Stem Height			Diameter			Leaf Number ⁺			Biomass ⁺		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept IG-Amb)	59.96	19.65	3.05	3.50	1.07	3.27	8.08	2.20	3.68	311.97	59.19	5.27
WG-Amb	-73.36	17.29	-4.24	2.15	1.05	2.06	-7.47	1.92	-3.90	-252.91	53.79	-4.70
IG-DSW	-30.71	13.75	-2.23	-1.56	0.83	-1.88	-3.90	1.55	-2.52	-50.75	42.73	-1.19
HN Pop	13.22	14.48	0.91	-1.02	0.86	-1.19	0.06	1.56	0.04	75.22	44.76	1.68
CRH Pop	-35.37	23.74	-1.49	-2.20	1.41	-1.56	-4.79	2.55	-1.88	-76.46	73.42	-1.04
CRL Pop	1.62	13.52	0.12	-0.79	0.80	-0.99	-0.49	1.45	-0.34	10.02	41.82	0.24
Seed Mass	2.55	6.16	0.41	-0.21	0.36	-0.58	-0.32	0.67	-0.49	-12.10	19.02	-0.64
Size at Planting	2.74	0.77	3.55	0.04	0.04	0.85	0.31	0.08	3.77	7.06	2.37	2.98
WG-Amb x HN Pop	4.88	23.06	0.21	-0.22	1.38	-0.16	4.18	2.46	1.70	-22.56	71.71	-0.32
IG-DSW x HN Pop	7.81	18.42	0.42	2.00	1.10	1.81	0.01	1.97	0.00	-32.00	57.24	-0.56
WG-Amb x CRH Pop	17.81	31.76	0.56	-2.55	1.89	-1.35	6.67	3.40	1.96	30.51	98.80	0.31
IG-DSW x CRH Pop	12.44	34.38	0.36	3.66	2.05	1.79	2.88	3.66	0.79	27.45	106.95	0.26
WG-Amb x CRL Pop	7.10	20.39	0.35	-0.31	1.22	-0.25	2.86	2.18	1.31	36.17	63.41	0.57
IG-DSW x CRL Pop	16.49	16.18	1.02	1.67	0.96	1.73	1.50	1.72	0.87	12.53	50.26	0.25

WS 2013

	Stem Height			Diameter			Leaf Number ⁺			Biomass ⁺		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept IG-Amb)	120.22	27.79	4.33	4.22	1.03	4.09	17.22	3.06	5.63	25.56	3.39	7.53
WG-Amb	100.82	25.79	-3.91	0.46	1.01	0.46	-11.71	2.73	-4.28	-13.92	3.07	-4.54
IG-DSW	-2.01	20.48	-0.10	0.66	0.80	0.82	-2.36	2.20	-1.07	-2.18	2.46	-0.89
HN Pop	39.66	21.45	1.85	0.82	0.83	0.99	0.37	2.20	0.17	1.50	2.50	0.60
CRH Pop	-13.22	35.17	-0.38	-0.07	1.36	-0.05	-2.25	3.61	-0.62	-2.86	4.10	-0.70
CRL Pop	6.23	20.04	0.31	0.60	0.78	0.78	0.49	2.05	0.24	0.65	2.33	0.28
Seed Mass	-10.16	9.11	-1.12	-0.67	0.35	-1.89	-2.05	0.94	-2.19	-2.22	1.06	-2.08
Size at Planting	2.10	1.13	1.87	-0.03	0.04	-0.66	0.05	0.12	0.43	0.13	0.13	1.01
WG-Amb x HN Pop	-20.04	34.36	-0.58	-0.59	1.34	-0.44	3.39	3.53	0.96	2.41	4.00	0.60
IG-DSW x HN Pop	-32.20	27.44	-1.17	-1.59	1.07	-1.49	-1.27	2.82	-0.45	-2.03	3.19	-0.64
WG-Amb x CRH Pop	5.22	47.31	0.11	-1.53	1.83	-0.83	6.41	4.88	1.31	5.75	5.53	1.04
IG-DSW x CRH Pop	2.60	51.22	0.05	2.73	1.98	1.37	-2.19	5.25	-0.42	-1.77	5.96	-0.30
WG-Amb x CRL Pop	16.94	30.39	0.56	-1.49	1.18	-1.26	4.23	3.12	1.35	4.09	3.54	1.16
IG-DSW x CRL Pop	-9.65	24.09	-0.40	-1.41	0.94	-1.51	-1.37	2.46	-0.56	-1.59	2.79	-0.57

	DS 2014											
	Stem Height			Diameter			Leaf Number ⁺			Biomass ⁺		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept IG-Amb)	118.58	25.80	4.60	4.24	0.93	4.53	14.12	2.48	5.68	22.38	2.86	7.82
WG-Amb	-100.79	23.02	-4.38	-1.86	0.91	-2.04	-9.54	2.52	-3.78	-12.10	2.80	-4.33
IG-DSW	-30.14	18.42	-1.64	0.01	0.72	0.01	-3.44	2.19	-1.57	-3.79	2.38	-1.59
HN Pop	44.21	18.82	2.35	0.94	0.75	1.25	2.08	1.64	1.27	3.19	1.93	1.65
CRH Pop	-34.27	30.87	-1.11	-0.41	1.24	-0.33	-4.19	2.70	-1.56	-4.89	3.17	-1.54
CRL Pop	17.42	17.55	0.99	0.44	0.71	0.63	-0.01	1.52	-0.01	0.54	1.79	0.30
Seed Mass	2.84	8.02	0.35	-0.36	0.32	-1.13	-0.21	0.71	-0.30	-0.04	0.83	-0.05
Size at Planting	2.14	1.00	2.14	-0.01	0.04	-0.24	0.22	0.09	2.51	0.28	0.10	2.72
WG-Amb x HN Pop	-12.20	30.15	-0.41	2.12	1.21	1.75	1.58	2.66	0.59	1.45	3.13	0.46
IG-DSW x HN Pop	-1.12	24.06	-0.05	-1.15	0.97	-1.19	-0.86	2.10	-0.41	-1.00	2.47	-0.41
WG-Amb x CRH Pop	4.24	41.65	0.10	1.16	1.66	0.70	3.12	3.70	0.84	3.11	4.34	0.72
IG-DSW x CRH Pop	41.85	44.92	0.93	4.38	1.80	2.43	2.94	3.90	0.75	3.31	4.59	0.72
WG-Amb x CRL Pop	-4.64	26.66	-0.17	0.80	1.07	0.75	0.83	2.36	0.35	0.71	2.77	0.26
IG-DSW x CRL Pop	-3.92	21.04	-0.19	-0.53	0.85	-0.62	0.55	1.81	0.31	0.30	2.13	0.14

Table S2.41- Summary of linear mixed models of growth traits (stem height, basal diameter, leaf number, and aboveground biomass) of seedlings from the 2011 transplant cohort of *Q. oleoides* seeds collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and planted directly into the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DSW); all seedlings at wet garden experienced ambient rainfall (WG-Amb). Covariates of seed mass and size of plant at transplanting (size) were included in analyses.

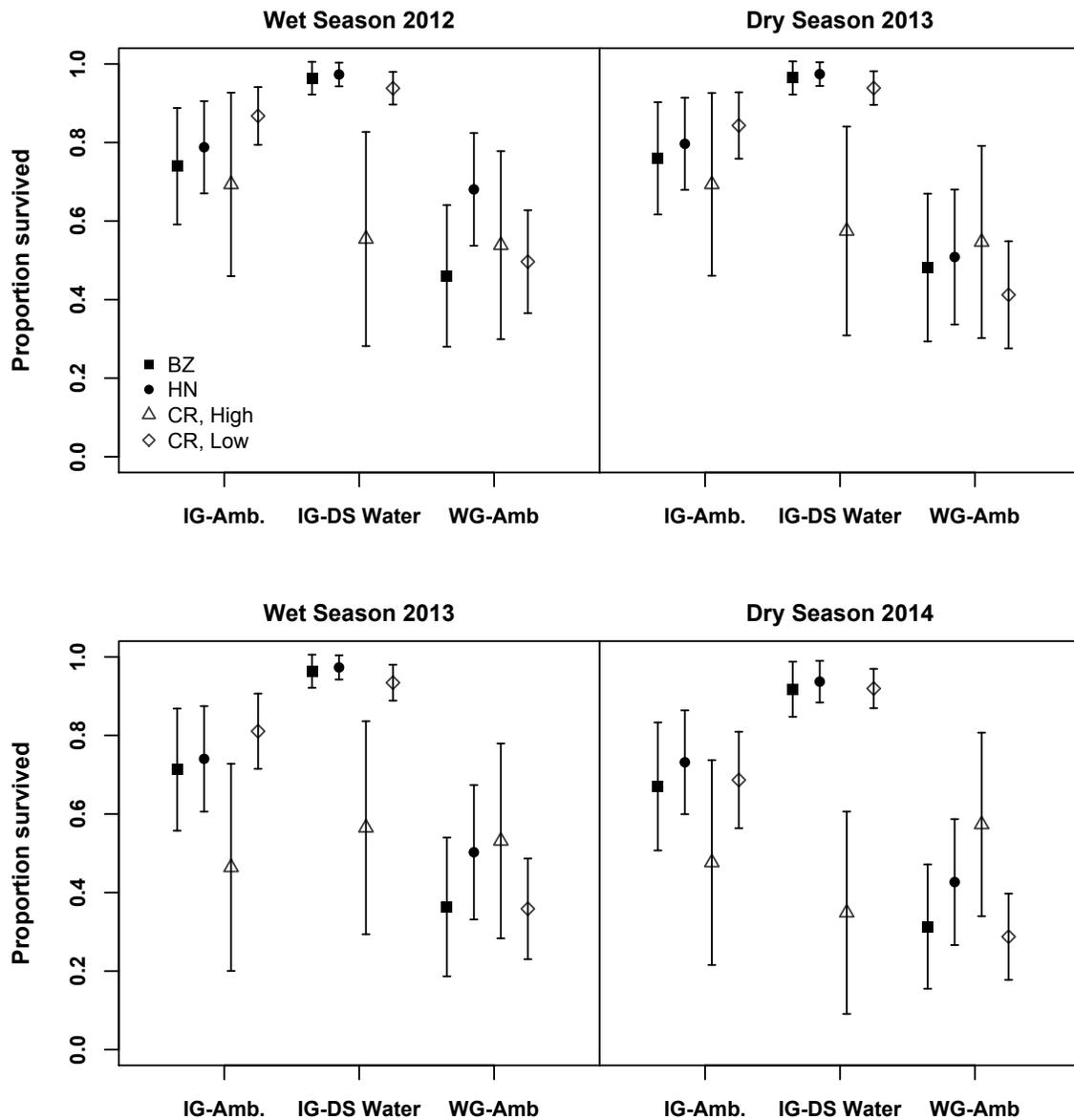


Figure S2.19- GLMM predicted survival of seedlings from 2011 transplant cohort at the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DS Water); all seedlings at wet garden experienced ambient rainfall (WG-Amb).

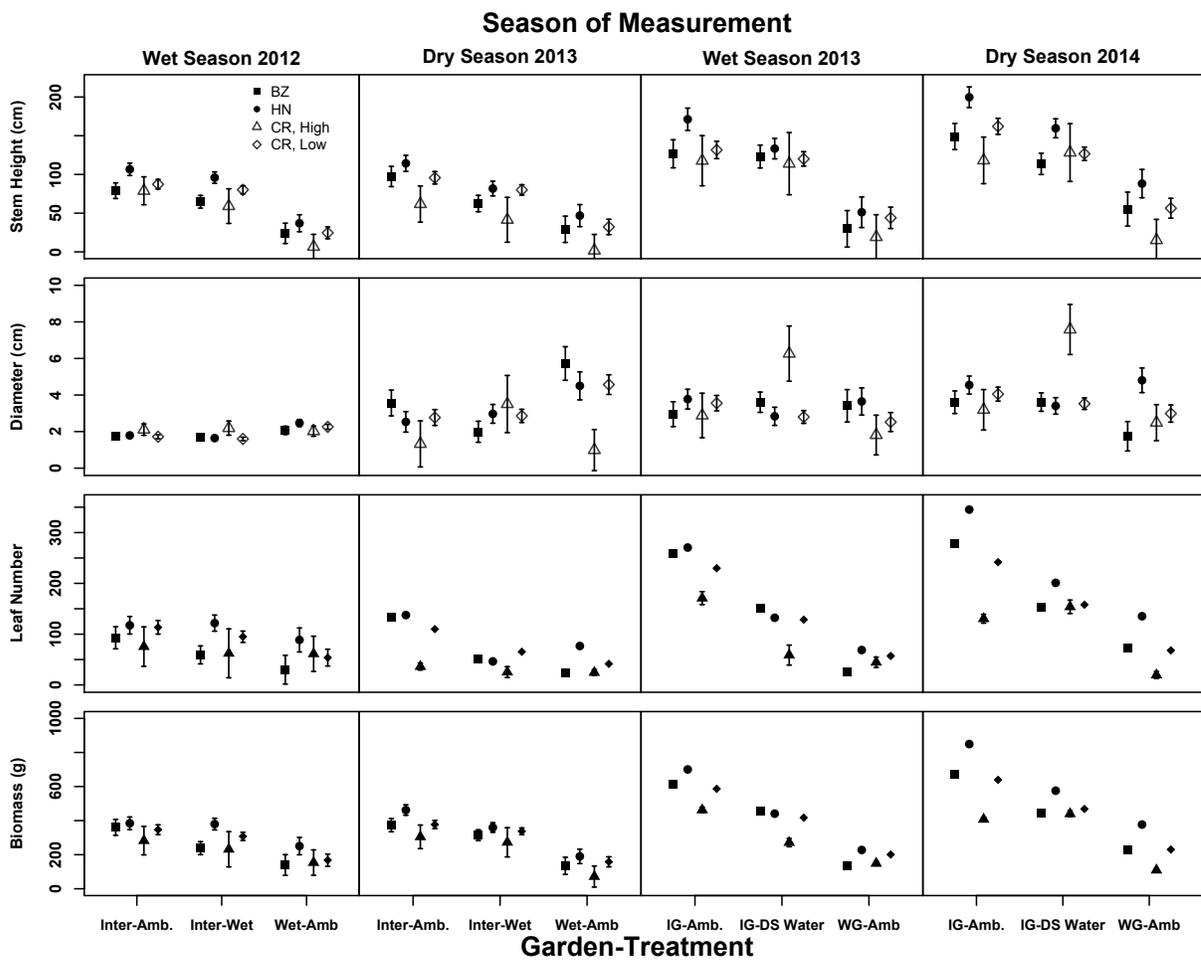


Figure S2.20- LMM predicted growth trait means of seedlings from 2011 transplant cohort the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DS Water); all seedlings at wet garden experienced ambient rainfall (WG-Amb).

