A multi-species synthesis of physiological mechanisms in drought-induced tree mortality

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A multi-species synthesis of physiological mechanisms in drought-induced tree mortality

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Widespread tree mortality associated with drought has been observed on all forested continents, and global change is expected to exacerbate vegetation vulnerability. Forest mortality has implications for future biosphere-atmosphere interactions of carbon, water, and energy balance, and is poorly represented in dynamic vegetation models. Reducing uncertainty requires improved mortality projections founded on robust physiological processes. However, the proposed mechanisms of drought-induced mortality, including hydraulic failure and carbon starvation, are unresolved. A growing number of empirical studies have investigated these mechanisms, but data have not been consistently analyzed across species and biomes using a standardized physiological framework. Here we show that xylem hydraulic failure was ubiquitous across multiple tree taxa at drought-induced mortality. All species assessed had 60% or higher loss of xylem hydraulic conductivity, consistent with proposed theoretical and modelled survival thresholds. We found diverse responses in non-structural