Effects	DF	DS 2011	DS 2012
		Dev	Dev
Treatment	3	6.67 *	4.47
Population	3	4.58	0.69
Seed Mass	1	0.79	1.31
Germination Date	1	1.31	0.01

Table S2.42- Summary of linear mixed nested model comparison to test effects of factors on survivorship of *Q. oleoides* seedlings the 2010 direct planting cohort at the end of the DS 2011 and 2012. Seeds were collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and planted into the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DS Water); all seedlings at wet garden experienced ambient rainfall (WG-Amb). Degrees of freedom (DF) shown is the difference between nested models for each factor. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***P<0.001

Effect	DS 2011			DS 2012		
	Est	SE	Z	Est	SE	Z
Intercept (IG-Amb)	11.66	7.37	1.58	1.59	6.53	0.24
IG-DSW	0.07	0.67	0.11	-0.15	0.42	-0.36
WG-Amb	-1.14	0.58	-1.94	-0.76	0.40	-1.89
HN	-1.61	1.05	-1.53	-0.76	0.93	-0.82
CRH	0.20	0.84	0.24	-0.24	0.64	-0.38
CRL	0.32	0.74	0.44	-0.28	0.57	-0.49
Seed Mass	0.26	0.54	0.49	0.43	0.38	1.14
Germination Date	0.00	0.00	-1.34	0.00	0.00	-0.09

Table S2.43- Summary generalized linear mixed model of survivorship of *Q. oleoides* seedlings the 2010 direct planting cohort at the end of the DS 2011 and 2012. Seeds were collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and into the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DSW); all seedlings at wet garden experienced ambient rainfall (WG-Amb).

DS 2011						
		Height		Diameter	Leaves	Biomass
Effect	DF	X ²		X ²	X ²	X ²
Treatment	2	4.42		7.87 *	7.60 *	5.42 +
Population	3	4.53		6.86 +	4.50	5.58
Seed Mass	1	3.22 +		6.11 *	5.42 *	5.16 *

DS 2012						
		Height		Diameter	Leaves	Biomass
Effect	DF	X ²		X ²	X ²	X ²
Treatment	2	5.61 +		4.23	3.54	5.02 +
Population	3	3.93		3.04	6.37 +	5.03
Seed Mass	1	1.31		0.84	0.08	0.30

Table S2.44- Summary of effect significance using nested model comparison of growth traits of *Q. oleoides* seedlings the 2010 direct planting cohort at the end of the DS 2011 and 2012. Seeds were collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and planted into the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DS Water); all seedlings at wet garden experienced ambient rainfall (WG-Amb). Degrees of freedom (DF) shown is the difference between nested models for each factor. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***P<0.001

	Height			Diameter			Leaf Number⁺			Biomass		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
DS 2011												
Intercept (IG-Amb)	8.90	2.81	3.17	1.31	0.29	4.58	1.91	0.37	5.17	19.97	6.75	2.96
WG-Amb	-4.86	2.37	-2.05	-0.50	0.22	-2.32	-0.81	0.29	-2.84	-12.88	6.14	-2.10
IG-DSW	0.68	2.00	0.34	0.22	0.18	1.22	0.06	0.26	0.22	2.11	5.40	0.39
HN	-0.54	3.08	-0.18	-0.06	0.33	-0.19	-0.45	0.43	-1.05	-3.57	7.34	-0.49
CRH	3.24	1.76	1.84	0.43	0.19	2.30	0.32	0.24	1.30	8.17	4.19	1.95
CRL	1.55	1.55	1.00	0.33	0.16	2.04	0.21	0.21	1.00	5.84	3.70	1.58
Seed Mass	1.99	1.10	1.81	0.29	0.12	2.51	0.36	0.15	2.35	6.02	2.62	2.29
DS 2012												
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (IG-Amb)	29.99	13.30	2.25	4.45	1.96	2.27	4.45	1.96	2.27	8.51	2.03	4.20
WG-Amb	-40.98	13.66	-3.00	-4.42	2.12	-2.09	-4.42	2.12	-2.09	-6.13	2.05	-2.99
IG-DSW	9.59	10.60	0.90	1.70	1.69	1.00	1.70	1.69	1.00	0.75	1.60	0.47
HN	7.83	7.70	1.02	0.19	1.47	0.13	0.19	1.47	0.13	0.40	1.36	0.29
CRH	9.08	4.68	1.94	1.29	0.89	1.45	1.29	0.89	1.45	1.50	0.83	1.82
CRL	5.29	4.20	1.26	1.26	0.80	1.58	1.26	0.80	1.58	1.57	0.74	2.12
Seed Mass	3.91	3.37	1.16	0.60	0.64	0.94	0.60	0.64	0.94	0.33	0.59	0.56

Table S2.45- Summary of linear mixed models of growth traits (stem height, basal diameter, leaf number, and aboveground biomass) of seedlings from the 2010 direct planting cohort of *Q. oleoides* seeds collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and planted directly into the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DSW); all seedlings at wet garden experienced ambient rainfall (WG-Amb).

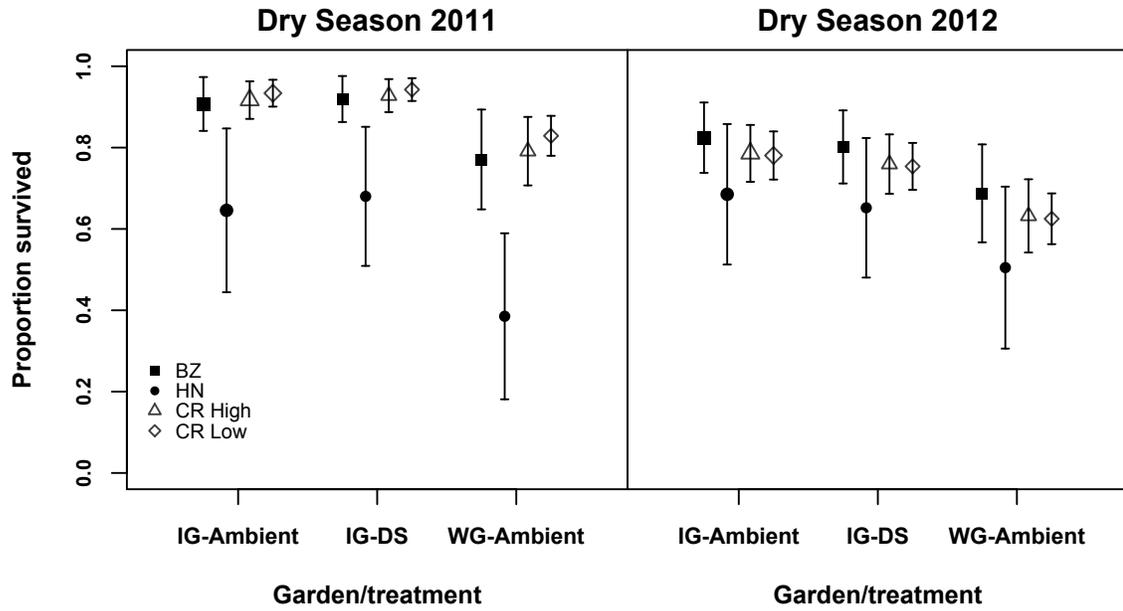


Figure S2.21- GLMM predicted survival of seedlings from 2010 direct planting cohort at the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DS Water); all seedlings at wet garden experienced ambient rainfall (WG-Amb).

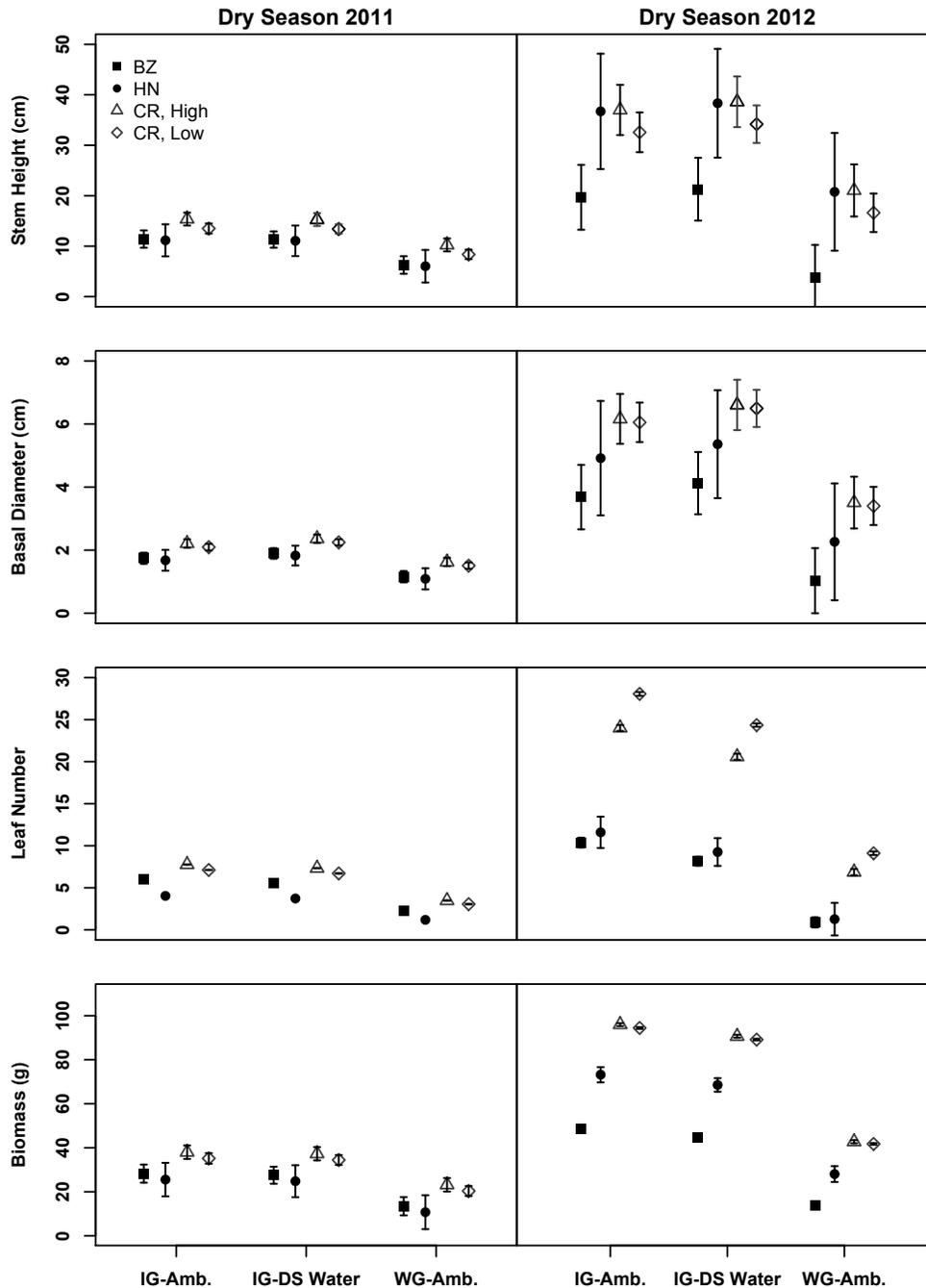


Figure S2.22- LMM predicted growth trait means of seedlings from 2010 direct planting cohort the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DS Water); all seedlings at wet garden experienced ambient rainfall (WG-Amb).

Effect	DF	WS 2012		DS 2013		WS 2013		DS 2014	
		X ²		X ²		X ²		X ²	
Treatment	2	17.10	***	16.84	***	16.00	***	13.85	***
Population	2	3.56		2.93		2.72		5.38	
Seed Mass	1	0.93		0.69		0.93		2.25	

Table S2.46- Summary generalized linear mixed model of survivorship of *Q. oleoides* seedlings the 2011 direct planting cohort. Seeds were collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and into the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DSW); all seedlings at wet garden experienced ambient rainfall (WG-Amb). Degrees of freedom (DF) shown is the difference between nested models for each factor. +0.10≥P>0.05; * P≤0.05, ** P≤0.01; ***P<0.001

	WS 2012			DS 2013			WS 2013			DS 2014		
	Est	SE	Z									
Intercept (IG-Amb)	0.86	1.00	0.86	1.07	0.97	1.11	0.85	0.92	0.93	-0.31	0.81	-0.38
IG-DSW	-0.03	0.58	-0.05	-0.23	0.57	-0.40	0.06	0.52	0.12	0.37	0.44	0.84
WG-Amb	-2.95	0.60	-4.89	-2.94	0.60	-4.90	-2.46	0.55	-4.49	-1.70	0.47	-3.58
HN	-2.26	1.54	-1.47	-2.24	1.51	-1.49	-2.16	1.45	-1.49	-1.34	1.36	-0.98
CRH	-0.11	0.66	-0.17	-0.16	0.65	-0.25	-0.40	0.62	-0.65	-0.56	0.55	-1.01
CRL	0.17	0.65	0.26	-0.01	0.64	-0.02	-0.26	0.61	-0.42	0.09	0.54	0.16
Seed Mass	0.28	0.29	0.98	0.24	0.28	0.84	0.26	0.27	0.97	0.38	0.25	1.50

Table S2.47- Summary of effect significance using nested model comparison of growth traits of *Q. oleoides* seedlings the 2011 direct planting cohort. Seeds were collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and planted into the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DSW); all seedlings at wet garden experienced ambient rainfall (WG-Amb).

WS 2012									
Effect	DF	Height X ²		Diameter X ²		Leaves X ²		Biomass X ²	
					**				
Treatment	2	35.76	***	52.94	*	35.90	***	39.44	***
Population	3	4.42		6.95	+	3.86		4.14	
Seed Mass	2	7.01	**	1.37		0.29		1.72	

DS 2013									
Effect	DF	Height X ²		Diameter X ²		Leaves X ²		Longest Leaf X ²	
Treatment	2	8.40	*	8.03	*	8.35	*	8.52	*
Population	3	4.58		5.85		4.00		4.52	
Seed Mass	2	0.24		0.54		0.23		0.23	

WS 2013									
Effect	DF	Height X ²		Diameter X ²		Leaves X ²		Longest Leaf X ²	
Treatment	2	12.49	**	10.61	**	11.95	**	13.57	**
Population	3	2.74		1.32		1.02		2.01	
Seed Mass	2	0.15		0.00		0.03		0.00	

DS 2014									
Effect	DF	Height X ²		Diameter X ²		Leaves X ²		Longest Leaf X ²	
Treatment	2	9.38	**	4.74	+	9.25	*	10.28	**
Population	3	6.96	+	6.66	+	4.87		6.80	+
Seed Mass	2	0.03		0.17		0.48		0.27	

Table S2.48- Summary of effect significance using nested model comparison of growth traits of *Q. oleoides* seedlings the 2011 direct planting cohort. Seeds were collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and planted into the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DSW); all seedlings at wet garden experienced ambient rainfall (WG-Amb). Degrees of freedom (DF) shown is the difference between nested models for each factor. +0.10≥P>0.05; * P≤0.05, ** P≤0.01; ***P<0.001

WS 2012												
	Height			Diameter			Leaf Number⁺			Biomass⁺		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (IG-Amb)	43.13	8.98	4.80	0.63	0.11	5.66	3.26	0.95	3.43	3.26	0.95	3.43
WG-Amb	-32.58	4.68	-6.96	-0.66	0.06	-11.01	-3.88	0.54	-7.22	-3.88	0.54	-7.22
IG-DSW	16.31	3.17	5.15	0.18	0.04	4.48	1.11	0.36	3.08	1.11	0.36	3.08
HN	-23.20	21.42	-1.08	-0.55	0.30	-1.83	0.72	2.52	0.29	0.72	2.52	0.29
CRH	9.89	6.48	1.53	0.12	0.08	1.43	1.06	0.70	1.51	1.06	0.70	1.51
CRL	4.87	5.93	0.82	0.10	0.08	1.28	1.29	0.65	1.97	1.29	0.65	1.97
Seed Mass	-8.72	3.25	-2.68	-0.05	0.04	-1.17	-0.18	0.33	-0.54	-0.18	0.33	-0.54
DS 2013												
	Height			Diameter			Leaf Number⁺			Biomass⁺		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (IG-Amb)	-25.86	10.42	-2.48	0.27	0.20	1.30	3.26	0.95	3.43	3.26	0.95	3.43
WG-Amb	5.57	8.82	0.63	-0.42	0.17	-2.52	-3.88	0.54	-7.22	-3.88	0.54	-7.22
IG-DSW	9.98	23.51	0.42	0.05	0.14	0.39	1.11	0.36	3.08	1.11	0.36	3.08
HN	13.52	6.48	2.09	0.18	0.40	0.46	0.72	2.52	0.29	0.72	2.52	0.29
CRH	11.95	6.05	1.98	0.19	0.11	1.71	1.06	0.70	1.51	1.06	0.70	1.51
CRL	1.51	3.09	0.49	0.25	0.10	2.41	1.29	0.65	1.97	1.29	0.65	1.97
Seed Mass	-8.72	3.25	-2.68	0.04	0.05	0.73	-0.18	0.33	-0.54	-0.18	0.33	-0.54

WS 2013												
	Height			Diameter			Leaf Number ⁺			Biomass ⁺		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (IG-Amb)	47.03	15.69	3.00	0.87	0.31	2.76	7.25	2.10	3.45	7.25	2.10	3.45
WG-Amb	-24.06	8.42	-2.86	-0.48	0.18	-2.59	-2.93	0.92	-3.20	-2.93	0.92	-3.20
IG-DSW	9.61	5.82	1.65	0.15	0.13	1.17	0.43	0.58	0.73	0.43	0.58	0.73
HN	34.47	35.79	0.96	0.43	0.73	0.59	2.19	4.38	0.50	2.19	4.38	0.50
CRH	15.21	9.87	1.54	0.17	0.20	0.86	1.09	1.21	0.90	1.09	1.21	0.90
CRL	12.86	9.24	1.39	0.21	0.19	1.10	1.07	1.13	0.94	1.07	1.13	0.94
Seed Mass	-1.84	4.73	-0.39	-0.01	0.10	-0.06	0.10	0.58	0.17	0.10	0.58	0.17

DS 2014												
	Height			Diameter			Leaf Number ⁺			Biomass ⁺		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (IG-Amb)	23.48	15.39	1.53	0.48	0.32	1.51	2.27	1.65	1.38	2.27	1.65	1.38
WG-Amb	-8.55	8.33	-1.03	-0.09	0.17	-0.54	1.29	0.89	1.45	1.29	0.89	1.45
IG-DSW	15.62	5.34	2.92	0.19	0.11	1.79	2.25	0.57	3.93	2.25	0.57	3.93
HN	62.54	40.56	1.54	0.96	0.82	1.17	4.28	4.33	0.99	4.28	4.33	0.99
CRH	22.98	11.24	2.04	0.30	0.23	1.30	1.79	1.20	1.49	1.79	1.20	1.49
CRL	26.01	10.53	2.47	0.50	0.21	2.34	2.40	1.13	2.13	2.40	1.13	2.13
Seed Mass	0.96	5.37	0.18	0.04	0.11	0.41	0.40	0.57	0.69	0.40	0.57	0.69

Table S2.49- Summary of linear mixed models of growth traits (stem height, basal diameter, leaf number, and aboveground biomass) of seedlings from the 2011 direct planting cohort of *Q. oleoides* seeds collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) and planted directly into the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DS Water); all seedlings at wet garden experienced ambient rainfall (WG-Amb).

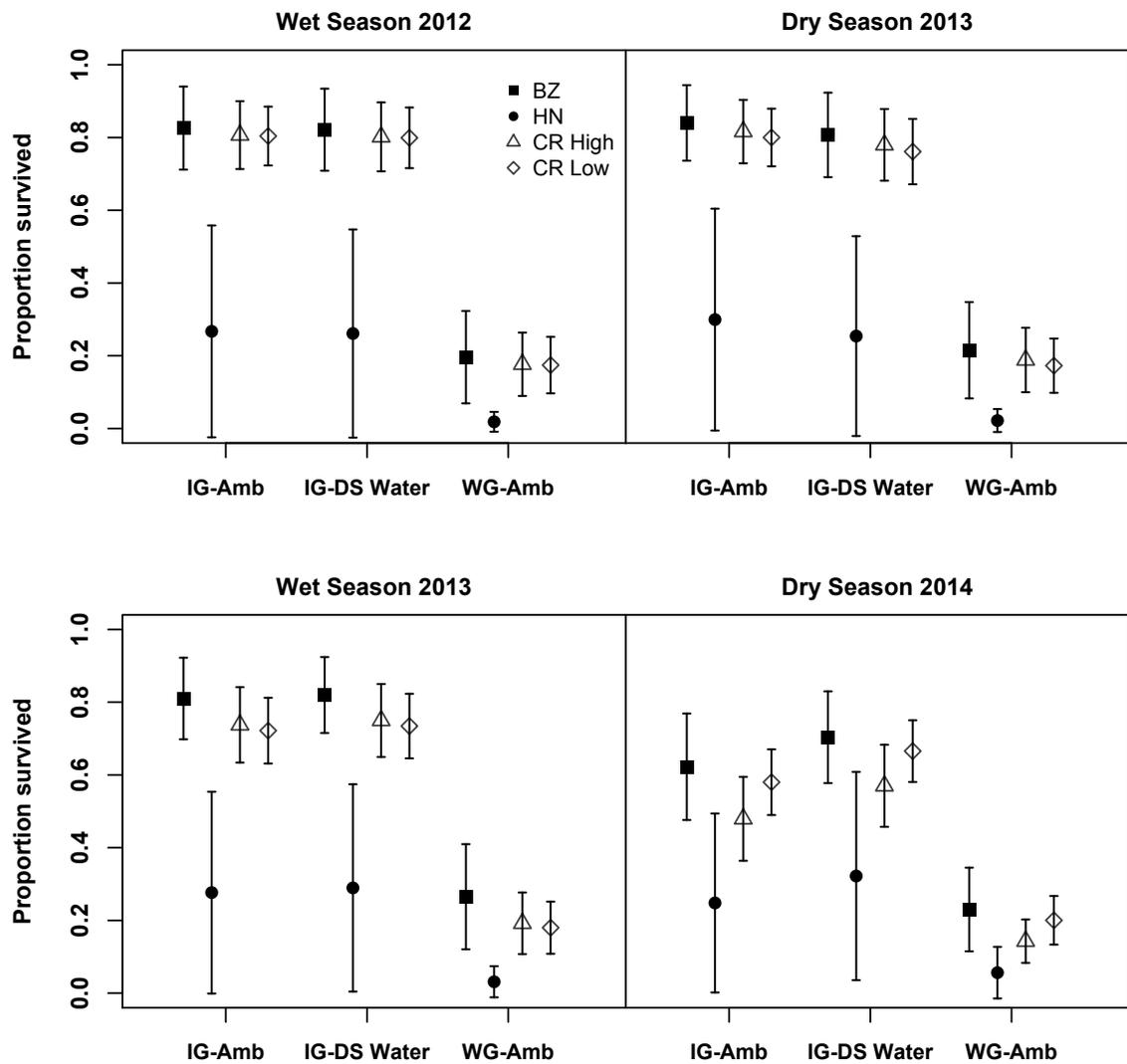


Figure S2.23- GLMM predicted survival of seedlings from 2011 direct planting cohort at the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DS Water); all seedlings at wet garden experienced ambient rainfall (WG-Amb).

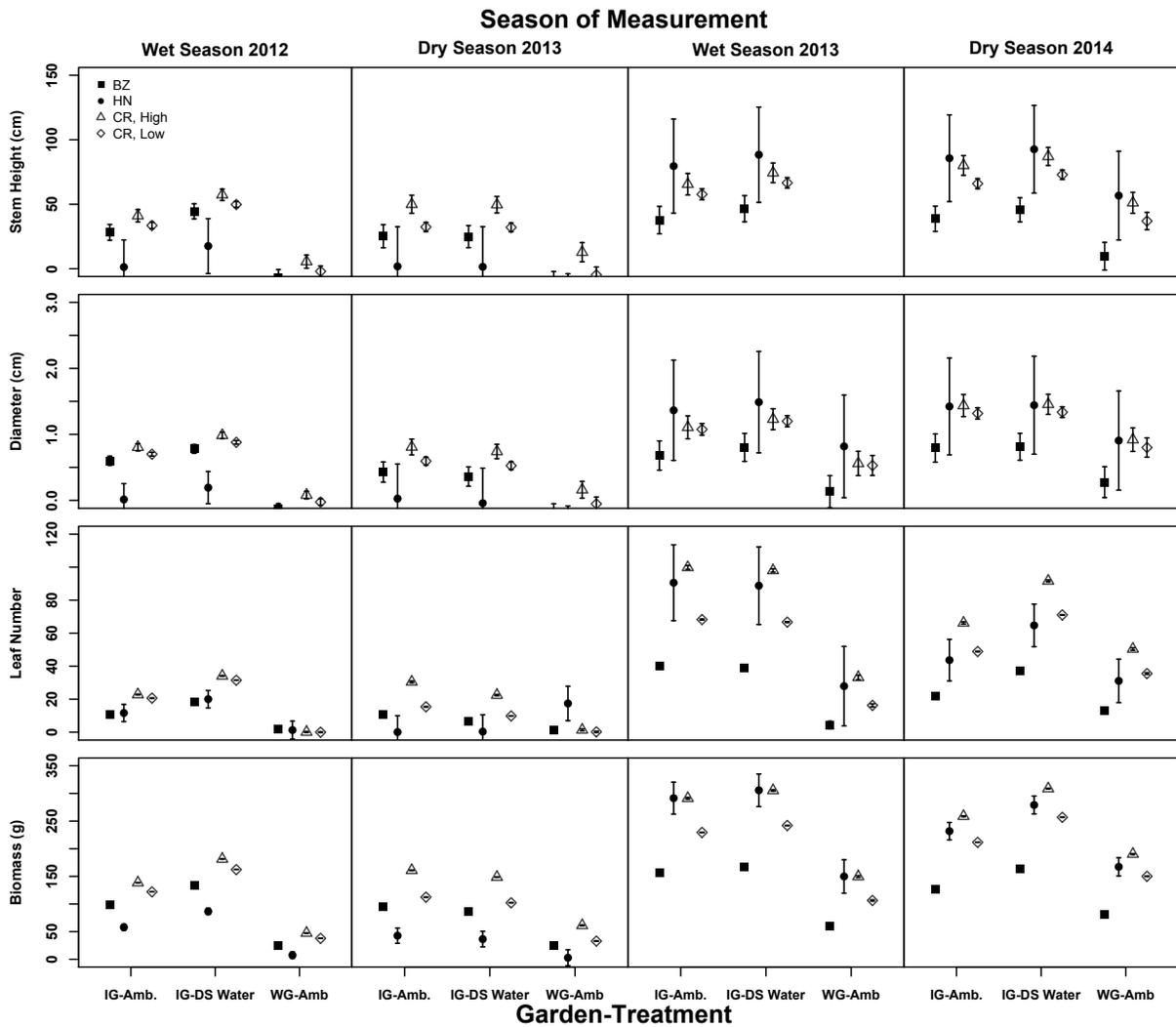


Figure S2.24- LMM predicted growth trait means of seedlings from 2011 direct planting cohort the intermediate and wet gardens in Costa Rica. Seedlings were exposed to two treatments at the intermediate garden: ambient rainfall levels at the intermediate garden (IG-Amb), and added water during the dry season (IG-DS Water); all seedlings at wet garden experienced ambient rainfall (WG-Amb)

Appendix 3- Supplemental Material for Chapter 3

Effect	PD			MD		
	Est	SE	T	Est	SE	T
Intercept (Both)	-1.33	0.12	-11.08	5.53	30.52	0.18
DS Water	-0.03	0.14	-0.20	-7.63	52.09	-0.15
WS Water	-0.03	0.14	-0.19	-7.76	43.17	-0.18
Ambient	-0.10	0.14	-0.73	-7.78	78.57	-0.10
Wet Season	1.14	0.03	34.72	-15.02	15.21	-0.99
HN	0.01	0.09	0.06	-2.04	39.15	-0.05
CRH	-0.01	0.08	-0.17	-3.76	35.97	-0.10
CRL	-0.02	0.07	-0.29	11.08	30.80	0.36
DS Water x WS	--	--	--	15.90	23.39	0.68
Ambient x WS	--	--	--	-3.03	22.99	-0.13
WS Water x WS	--	--	--	15.68	21.61	0.73
DS Water x HN	--	--	--	1.99	65.80	0.03
DS Water x CRH	--	--	--	7.60	86.87	0.09
DS Water x CRL	--	--	--	2.16	57.27	0.04
Ambient x HN	--	--	--	3.75	60.32	0.06
Ambient x CRH	--	--	--	121.66	84.56	1.44
Ambient x CRL	--	--	--	3.74	55.14	0.07
WS Water x HN	--	--	--	-11.13	52.65	-0.21
WS Water x CRH	--	--	--	-4.26	79.45	-0.05
WS Water x CRL	--	--	--	-10.98	43.55	-0.25

Table S3.1- Summary of LMM output for leaf predawn (PD) and midday (MD) water potentials on experimental seedlings at the dry garden (Honduras) site. Treatment abbreviations are ‘Both’- supplemental water during dry and wet season, ‘DS Water’- supplemental water added during the dry season, ‘WS Water’- supplemental water during the wet season, and ‘Ambient’- plants experience ambient rainfall.

Effect	$\delta^{13}\text{C}$			SLA ⁺			SD			SPI		
	Est.	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (DG)	772.83	13.53	57.10	7.54	0.36	21.18	933.26	50.93	18.32	0.50	0.03	17.46
Inter. Garden (IG)	101.11	16.93	5.97	-0.47	0.44	-1.07	-4.48	55.59	-0.08	-0.08	0.03	-2.56
Wet Garden (WG)	73.82	22.29	3.31	-2.00	0.55	-3.63	-139.27	67.02	-2.08	0.00	0.04	-0.01
Wet Season (WS)	-1.60	7.19	-0.22	1.05	0.28	3.72	--	--	--	--	--	--
HN	-3.50	13.63	-0.26	0.32	0.25	1.28	-26.93	46.94	-0.57	-0.01	0.03	-0.48
CRH	31.59	13.57	2.33	0.26	0.23	1.16	-20.72	42.59	-0.49	0.02	0.02	0.87
CRL	34.41	15.09	2.28	0.35	0.20	1.77	-24.45	36.37	-0.67	0.00	0.02	-0.12
Inter x HN	-11.09	16.49	-0.67	0.09	0.34	0.27	--	--	--	--	--	--
Inter x CRH	-22.22	15.35	-1.45	0.02	0.31	0.05	--	--	--	--	--	--
Inter x CRL	-40.30	16.33	-2.47	-0.65	0.29	-2.25	--	--	--	--	--	--
Wet x HN	29.10	25.24	1.15	--	--	--	--	--	--	--	--	--
Wet x CRH	-18.97	21.79	-0.87	--	--	--	--	--	--	--	--	--
Wet x CRL	-0.05	20.72	0.00	--	--	--	--	--	--	--	--	--
IG. X WS	-25.77	8.74	-2.95	-1.44	0.25	-5.76	--	--	--	--	--	--
WG x WS	-34.99	10.96	-3.19	-0.61	0.33	-1.86	--	--	--	--	--	--

Estimates are on square root transformed scale⁺

Table S3.2- Summary of LMM output for specific leaf area (SLA), carbon isotope discrimination ($\delta^{13}\text{C}$), stomatal density (SD), and stomatal pore index (SPI). Traits on experimental seedlings from *Q. oleoides* seeds collected from four populations throughout Central America (Honduras-HN, Belize-BZ, Costa Rica high-elevation- CRH, Costa Rica low-elevation-CRL) and germinated in shadehouses and transplanted (transplant cohort) into common gardens at Honduras (dry garden-DG) and Costa Rica (intermediate garden-IG and wet garden-WG). Measurements were collected during the wet season (WS, 2012) and dry season (DS, 2013).

		$\delta^{13}\text{C}$					SLA ⁺				
Factor Contrasts		DF	Est	SE	T		DF	Est	SE	T	
DG-dry	IG-dry	20.80	-82.70	13.89	-5.95	***	18.10	0.50	0.44	1.07	
DG-dry	WG-dry	23.60	-76.30	17.51	-4.36	***	19.20	2.00	0.55	3.63	**
DG-dry	DG-wet	296.60	1.60	7.19	0.22		648.70	-0.90	0.20	-4.54	***
DG-dry	IG-wet	20.90	-55.30	13.90	-3.98	***	18.00	1.00	0.44	2.25	*
DG-dry	WG-wet	23.10	-39.70	17.42	-2.28	*	18.80	1.70	0.55	3.08	*
IG-dry	WG-dry	20.90	6.40	16.88	0.38		17.10	1.50	0.53	2.86	*
IG-dry	DG-wet	21.80	84.30	14.14	5.96	***	18.70	-1.40	0.45	-3.10	*
IG-dry	IG-wet	338.40	27.40	4.96	5.52	***	641.30	0.50	0.14	3.63	**
IG-dry	WG-wet	20.40	43.00	16.79	2.56	*	17.60	1.20	0.54	2.26	*
WG-dry	DG-wet	24.30	77.90	17.72	4.40	***	19.60	-2.90	0.56	-5.25	**
WG-dry	IG-wet	21.00	21.00	16.90	1.24		17.90	-1.00	0.54	-1.86	+
WG-dry	WG-wet	295.90	36.60	8.26	4.43	***	641.00	-0.30	0.25	-1.23	
DG-wet	IG-wet	21.90	-56.90	14.15	-4.02	***	18.80	1.90	0.45	4.26	***
DG-wet	WG-wet	23.80	-41.30	17.64	-2.34	*	19.50	2.60	0.55	4.71	***
IG-wet	WG-wet	20.50	15.60	16.79	0.93		17.50	0.70	0.54	1.29	

Estimates are on square root transformed scale⁺

Table S3.3- Summary of pairwise contrasts of garden x season interaction from mixed effects models of specific leaf area (SLA) and carbon isotope discrimination ($\delta^{13}\text{C}$). Factors include dry garden (DG), intermediate garden (IG) and wet gardens (WG) in the dry (-dry) and wet (-wet) seasons. Traits was measured on leaves from experimental seedlings from *Q. oleoides* seeds collected from four populations throughout Central America (abbreviated in Table S3.2) and germinated in shadehouses and transplanted (transplant cohort) into common gardens at Honduras and Costa Rica. Measurements were collected during the wet season (2012) and dry season (2013). +0.10 \geq P>0.05; * P \leq 0.05, ** P \leq 0.01; ***<0.001

		SLA ⁺				
Factor Contrasts		DF	Est	SE	T	
BZ-dry	BZ-wet	641.20	-0.40	0.24	-1.56	
BZ-dry	HN-dry	646.20	-0.30	0.25	-1.28	
BZ-dry	HN-wet	643.10	-0.80	0.25	-3.10	**
BZ-dry	CRH- dry	642.20	-0.30	0.23	-1.16	
BZ-dry	CRH-wet	641.50	-0.60	0.23	-2.86	**
BZ-dry	CRL-dry	642.50	-0.30	0.20	-1.77	+
BZ-dry	CRL-wet	641.90	-0.10	0.22	-0.33	
BZ-wet	HN-dry	646.30	0.10	0.25	0.22	
BZ-wet	HN-wet	643.50	-0.40	0.24	-1.71	+
BZ-wet	CRH- dry	642.30	0.10	0.23	0.49	
BZ-wet	CRH-wet	641.60	-0.30	0.21	-1.31	
BZ-wet	CRL-dry	642.80	0.00	0.20	0.11	
BZ-wet	CRL-wet	641.60	0.30	0.21	1.41	
HN-dry	HN-wet	645.10	-0.50	0.26	-1.79	+
HN-dry	CRH- dry	643.20	0.10	0.23	0.23	
HN-dry	CRH-wet	646.50	-0.30	0.24	-1.41	
HN-dry	CRL-dry	644.50	0.00	0.21	-0.16	
HN-dry	CRL-wet	646.30	0.20	0.23	1.06	
HN-wet	CRH- dry	642.30	0.50	0.24	2.17	*
HN-wet	CRH-wet	642.30	0.10	0.23	0.57	
HN-wet	CRL-dry	642.40	0.40	0.21	2.03	*
HN-wet	CRL-wet	641.90	0.70	0.23	3.11	**
CRH-dry	CRH-wet	642.20	-0.40	0.21	-1.82	
CRH-dry	CRL-dry	641.40	-0.10	0.18	-0.48	
CRH-dry	CRL-wet	641.90	0.20	0.21	0.92	
CRH-wet	CRL-dry	642.30	0.30	0.18	1.64	
CRH-wet	CRL-wet	641.30	0.60	0.20	2.91	**
CRL-dry	CRL-wet	642.30	0.30	0.17	1.59	

Table S3.4- Summary of pairwise contrasts of population x season interaction from mixed effects models of specific leaf area (SLA) and carbon isotope discrimination ($\delta^{13}\text{C}$). Factors include dry garden (DG), intermediate garden (IG) and wet gardens (WG) in the dry (-dry) and wet (-wet) seasons. Traits was measured on leaves from experimental seedlings from *Q. oleoides* seeds collected from four populations throughout Central America (abbreviated in Table S3.2) and germinated in shadehouses and transplanted (transplant cohort) into common gardens at Honduras and Costa Rica. Measurements were collected during the wet season (2012) and dry season (2013). +0.10 \geq P>0.05; * P \leq 0.05, ** P \leq 0.01; ***<0.001

Stomatal pore length		
Effect	DF	χ^2
Garden (G)	11,13	9.16 *
Population (P)	10,13	5.48
Seed Mass	18,19	2.58
Size at Planting	18,19	1.87
G x P	13,19	7.12
Block (G)	17,19	66.91 ***
MF (Pop)	17,19	0.97

Table S3.5- Summary of nested LMM comparisons to test for effect significance in models of stomatal pore length of seedlings from *Q. oleoides* seeds collected from four populations throughout Central America (abbreviated in Table S3.2) and germinated in shadehouses and transplanted (transplant cohort) into common gardens at Honduras and Costa Rica. Measurements were collected during dry season (2013). $+0.10 \geq P > 0.05$; * $P < 0.05$, ** $P \leq 0.01$; *** < 0.001

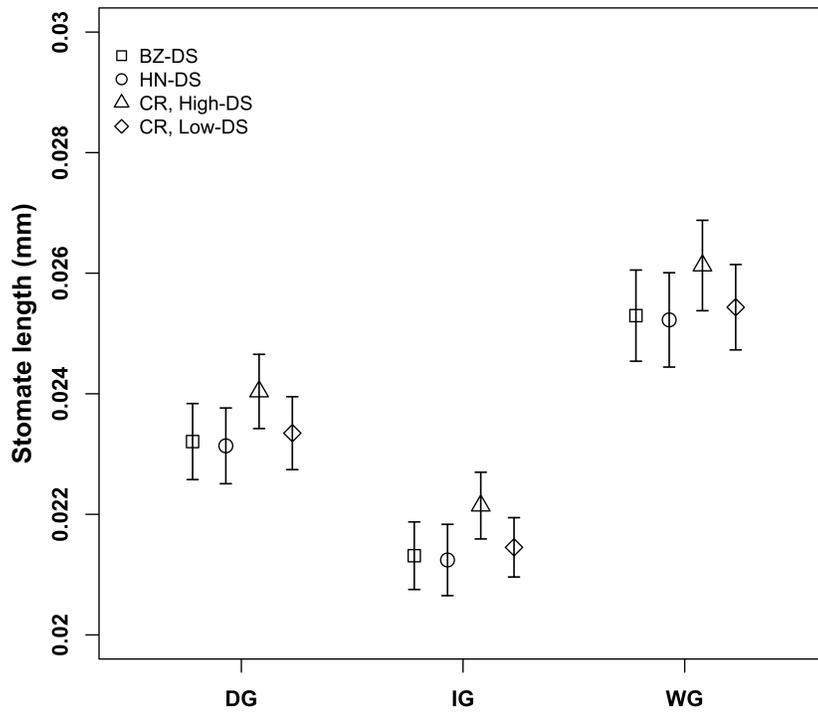


Figure S3.1- LMM predicted mean (SE) of stomate length measured on leaves on experimental seedlings from *Q. oleoides* seeds collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CR-High; Costa Rica low-elevation, CR-Low) throughout Central America and germinated in shadehouses and transplanted (transplant cohort) into common gardens at Honduras and Costa Rica.

Effect	$\delta^{13}\text{C}$		SLA		SD		SPI	
	DF	χ^2	DF	χ^2	DF	χ^2	DF	χ^2
Garden (G)	12,14	2.34	11,13	0.64	10,12	4.34	10,12	3.38
Population (P)	11,14	1.76	12,13	7.19 +	9,12	5.84	9,12	2.77
Season (S)	13,14	0.03	12,13	13.07 ***	--	--	--	--
Seed Mass	25,26	1.69	17,18	0.06	16,17	1.12	16,17	0.25
Nitrogen	25,26	0.81	--	--	--	--	--	--
T x P	--	--	--	--	12,17	11.25 *	12,17	3.60
T x S	17,19	15.96 ***	16,18	11.37 **	--	--	--	--
P x S	16,19	3.13	15,18	5.78	--	--	--	--
T x P x S	--	--	--	--	--	--	--	--
Block (T)	17,19	0.88	16,18	52.08 ***	15,17	0.34	15,17	3.24
MF (P)	17,19	7.39 *	16,18	0.05	15,17	0.00	15,17	0.00
ID (MF (P))	19,20	0.00	18,19	0.00	--	--	--	--
MF (P) x S	19,23	0.88	18,22	0.00	--	--	--	--

Table S3.6- Summary of nested LMM comparisons to test for effect significance in models of carbon isotope discrimination ($\delta^{13}\text{C}$), specific leaf area (SLA), stomatal density (SD), and stomatal pore index (SPI). Traits on experimental seedlings from *Q. oleoides* seeds collected from four populations throughout Central America (abbreviated in Table S3.2) and planted into common gardens (directly planted cohort) at Honduras and Costa Rica. Measurements were collected during the wet season (2012) and dry season (2013). +0.10 \geq P>0.05; * P \leq 0.05, ** P \leq 0.01; ***<0.001

Effect	$\delta^{13}\text{C}$			SLA ⁺			SD			SPI		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (IG)	-27.80	0.38	-72.58	1.79	0.04	40.35	1123.50	158.40	7.09	0.42	0.07	6.10
WG	-0.58	0.25	-2.34	-0.03	0.06	-0.52	-360.30	192.60	-1.87	0.08	0.06	1.36
DG	0.05	0.22	0.20	-0.02	0.05	-0.41	-297.30	213.70	-1.39	0.11	0.06	1.96
Wet Season (WS)	-0.41	0.22	-1.82	-0.03	0.02	-1.18	--	--	--	--	--	--
HN	-0.04	0.53	-0.07	0.11	0.04	2.77	-336.90	224.80	-1.50	-0.03	0.08	-0.35
CRH	-0.58	0.41	-1.41	0.05	0.03	1.73	-225.80	172.90	-1.31	0.05	0.07	0.70
CRL	-0.30	0.37	-0.81	0.03	0.03	1.23	-472.70	167.00	-2.83	0.04	0.06	0.62
WS x WG	1.43	0.35	4.06	0.07	0.03	1.98	--	--	--	--	--	--
WS x DG	0.39	0.28	1.40	0.10	0.03	3.57	--	--	--	--	--	--

Estimates on log transformed scale⁺

Table S3.7- Summary of LMM output for carbon isotope discrimination ($\delta^{13}\text{C}$), specific leaf area (SLA), stomatal density (SD), and stomatal pore index (SPI). Traits on experimental seedlings from *Q. oleoides* seeds collected from four populations throughout Central America (abbreviated in Table S3.2) and planted into common gardens (directly planted cohort) at Honduras (dry garden, DG) and Costa Rica (intermediate garden, IG and wet garden, WG). Measurements were collected during the wet season 2013 (WS) and dry season (DS, 2013).

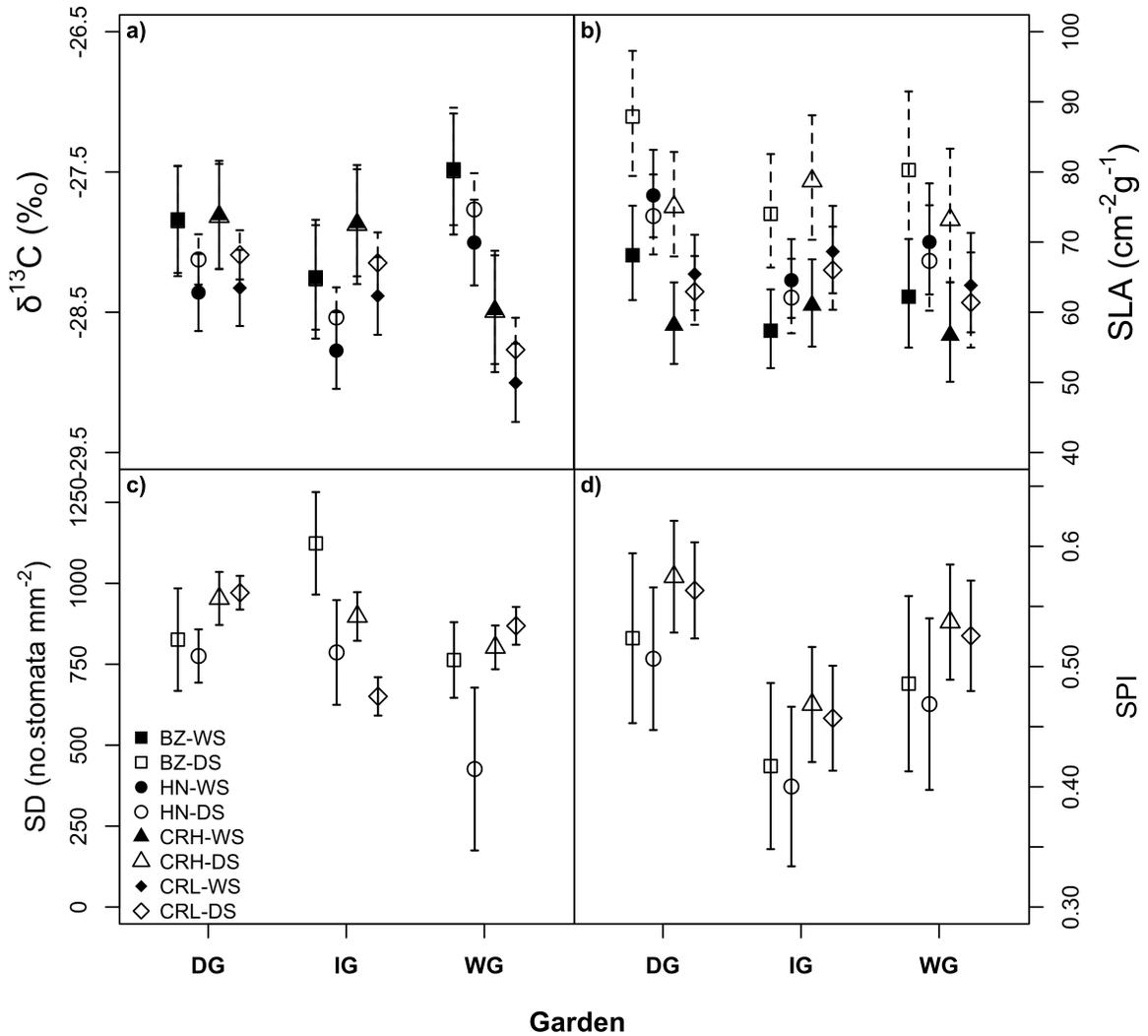


Figure S3.2- LMM predicted mean (SE) for leaf-level traits related to carbon and water-use, a) carbon isotope discrimination ($\delta^{13}\text{C}$), b) specific leaf area (SLA), c) stomatal density (SD), and d) stomatal pore index (SPI). Traits were measured on experimental seedlings from *Q. oleoides* seeds collected from four populations (Belize, BZ; Honduras, HN; Costa Rica high-elevation, CRH; Costa Rica low-elevation, CRL) populations throughout Central America and planted directly into common gardens (directly planted cohort) at Honduras (dry garden –DG) and Costa Rica (intermediate- IG and wet-WG gardens). Measurements were collected during the wet season (WS- closed symbols) and dry season (DS- open symbols).

Effect	A			g_s^+			A/ g_s		
	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (Ambient)	8.11	0.96	8.45	-1.29	0.06	-20.02	11.21	0.30	36.75
Both	3.12	1.23	2.54	0.19	0.07	2.64	-0.36	0.32	-1.12
DS Water	2.94	1.19	2.47	0.20	0.07	2.75	-0.41	0.32	-1.30
WS Water	-0.29	1.21	-0.24	-0.04	0.07	-0.55	0.40	0.32	1.24
HN	-0.19	0.51	-0.37	-0.02	0.03	-0.79	0.11	0.12	0.92
CRH	-2.06	0.50	-4.16	-0.13	0.03	-4.87	0.16	0.12	1.28
CRL	-1.36	0.58	-2.36	-0.09	0.03	-2.94	0.10	0.14	0.71
Wet Season (WS)	7.25	0.69	10.49	0.68	0.04	15.73	-3.43	0.21	-16.57
Seed Mass	--	--	--	--	--	--	--	--	--
Size at Planting	--	--	--	--	--	--	--	--	--
Time	0.00	0.00	-2.61	--	--	--	--	--	--
Herbivory	3.63	0.97	3.74	0.26	0.06	4.47	-1.01	0.25	-3.98
Machine1	--	--	--	0.18	0.03	6.02	-1.46	0.17	-8.67
Machine2	--	--	--	0.06	0.03	2.30	-0.25	0.15	-1.70
Both a WS	-2.43	0.75	-3.23	-0.19	0.04	-4.60	0.10	0.23	0.43
DS Water x WS	-3.24	0.69	-4.67	-0.09	0.04	-2.15	-0.35	0.25	-1.40
WS Water x WS	0.80	0.77	1.04	0.06	0.04	1.38	-0.58	0.25	-2.34
HN x WS	0.25	0.69	0.36	0.36	0.02	0.04	--	--	--
CRH x WS	1.73	0.67	2.58	2.58	0.09	0.04	--	--	--
CRL x WS	1.59	0.78	2.04	2.04	0.09	0.04	--	--	--

Estimates on log transformed scale⁺

Table S3.8- Summary of LMM output for maximum photosynthetic rate (A), stomatal conductance (g_s), intrinsic water-use efficiency (A/ g_s). Traits on experimental seedlings from *Q. oleoides* seeds collected from four populations throughout Central America (abbreviated in Table S3.2) and germinated in shadehouses and transplanted (transplant cohort) into the dry garden site (Honduras) and seedlings were subjected to one of four watering treatments: ambient rainfall (Amb.), supplemental water during the wet season (WS), supplemental water during the dry season (DS), and supplemental water during both season (Both). Measurements were collected during the wet season (2012) and dry season (2013).

		A				g _s				A/g _s				δ ¹³ C				
Factor Contrasts		DF	Est	SE	T	DF	Est	SE	T	DF	Est	SE	T	DF	Est	SE	T	
Amb-DS	Both-DS	25	-3.20	1.22	-2.61 *	26	-0.20	0.08	-2.44 *	24	-0.10	0.12	-1.14	40	0.40	0.19	2.03 *	
Amb-DS	DSW-DS	23	-3.00	1.18	-2.54 *	24	-0.20	0.07	-2.52 *	22	-0.20	0.12	-1.35	36	0.40	0.18	2.49 *	
Amb-DS	WSW-DS	25	0.30	1.20	0.24	26	0.00	0.08	0.53	23	0.10	0.12	0.78	***	43	0.30	0.19	1.45
Amb-DS	Amb-WS	793	-8.00	0.66	-12.11 ***	790	-0.70	0.04	-20.22 ***	361	-0.40	0.05	-8.40 ***	***	681	0.00	0.14	-0.08
Amb-DS	Both-WS	34	-8.50	1.32	-6.44 ***	32	-0.80	0.08	-10.14 ***	29	-0.60	0.13	-4.86 ***	***	42	0.00	0.20	0.11
Amb-DS	DSW-WS	30	-7.50	1.26	-5.94 ***	29	-0.70	0.08	-9.48 ***	26	-0.50	0.13	-4.18 ***	***	37	-0.10	0.18	-0.49
Amb-DS	WSW-WS	32	-8.50	1.28	-6.62 ***	31	-0.70	0.08	-9.29 ***	27	-0.60	0.13	-4.77 ***	***	46	0.00	0.20	-0.22
Both-DS	DSW-DS	23	0.20	1.19	0.15	24	0.00	0.08	-0.02	22	0.00	0.12	-0.19	35	0.10	0.18	0.32	
Both-DS	WSW-DS	25	3.50	1.21	2.87 *	26	0.20	0.08	2.98 *	24	0.20	0.12	1.91	41	-0.10	0.19	-0.58	
Both-DS	Amb-WS	30	-4.80	1.28	-3.78 ***	30	-0.50	0.08	-6.86 ***	27	-0.30	0.13	-2.16 *	43	-0.40	0.20	-2.03 *	
Both-DS	Both-WS	796	-5.30	0.70	-7.60 ***	792	-0.60	0.04	-16.72 ***	382	-0.50	0.05	-9.39 ***	***	687	-0.40	0.14	-2.60 *
Both-DS	DSW-WS	30	-4.30	1.27	-3.41 **	29	-0.60	0.08	-7.08 ***	26	-0.40	0.13	-3.06 *	36	-0.50	0.18	-2.60 *	
Both-DS	WSW-WS	31	-5.30	1.29	-4.11 ***	31	-0.60	0.08	-6.89 ***	28	-0.50	0.13	-3.64 ***	45	-0.40	0.20	-2.16 *	
DSW-DS	WSW-DS	23	3.30	1.18	2.80 *	24	0.20	0.07	3.07 *	22	0.30	0.12	2.14 *	37	-0.20	0.18	-0.94	
DSW-DS	Amb-WS	28	-5.00	1.25	-4.03 ***	28	-0.50	0.08	-7.00 ***	25	-0.30	0.13	-2.01	+	39	-0.50	0.18	-2.46 *
DSW-DS	Both-WS	31	-5.50	1.28	-4.26 ***	30	-0.60	0.08	-7.98 ***	27	-0.50	0.13	-3.64 **	37	-0.40	0.19	-2.27 *	
DSW-DS	DSW-WS	784	-4.50	0.63	-7.13 ***	783	-0.60	0.03	-16.11 ***	305	-0.40	0.05	-7.70 ***	***	669	-0.50	0.11	-4.70 ***
DSW-DS	WSW-WS	29	-5.50	1.25	-4.37 ***	29	-0.60	0.08	-7.03 ***	26	-0.40	0.13	-3.51 **	41	-0.50	0.19	-2.60 *	
WSW-DS	Amb-WS	30	-8.30	1.26	-6.58 ***	30	-0.80	0.08	-9.84 ***	27	-0.50	0.13	-4.05 ***	46	-0.30	0.20	-1.46	
WSW-DS	Both-WS	33	-8.80	1.31	-6.70 ***	32	-0.90	0.08	-10.69 ***	28	-0.70	0.13	-5.62 ***	43	-0.30	0.20	-1.28	
WSW-DS	DSW-WS	30	-7.80	1.26	-6.21 ***	29	-0.80	0.08	-10.04 ***	26	-0.60	0.13	-4.96 ***	39	-0.40	0.18	-1.99 *	
WSW-DS	WSW-WS	794	-8.80	0.68	-12.98 ***	791	-0.80	0.04	-20.93 ***	374	-0.70	0.05	-13.79 ***	***	697	-0.30	0.15	-2.18 *
Amb-WS	Both-WS	29	-0.40	1.27	-0.35	29	-0.10	0.08	-1.14	26	-0.20	0.13	-1.67	45	0.00	0.20	0.17	
Amb-WS	DSW-WS	26	0.50	1.22	0.43	26	0.00	0.08	-0.15	24	-0.10	0.12	-0.90	41	-0.10	0.19	-0.41	
Amb-WS	WSW-WS	29	-0.40	1.25	-0.36	29	0.00	0.08	-0.06	26	-0.20	0.13	-1.51	49	0.00	0.20	-0.15	
Both-WS	DSW-WS	25	1.00	1.22	0.79	26	0.10	0.08	1.03	24	0.10	0.12	0.81	38	-0.10	0.19	-0.59	
Both-WS	WSW-WS	29	0.00	1.27	0.00	29	0.10	0.08	1.08	26	0.00	0.13	0.18	47	-0.10	0.20	-0.32	
DS-WS	WSW-WS	26	-1.00	1.21	-0.80	26	0.00	0.08	0.09	24	-0.10	0.12	-0.63	43	0.00	0.19	0.24	

Table S3.9- Summary of post-hoc contrasts treatment x season interaction from mixed effects models of A, and g_s , A/g_s , and $\delta^{13}C$ measured on experimental seedlings (transplant cohort) at dry garden. Treatments abbreviations in Table S3.8. Measurements were taken in the wet season (WS) and dry season (DS). Degrees of freedom shown are denominator DF, numerator DF=1.+0.10 \geq P>0.05; * P \leq 0.05, ** P \leq 0.01; ***<0.001

Effect	A_{mass}			A_{area}		
	DF	χ^2		DF	χ^2	
Treatment (T)	16,19	3.24		16,19	4.01	
Population (P)	16,19	1.94		16,19	2.28	
Season (S)	18,19	101.85	***	18,19	58.89	***
Seed Size	45,46	0.01		42,43	0.28	
Planting Size	45,46	2.48		42,43	12.95	***
Herbivory	45,46	21.17	***	42,43	14.55	***
Nitrogen	--	--	--	--	--	--
Time	45,46	0.45		42,43	1.85	
Machine	44,46	13.42	**	42,43	7.79	*
T x P	28,37	8.55		25,34	3.93	
T x S	34,37	17.93	***	31,34	19.98	***
P x S	34,37	1.34		31,34	8.19	*
T x P x S	37,46	10.27		34,43	8.53	
Block (T)	41,43	57.92	***	41,43	71.32	***
MF (P)	41,43	0.34		41,43	0.34	
ID (MF(P))	43,46	0.00		43,46	0.13	
MF (P) x S	46,50	0.15		46,50	0.13	

Table S3.10- Summary of nested LMM comparisons to test for effect significance in models of maximum photosynthetic rate on a leaf mass (A_{mass}) and leaf areas basis (A_{area}). Seeds collected from four populations throughout Central America (abbreviated in Table S3.2) and planted into common gardens (directly planted cohort) at Honduras and Costa Rica. Measurements were collected during the wet season (2012) and dry season (2013). +0.10 \geq P>0.05; * P \leq 0.05, ** P \leq 0.01; ***<0.001

Effect	A_{mass}			A_{area}^+		
	Est	SE	T	Est	SE	T
Intercept (Ambient)	23.38	7.12	3.28	0.43	0.12	3.70
Both	19.03	7.63	2.50	0.28	0.11	2.47
DS Water	14.36	7.37	1.95	0.24	0.10	2.29
WS Water	1.50	7.60	0.20	0.07	0.11	0.63
HN Pop	2.98	2.69	1.11	-0.01	0.06	-0.20
CR High Pop	5.19	2.62	1.98	-0.06	0.06	-0.99
CR Low Pop	5.12	3.03	1.69	0.02	0.07	0.26
Wet Season	42.04	4.70	8.94	0.43	0.09	4.57
Size at Planting	--	--	--	0.02	0.01	3.78
Time	--	--	--	0.00	0.00	-1.23
Herbivory	33.29	6.07	5.49	0.40	0.09	4.67
Machine1	-0.57	4.05	-0.14	-0.07	0.06	-1.02
Machine2	10.51	3.59	2.92	0.06	0.06	1.14
Both x WS	-16.51	5.81	-2.84	-0.27	0.10	-2.73
DS Water x WS	-15.16	5.51	-2.75	-0.19	0.09	-2.21
WS Water x WS	1.24	5.96	0.21	-0.04	0.10	-0.38
HN Pop x WS	--	--	--	-0.01	0.09	-0.08
CR-High Pop x WS	--	--	--	0.15	0.08	1.83
CR-Low Pop x WS	--	--	--	0.05	0.10	0.51

Estimates on log transformed scale⁺

Table S3.11-Summary of LMM output for maximum photosynthetic rate on a leaf mass (A_{mass}), and leaf area basis (A_{area}). Traits on experimental seedlings from *Q. oleoides* seeds collected from four populations throughout Central America (abbreviated in Table S3.2) and planted into the dry garden site (directly planted cohort) and seedlings were subjected to one of four watering treatments, abbreviations in Table S3.8. Measurements were collected during the wet season (2012) and dry season (2013).

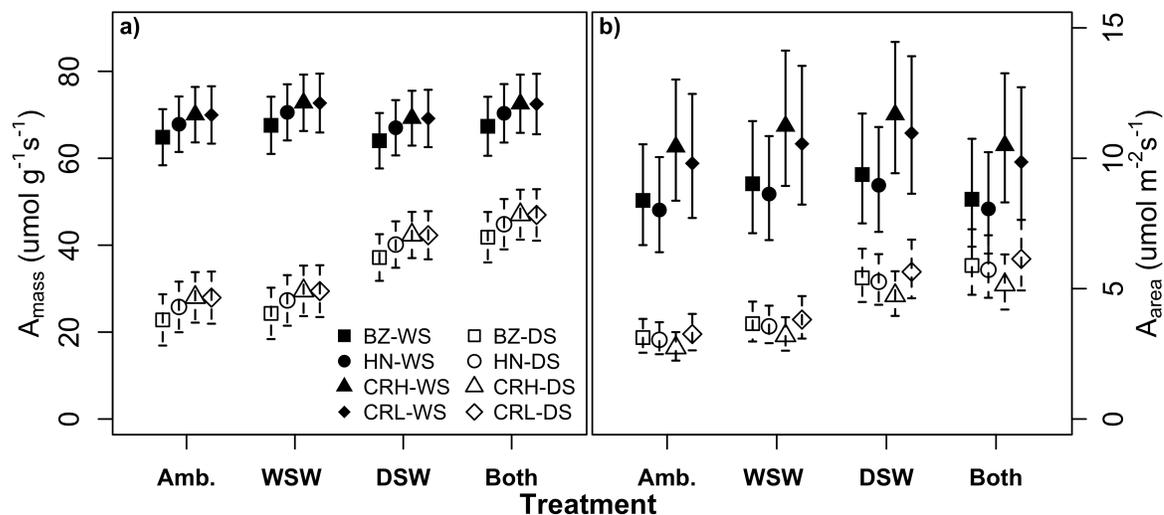


Figure S3.3- LMM predicted mean (SE) for photosynthetic rate on a) leaf mass (A_{mass}) and b) leaf area (A_{area}) basis. Traits were measured on experimental seedlings from *Q. oleoides* seeds germinated in shadehouses and transplanted into common garden at Honduras (dry garden –DG). Population abbreviations are the same as in Fig. S3.2. Treatments are indicated as follows: “Ambient” = no additional watering; “WSW”= wet season watering; “DSW”= dry season watering; “Both” = watering in wet and dry seasons. Measurements were collected during the wet season (closed symbols) and dry season (open symbols) except for SD, which was only collected during the dry season.

		A					g _s				
Factor Contrasts		DF	Est	SE	T		DF	Est	SE	T	
BZ-dry	BZ-WS	784	-5.80	0.65	-8.91	***	782	-0.60	0.04	-17.46	***
BZ-dry	HN-dry	783	0.20	0.54	0.36		783	0.00	0.03	1.06	
BZ-dry	HN-WS	784	-5.70	0.66	-8.64	***	784	-0.60	0.04	-17.79	***
BZ-dry	CRH- dry	785	2.10	0.53	3.98	***	785	0.10	0.03	4.88	***
BZ-dry	CRH-WS	786	-5.50	0.65	-8.41	***	785	-0.60	0.03	-17.12	***
BZ-dry	CRL-dry	780	1.40	0.61	2.35	*	780	0.10	0.03	3.00	**
BZ-dry	CRL-WS	784	-5.90	0.76	-7.71	***	783	-0.60	0.04	-15.28	***
BZ-WS	HN-dry	790	6.00	0.66	9.07	***	788	0.70	0.04	18.62	***
BZ-WS	HN-WS	781	0.10	0.57	0.11		782	0.00	0.03	-0.17	
BZ-WS	CRH- dry	790	7.90	0.65	12.09	***	788	0.80	0.03	22.07	***
BZ-WS	CRH-WS	781	0.30	0.56	0.61		781	0.00	0.03	1.21	
BZ-WS	CRL-dry	787	7.20	0.72	10.01	***	784	0.70	0.04	18.95	***
BZ-WS	CRL-WS	780	-0.10	0.64	-0.11		780	0.00	0.03	0.15	
HN-dry	HN-WS	789	-5.90	0.63	-9.46	***	786	-0.70	0.03	-19.11	***
HN-dry	CRH- dry	781	1.90	0.47	4.11	***	780	0.10	0.03	4.02	***
HN-dry	CRH-WS	791	-5.60	0.61	-9.29	***	788	-0.60	0.03	-18.42	***
HN-dry	CRL-dry	781	1.20	0.55	2.24	*	781	0.10	0.03	2.14	*
HN-dry	CRL-WS	788	-6.10	0.73	-8.35	***	786	-0.60	0.04	-16.26	***
HN-WS	CRH- dry	789	7.80	0.61	12.80	***	786	0.80	0.03	22.63	***
HN-WS	CRH-WS	780	0.30	0.51	0.54		779	0.00	0.03	1.41	
HN-WS	CRL-dry	786	7.20	0.68	10.51	***	784	0.70	0.04	19.35	***
HN-WS	CRL-WS	780	-0.10	0.61	-0.22		779	0.00	0.03	0.30	
CRH-dry	CRH-WS	790	-7.60	0.59	-12.81	***	788	-0.70	0.03	-22.13	***
CRH-dry	CRL-dry	782	-0.70	0.54	-1.25		782	0.00	0.03	-1.28	
CRH-dry	CRL-WS	788	-8.00	0.71	-11.21	***	785	-0.70	0.04	-19.22	***
CRH-WS	CRL-dry	787	6.90	0.66	10.41	***	785	0.70	0.04	18.74	***
CRH-WS	CRL-WS	779	-0.40	0.60	-0.69		779	0.00	0.03	-0.92	
CRL-dry	CRL-WS	785	-7.30	0.77	-9.48	***	783	-0.70	0.04	-16.86	***

Table S3.12- Summary of post-hoc contrasts population x season interaction from mixed effects models of A, and g_s, measured on experimental seedlings (transplant cohort) at dry garden. Degrees of freedom shown are denominator DF, numerator DF=1 for all contrasts. +0.10≥P>0.05; * P≤ 0.05, ** P≤0.01; ***<0.001

Effect	$\delta^{13}\text{C}$			SLA*			SD			SPI		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (Ambient)	-27.88	0.24	-116.40	1.76	0.02	95.74	857.39	44.80	19.14	0.46	0.03	16.31
Both	-0.82	0.30	-2.72	0.01	0.02	0.66	-12.36	46.24	-0.27	-0.03	0.03	-1.23
DS Water (DSW)	-0.97	0.27	-3.53	0.01	0.02	0.31	-17.04	44.22	-0.39	-0.02	0.03	-0.90
WS Water (WSW)	-0.49	0.32	-1.51	0.02	0.02	-1.04	-12.23	47.17	-0.26	0.03	0.03	0.89
HN	0.14	0.28	0.50	0.09	0.01	15.04	11.14	30.27	0.37	0.00	0.02	0.22
CRH	-0.74	0.29	-2.59	0.04	0.01	3.77	24.93	29.51	0.85	0.02	0.02	0.95
CRL	-0.63	0.32	-1.98	0.06	0.01	5.07	18.83	34.41	0.55	0.02	0.02	1.03
Wet Season (WS)	0.02	0.27	0.06	0.03	0.01	2.24	--	--	--	--	--	--
Seed Mass	--	--	--	--	--	--	--	--	--	--	--	--
Size at Planting	0.03	0.01	1.93	0.00	0.00	-3.23	9.27	4.38	2.12	0.01	0.00	2.18
Time	--	--	--	--	--	--	--	--	--	--	--	--
Herbivory	--	--	--	0.06	0.02	3.33	--	--	--	--	--	--
Machine1	--	--	--	--	--	--	--	--	--	--	--	--
Machine2	--	--	--	--	--	--	--	--	--	--	--	--
Both a WS	0.44	0.34	1.28	--	--	--	--	--	--	--	--	--
DS Water x WS	0.42	0.39	1.08	--	--	--	--	--	--	--	--	--
WS Water x WS	0.47	0.40	1.16	--	--	--	--	--	--	--	--	--
HN Pop x WS	1.69	0.47	0.37	1.26	--	--	--	--	--	--	--	--
CRH x WS	-0.16	0.27	0.33	0.82	--	--	--	--	--	--	--	--
CRL x WS	--	0.02	0.38	0.06	--	--	--	--	--	--	--	--
Both x HN	--	0.72	0.35	2.04	--	--	--	--	--	--	--	--
Both x CRH	--	0.93	0.32	2.87	--	--	--	--	--	--	--	--
Both x CRL	--	0.73	0.38	1.92	--	--	--	--	--	--	--	--
DS x HN	--	0.56	0.41	1.36	--	--	--	--	--	--	--	--
DS x CRH	--	0.90	0.38	2.38	--	--	--	--	--	--	--	--
DS x CRL	--	0.11	0.43	0.26	--	--	--	--	--	--	--	--
WS x HN	--	0.20	0.38	0.52	--	--	--	--	--	--	--	--
WS x CRH	--	0.24	0.37	0.67	--	--	--	--	--	--	--	--
WS x CRL	--	0.07	0.42	0.17	--	--	--	--	--	--	--	--
HN x DSW x WS	--	0.00	0.54	0.00	--	--	--	--	--	--	--	--
HN x Ambient x WS	--	0.32	0.51	0.62	--	--	--	--	--	--	--	--
HN x WSW x WS	--	0.05	0.59	0.08	--	--	--	--	--	--	--	--
CRH x DSW x WS	--	0.20	0.49	0.42	--	--	--	--	--	--	--	--
CRH x Ambient x WS	--	0.09	0.46	0.18	--	--	--	--	--	--	--	--
CRH x WSW x WS	--	0.05	0.54	0.08	--	--	--	--	--	--	--	--
CRL x DSW x WS	--	0.36	0.54	0.68	--	--	--	--	--	--	--	--
CRL x Ambient x WS	--	0.47	0.53	0.89	--	--	--	--	--	--	--	--
CRL x WSW x WS	--	0.19	0.62	0.31	--	--	--	--	--	--	--	--

Table S3.13- Summary of LMM output for carbon isotope discrimination ($\delta^{13}\text{C}$), specific leaf area (SLA), stomatal density (SD), and stomatal pore index (SPI). Traits on experimental seedlings from *Q. oleoides* seeds collected from four populations throughout Central America (abbreviated in Table S3.2) and germinated in shadehouses and transplanted (transplant cohort) into the dry garden site (Honduras) and seedlings were subjected to one of four watering treatments, abbreviations in Table S3.8. Measurements were collected during the wet season (2012) and dry season (2013).

Effect	A			g_s			A/g_s			$\delta^{13}C$		SLA		SD		SPI	
	DF	χ^2		χ^2		χ^2	DF	χ^2	DF	χ^2	DF	χ^2	DF	χ^2		χ^2	
Treatment (T)	15,18	0.73		3.27		3.51	13,16	0.23	12,15	0.32	11,14	6.20	+			3.15	
Population (P)	15,18	0.62		3.17		3.68	13,16	0.95	12,15	8.21	*	11,14	4.88			1.01	
Season (S)	17,18	26.62	***	27.96	***	15.67	***	15,16	1.68	14,15	30.45	***	--	--		--	
Seed Mass	40,41	1.40		3.18	+	2.61	38,39	0.31	38,39	0.27	21,22	1.67				2.43	
Herbivory	40,41	0.44		2.74	+	6.68	*	38,39	0.02	38,39	0.07	21,22	0.05			0.11	
Nitrogen	--	--		--		--	38,39	0.84	--	--	--	--	--			--	
Time	40,41	3503.50	***	0.90		2.71	+	--	--	--	--	--	--			--	
Machine	39,41	10.00	*	45.73	***	84.64	***	--	--	--	--	--	--			--	
T x P	24,33	3.20		5.44		5.99	21,31	16.12	+	20,30	11.60	14,22	5.14			6.28	
T x S	30,33	5.56		36.19	***	40.01	***	28,31	1.43	27,30	2.57	--	--			--	
P x S	30,33	3.27		6.78	+	8.99	*	28,31	1.54	37,30	3.95	--	--			--	
T x S x P	33,41	3.37		5.37		6.39	31,39	10.46	30,39	17.82	*	--	--			--	
Block (T)	39,41	16.98	***	47.36	***	33.48	***	37,39	4.92	+	37,39	175.78	***	20,22	0.17	0.40	
MF (P)	39,41	0.02		0.00		0.00	37,39	5.83	*	37,39	0.34	20,22	0.00			0.00	
ID (MF(P))	42,45	0.16		0.00		0.00	39,42	0.00	39,42	0.00	--	--	--			--	
MF (P) x S	42,46	0.60		2.21		0.87	39,43	0.57	39,43	2.45	--	--	--			--	

Table S3.14- Summary of nested LMM comparisons to test for effect significance in models of gas exchange traits: photosynthetic rate (A), stomatal conductance (g_s), intrinsic water-use efficiency (A/g_s), carbon isotope discrimination ($\delta^{13}C$), specific leaf area (SLA), stomatal density (SD), and stomatal pore index (SPI). Traits on experimental seedlings from *Q. oleoides* seeds collected from four populations throughout Central America (abbreviated in Table S3.2) and planted into common gardens (directly planted cohort) at the dry garden site (Honduras) and seedlings were subjected to one of four watering treatments, abbreviations in Table S3.8. Block, maternal family (MF) and seedling ID were treated as random effects.
+0.10 \geq P>0.05; * P \leq 0.05, ** P \leq 0.01; ***<0.001

Effect	A			g_s^*			A/ g_s		
	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (Both)	39.19	142.47	0.28	-1.07	0.11	-9.39	2.41	0.10	24.55
DSW	1.00	90.72	0.01	-0.06	0.09	-0.70	0.06	0.06	0.99
Ambient (Amb)	-0.47	95.94	-0.01	-0.11	0.09	-1.24	0.09	0.06	1.36
WSW	0.82	100.90	0.01	-0.08	0.09	-0.82	0.08	0.07	1.18
WS	2.50	108.39	0.02	0.22	0.11	1.97	-0.25	0.09	-2.71
HN	5.93	165.49	0.04	-0.05	0.09	-0.59	0.01	0.07	0.14
CRH	-15.60	156.48	-0.10	-0.08	0.08	-0.99	0.03	0.07	0.43
CRL	-33.11	134.12	-0.25	-0.03	0.08	-0.43	-0.01	0.06	-0.17
Machine1	--	--	--	0.36	0.06	5.59	-0.45	0.05	-8.86
Machine2	--	--	--	0.38	0.05	7.19	-0.42	0.04	-9.55
Time	--	--	--	--	--	--	-0.21	0.11	-2.02
Herbivory	--	--	--	-0.05	0.03	-1.55	0.07	0.03	2.56
Seed Mass	--	--	--	-0.05	0.02	-2.11	--	--	--
DSW x WS	-432.05	166.13	-2.60	-0.30	0.08	-3.67	0.29	0.06	4.61
Amb x WS	4.83	164.05	0.03	0.19	0.07	2.72	-0.10	0.06	-1.71
WSW x WS	2.57	154.37	0.02	0.15	0.07	2.30	-0.07	0.05	-1.31
HN x DSW	--	--	--	--	--	--	--	--	--
HN x Amb	--	--	--	--	--	--	--	--	--
HN x WSW	--	--	--	--	--	--	--	--	--
CRH x DSW	--	--	--	--	--	--	--	--	--
CRH x Amb	--	--	--	--	--	--	--	--	--
CRH x WSW	--	--	--	--	--	--	--	--	--
CRL x DSW	--	--	--	--	--	--	--	--	--
CRL x Amb	--	--	--	--	--	--	--	--	--
CRL x WS W	--	--	--	--	--	--	--	--	--
HN x WS	--	--	--	-0.08	0.13	-0.61	0.10	0.11	0.94
CRH x WS	--	--	--	0.04	0.13	0.35	0.03	0.10	0.32
CRL x WS	--	--	--	-0.14	0.11	-1.26	0.18	0.09	2.11
HN x DSW x WS	--	--	--	--	--	--	--	--	--
HN x Amb x WS	--	--	--	--	--	--	--	--	--
HN x WSW x WS	--	--	--	--	--	--	--	--	--
CRH x DSW x WS	--	--	--	--	--	--	--	--	--
CRH x Amb x WS	--	--	--	--	--	--	--	--	--
CRH x WSW x WS	--	--	--	--	--	--	--	--	--
CRL x DSW x WS	--	--	--	--	--	--	--	--	--
CRL x Amb x WS	--	--	--	--	--	--	--	--	--
CRL x WSW x WS	--	--	--	--	--	--	--	--	--

*Estimates on log transformed scale

Table S3.15- Summary LMM output for maximum photosynthetic rate (A), stomatal conductance (g_s), intrinsic water-use efficiency (A/ g_s). Traits on experimental seedlings from *Q. oleoides* seeds collected from four populations throughout Central America (abbreviated in Table S3.2) and planted into the dry garden site (directly planted cohort) and seedlings were subjected to one of four watering treatments, abbreviations in Table S3.8. Measurements were collected during the wet season (2012) and dry season (2013).

Effect	$\delta^{13}\text{C}$			SLA ⁺			SD			SPI		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (Both)	-28.08	0.35	-80.48	1.75	0.06	27.78	842.23	41.67	20.21	0.50	0.03	18.82
DS Water (DSW)	0.16	0.54	0.30	0.04	0.08	0.54	135.08	60.82	2.22	0.05	0.04	1.32
Ambient (Amb)	-1.51	0.88	-1.71	0.00	0.10	0.02	92.92	60.15	1.55	0.05	0.04	1.29
WS Water (WSW)	0.18	0.49	0.36	-0.03	0.08	-0.46	197.18	60.82	3.24	0.10	0.04	2.50
Wet Season	0.13	0.08	1.67	0.06	0.06	1.02	--	--	--	--	--	--
HN	-0.04	0.47	-0.07	0.09	0.07	1.27	--	--	--	--	--	--
CRH	0.21	0.40	0.52	0.16	0.06	2.85	--	--	--	--	--	--
CRL	0.05	0.35	0.14	0.03	0.05	0.65	--	--	--	--	--	--
Machine1	--	--	--	--	--	--	--	--	--	--	--	--
Machine2	--	--	--	--	--	--	--	--	--	--	--	--
Time	--	--	--	--	--	--	--	--	--	--	--	--
Herbivory	--	--	--	--	--	--	--	--	--	--	--	--
Seed Mass	--	--	--	--	--	--	--	--	--	--	--	--
DSW x WS	--	--	--	0.02	0.10	0.24	--	--	--	--	--	--
Ambient x WS	--	--	--	0.05	0.12	0.45	--	--	--	--	--	--
WSW x WS	--	--	--	-0.08	0.11	-0.70	--	--	--	--	--	--
HN x DSW	0.27	0.71	0.38	-0.01	0.10	-0.09	--	--	--	--	--	--
HN x Amb	1.77	0.98	1.80	0.04	0.11	0.35	--	--	--	--	--	--
HN x WSW	-0.97	0.68	-1.42	0.03	0.10	0.35	--	--	--	--	--	--
CRH x DSW	-0.60	0.61	-0.99	-0.19	0.09	-2.23	--	--	--	--	--	--
CRH x Amb	0.98	0.93	1.05	-0.06	0.10	-0.53	--	--	--	--	--	--
CRH x WSW	0.01	0.60	0.01	-0.15	0.09	-1.71	--	--	--	--	--	--
CRL x DSW	-0.11	0.55	-0.21	-0.03	0.08	-0.42	--	--	--	--	--	--
CRL x Amb	1.53	0.89	1.72	0.01	0.10	0.07	--	--	--	--	--	--
CRL x WSW	-0.06	0.50	-0.12	0.03	0.07	0.43	--	--	--	--	--	--
HN x WS	--	--	--	-0.14	0.09	-1.58	--	--	--	--	--	--
CRH x WS	--	--	--	-0.08	0.07	-1.06	--	--	--	--	--	--
CRL x WS	--	--	--	0.00	0.06	0.07	--	--	--	--	--	--
HN x DSW x WS	--	--	--	0.04	0.13	0.33	--	--	--	--	--	--
HN x Amb x WS	--	--	--	0.08	0.15	0.51	--	--	--	--	--	--
HN x WSW x WS	--	--	--	0.15	0.14	1.06	--	--	--	--	--	--
CRH x DSW x WS	--	--	--	0.14	0.12	1.18	--	--	--	--	--	--
CRH x Amb x WS	--	--	--	-0.01	0.13	-0.07	--	--	--	--	--	--
CRH x WSW x WS	--	--	--	0.24	0.13	1.82	--	--	--	--	--	--
CRL x DSW x WS	--	--	--	-0.06	0.10	-0.62	--	--	--	--	--	--
CRL x Amb x WS	--	--	--	-0.04	0.12	-0.38	--	--	--	--	--	--
CRL x WSW x WS	--	--	--	0.04	0.12	0.32	--	--	--	--	--	--

^aEstimates on log transformed scale

Table S3.16- Summary of LMM output for carbon isotope discrimination ($\delta^{13}\text{C}$), specific leaf area (SLA), stomatal density (SD), and stomatal pore index (SPI). Traits on experimental seedlings seeds collected from four populations throughout Central America (abbreviated in Table S3.2) and planted into the dry garden site (directly planted cohort) and seedlings were subjected to one of four watering treatments, abbreviations in Table S3.8.

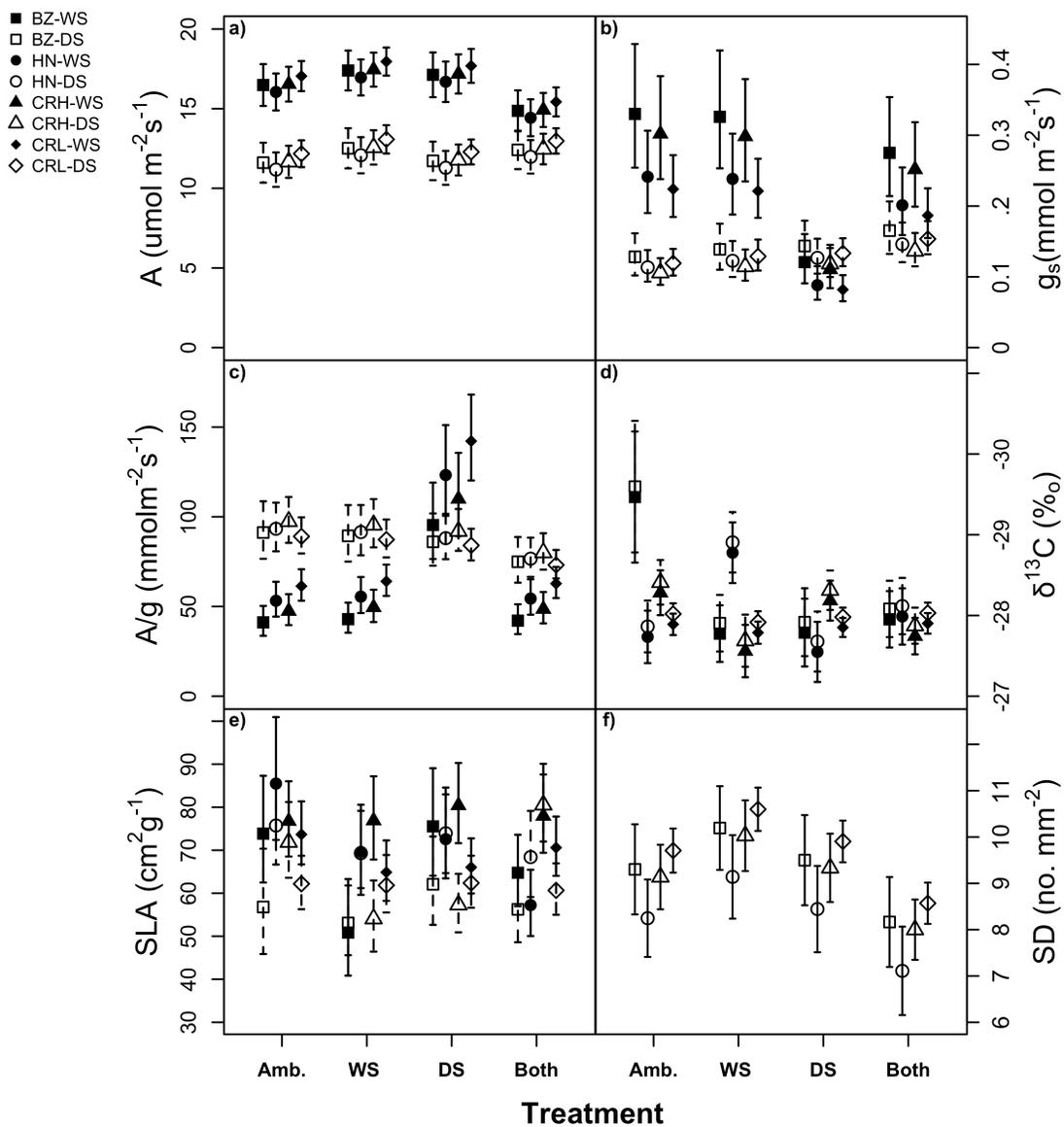


Figure S3.4- LMM predicted mean (SE) for leaf-level traits related to carbon and water-use, a) maximum photosynthetic rate (A), b) stomatal conductance (g_s), c) intrinsic water-use efficiency (A/g), d) carbon isotope discrimination ($\delta^{13}C$), e) specific leaf area (SLA), and e) stomatal density (SD). Traits on experimental seedlings from *Q. oleoides* seeds planted into common garden (directly planted cohort) the dry garden site (Honduras). Population abbreviations are the same as in Fig. S3.4. Treatments are indicated as follows: “Ambient” = no additional watering; “WSW”= wet season watering; “DSW”= dry season watering; “Both” = watering in wet and dry seasons. Measurements were collected during the wet season (closed symbols) and dry season (open symbols) except for SD, which was only collected during the dry season.

Effect	$\delta^{13}\text{C}$			SLA			SD			SPI		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (Amb.)	-29.70	0.21	-141.25	7.32	0.34	21.83	1021.41	77.04	13.26	0.46	0.04	11.28
IG-DSW	0.39	0.37	1.04	-1.53	0.57	-2.70	-143.44	62.54	-2.29	0.08	0.04	1.76
WG-Amb	0.20	0.27	0.74	0.13	0.45	0.29	-23.49	49.71	-0.47	-0.02	0.04	-0.45
WS	0.38	0.09	4.13	-0.63	0.15	-4.35	--	--	--	--	--	--
HN	0.21	0.20	1.06	0.20	0.17	1.17	-59.51	57.63	-1.03	-0.03	0.03	-1.03
CRH	-0.23	0.18	-1.27	0.12	0.15	0.77	55.78	50.72	1.10	0.00	0.02	0.20
CRL	0.05	0.15	0.34	0.01	0.13	0.08	-24.58	42.24	-0.58	-0.01	0.02	-0.44
Seed Mass	--	--	--	--	--	--	-56.82	24.84	-2.29	-0.02	0.01	-1.71
Size at Planting	--	--	--	--	--	--	--	--	--	--	--	--
Nitrogen	-0.26	0.13	-2.09	--	--	--	--	--	--	--	--	--
IG-DSW x WS	-0.28	0.14	-1.99	0.71	0.30	2.39	--	--	--	--	--	--
WG-Amb x WS	0.14	0.17	0.79	-0.75	0.20	-3.70	--	--	--	--	--	--
IG-DSW x HN	0.32	0.26	1.23	--	--	--	--	--	--	--	--	--
IG-DSW x CRH	0.25	0.23	1.08	--	--	--	--	--	--	--	--	--
IG-DSW x CRL	0.29	0.19	1.51	--	--	--	--	--	--	--	--	--
WG-Amb x HN	-0.63	0.44	-1.44	--	--	--	--	--	--	--	--	--
WG-Amb x CRH	0.02	0.36	0.06	--	--	--	--	--	--	--	--	--
WG-Amb x CRL	-0.64	0.31	-2.11	--	--	--	--	--	--	--	--	--

Table S3.17- Summary of LMM output for carbon isotope discrimination ($\delta^{13}\text{C}$), specific leaf area (SLA), stomatal density (SD), and stomatal pore index (SPI). Traits on experimental seedlings from *Q. oleoides* seeds collected from four populations throughout Central America and germinated in shadehouses and transplanted (transplant cohort) into common gardens in Costa Rica- intermediate (IG) and wet (WG) gardens. Seedlings at the intermediate garden were subjected to two watering treatments: ambient rainfall and added water during the dry season. Due to the design not being full-factorial treatment represents the three possible conditions: IG-ambient rainfall, IG-DS Water and WG-ambient rainfall. Measurements were collected during the wet season (WS, 2012) and dry season (DS, 2013).

Factor Contrasts		$\delta^{13}\text{C}$				SLA					
		DF	Est	SE	T	DF	Est	SE	T		
IG, Amb-DS	WG, Amb- DS	22.70	-0.10	0.28	-0.25	17.60	1.50	0.57	2.70		
IG, Amb-DS	IG-DSW-DS	18.40	-0.40	0.22	-1.91	15.60	-0.10	0.45	-0.29		
IG, Amb-DS	IG, Amb-WS	866.30	-0.40	0.10	-3.55	***	838.70	0.60	0.15	4.35	***
IG, Amb-DS	WG, Amb-WS	23.10	-0.60	0.28	-2.08	*	17.30	1.50	0.57	2.57	*
IG, Amb-DS	IG-DSW-WS	18.70	-0.50	0.22	-2.31	*	16.20	1.30	0.45	2.76	**
WG, Amb- DS	IG, DSW-DS	22.90	-0.30	0.28	-1.23		17.80	-1.70	0.57	-2.92	**
WG, Amb- DS	IG,Amb-WS	23.00	-0.30	0.28	-1.03		18.20	-0.90	0.57	-1.57	
WG, Amb- DS	WG, Amb-WS	854.90	-0.50	0.17	-3.09	**	838.20	-0.10	0.26	-0.30	
WG, Amb- DS	IG, Amb-WS	22.90	-0.40	0.28	-1.54		18.20	-0.30	0.57	-0.49	
IG, DSW-DS	IG,Amb-WS	18.80	0.10	0.22	0.26		16.50	0.80	0.46	1.67	
IG, DSW-DS	WG, Amb-WS	22.90	-0.20	0.28	-0.61		17.50	1.60	0.57	2.79	
IG, DSW-DS	IG, DSW-WS	855.70	-0.10	0.10	-0.88		839.10	1.40	0.15	9.31	***
IG, Amb-WS	WG, Amb-WS	22.30	-0.20	0.28	-0.82		17.80	0.80	0.57	1.44	
IG, Amb-WS	IG, DSW-WS	18.30	-0.10	0.22	-0.66		16.60	0.60	0.46	1.35	
WG, Amb-WS	IG, DSW-WS	22.20	0.10	0.28	0.30		17.80	-0.20	0.57	-0.36	

Table S3.18- Summary of pairwise contrasts of treatment x season interaction from mixed effects models of carbon isotope discrimination ($\delta^{13}\text{C}$) and specific leaf area (SLA). Factors include intermediate garden (IG, Amb), intermediate garden- dry season water (IG,DSW) and wet garden (WG,Amb) in the dry (DS) and wet (WS) seasons. Traits were measured on leaves from experimental seedlings from *Q. oleoides* seeds collected from four populations throughout Central America and germinated in shadehouses and transplanted into common intermediate and wet gardens in Costa Rica. Measurements were collected during the wet season (2012) and dry season (2013). +0.10 \geq P>0.05; * P \leq 0.05, ** P \leq 0.01; ***<0.001

Effect	$\delta^{13}\text{C}$		SLA		SD		SPI	
	DF	χ^2	DF	χ^2	DF	χ^2	DF	χ^2
Treatment (T)	12,14	0.40	11,13	5.58 +	10,12	3.52	10,12	4.93 +
Population (P)	11,14	2.69	10,13	1.84	9,12	2.61	9,12	3.78
Season (S)	13,14	1.05	12,13	0.19	--	--	--	--
Seed Mass	18,19	0.00	17,18	0.22	16,17	3.16 +	16,17	0.89
Nitrogen	18,19	1.14	--	--	--	--	--	--
T x P	19,23	2.65	--	--	12,17	7.48	12,17	2.78
T x S	17,19	17.38 ***	16,18	1.83	--	--	--	--
P x S	16,19	0.40	15,18	1.07	--	--	--	--
T x P x S	--	--	--	--	--	--	--	--
Block (T)	17,19	3.90	16,18	1447.50 ***	15,17	0.18	15,17	0.36
MF (P)	17,19	3.64	16,18	1447.50 ***	15,17	0.00	15,17	0.00
ID (MF(P))	19,20	0.01	18,19	0.00	--	--	--	--
MF (P) x S	19,23	0.08	18,24	0.00	--	--	--	--

Table S3.19- Summary of nested LMM comparisons to test for effect significance in models of carbon isotope discrimination ($\delta^{13}\text{C}$), specific leaf area (SLA), stomatal density (SD), and stomatal pore index (SPI). Traits on experimental seedlings from *Q. oleoides* seeds collected from four populations throughout Central America and planted directly into common gardens in Costa Rica- intermediate (IG) and wet (WG) gardens. Seedlings at the intermediate garden were subjected to two watering treatments: ambient rainfall and added water during the dry season. Due to the design not being full-factorial treatment represents the three possible conditions: IG-ambient rainfall, IG-DS Water and WG-ambient rainfall. Measurements were collected during the wet season (2012) and dry season (2013). +0.10 \geq P>0.05; * P \leq 0.05, ** P \leq 0.01; ***<0.001

Effect	$\delta^{13}\text{C}$			SLA*			SD			SPI		
	Est	SE	T	Est	SE	T	Est	SE	T	Est	SE	T
Intercept (IG-Amb)	-27.93	0.39	-71.41	52.84	9.81	5.39	441.92	183.75	2.41	0.47	0.06	7.94
WG-Amb	-0.62	0.45	-1.36	-2.23	12.08	-0.19	106.12	64.62	1.64	0.08	0.04	2.12
IG-DSW	-0.15	0.40	-0.37	7.60	10.80	0.70	133.84	64.21	2.08	0.01	0.04	0.31
WS	-0.42	0.21	-1.95	9.25	11.79	0.78	--	--	--	--	--	--
HN	-0.76	0.49	-1.56	5.27	7.06	0.75	157.18	166.81	0.94	-0.04	0.08	-0.50
CRH	-0.29	0.34	-0.86	4.94	10.97	0.45	150.71	128.30	1.18	0.01	0.06	0.25
CRL	-0.37	0.30	-1.20	11.87	10.23	1.16	71.94	114.51	0.63	-0.03	0.06	-0.58
Seed Size	--	--	--	--	--	--	175.02	65.48	2.67	--	--	--
WG-Amb x WS	1.44	0.34	4.25	16.48	15.17	1.09	--	--	--	--	--	--
IG-DSW x WS	0.04	0.29	0.12	-15.96	13.05	-1.22	--	--	--	--	--	--
CRH x WG-Amb	--	--	--	11.61	13.39	0.87	--	--	--	--	--	--
CRH x IG_DSW	--	--	--	-13.98	12.59	-1.11	--	--	--	--	--	--
CRL x WG-Amb	--	--	--	0.06	12.67	0.01	--	--	--	--	--	--
CRL x IG-DSW	--	--	--	-11.90	11.41	-1.04	--	--	--	--	--	--
HN x WS	--	--	--	-1.77	9.59	-0.19	--	--	--	--	--	--
CRH x WS	--	--	--	-7.90	13.23	-0.60	--	--	--	--	--	--
CRL x WS	--	--	--	-11.10	12.30	-0.90	--	--	--	--	--	--
CRH x WG-Amb x WS	--	--	--	-19.82	17.20	-1.15	--	--	--	--	--	--
CRH x IG-DSW x WS	--	--	--	25.28	15.48	1.63	--	--	--	--	--	--
CRL x WG-Amb x WS	--	--	--	-7.46	16.18	-0.46	--	--	--	--	--	--
CRL x IG-DSW x WS	--	--	--	16.46	13.89	1.19	--	--	--	--	--	--

Table S3.20- Summary of nested LMM comparisons for carbon isotope discrimination ($\delta^{13}\text{C}$), specific leaf area (SLA), stomatal density (SD), and stomatal pore index (SPI). Traits on seedlings from *Q. oleoides* seeds collected from four populations throughout Central America and planted directly into common gardens in Costa Rica- intermediate (IG) and wet (WG) gardens. Treatment represents the three possible conditions: IG-ambient rainfall, IG-DS Water and WG-ambient rainfall. Measurements were collected during the wet season (2012) and dry season (2013).

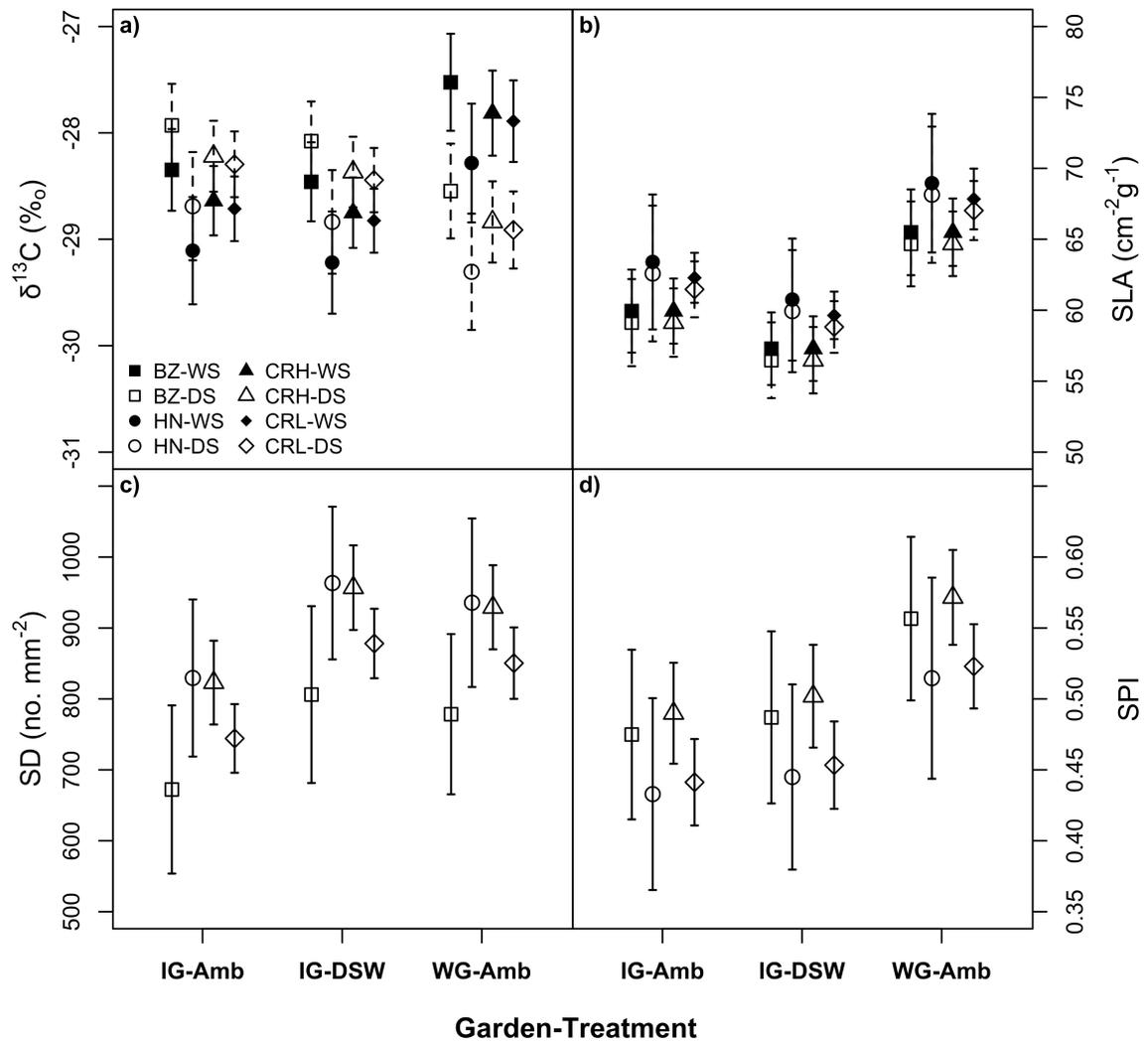


Figure S3.5- Mixed effects model predicted mean (SE) for leaf-level traits related to carbon and water-use, a) specific leaf are (SLA), b) carbon isotope discrimination ($\delta^{13}\text{C}$), c) stomatal density (SD), and d) stomatal pore index (SPI). Traits were measured on experimental seedlings from *Q. oleoides* planted directly into common gardens in Costa Rica- intermediate (IG) and wet (WG) gardens. Population abbreviations are the same as in Fig. S3.2. Seedlings at the intermediate garden were subjected to two watering treatments: ambient rainfall and added water during the dry season. Due to the design not being full-factorial treatment represents the three possible conditions: IG-ambient rainfall, IG-DS Water and WG-ambient rainfall. Measurements were collected during the wet season (WS- closed symbols) and dry season (DS- open symbols).

		$\delta^{13}\text{C}$			
Factor Contrasts		DF	Est	SE	T
IG, Amb-DS	WG, Amb- DS	8	0.60	0.45	1.36
IG, Amb-DS	IG, DSW-DS	10	0.10	0.40	0.37
IG, Amb-DS	IG, Amb-WS	101	0.40	0.21	1.95 *
IG, Amb-DS	WG, Amb-WS	9	-0.40	0.47	-0.86
IG, Amb-DS	IG, DSW-WS	10	0.50	0.40	1.32
WG, Amb- DS	IG, DSW-DS	8	-0.50	0.45	-1.05
WG, Amb- DS	IG, Amb-WS	8	-0.20	0.45	-0.44
WG, Amb- DS	WG, Amb-WS	110	-1.00	0.26	-3.89 ***
WG, Amb- DS	IG, Amb-WS	8	-0.10	0.45	-0.19
IG, DSW-DS	IG, Amb-WS	10	0.30	0.40	0.68
IG, DSW-DS	WG, Amb-WS	9	-0.60	0.46	-1.20
IG, DSW-DS	IG, DSW-WS	109	0.40	0.20	1.91 +
IG, Amb-WS	WG, Amb-WS	9	-0.80	0.46	-1.77
IG, Amb-WS	IG, DSW-WS	9	0.10	0.40	0.28
WG, Amb-WS	IG, DSW-WS	9	0.90	0.46	2.03

Table S3.21- Summary of post-hoc contrasts treatment x season interaction from mixed effects model carbon isotope discrimination ($\delta^{13}\text{C}$), measured on experimental seedlings from *Q. oleoides* seeds collected from four populations throughout Central America and planted directly into common gardens in Costa Rica- intermediate (IG) and wet (WG) gardens. Seedlings at the intermediate garden were subjected to two watering treatments: ambient rainfall (and added water during the dry season. Treatment represents the three possible conditions: IG-ambient rainfall (IG, Amb), IG-DS Water (IG, DSW) and WG-ambient rainfall (WG, Amb). Measurements were taken in the wet season (WS) and dry season (DS). Degrees of freedom shown are denominator DF, numerator DF=1. +0.10 \geq P>0.05; * P \leq 0.05, ** P \leq 0.01; ***<0.001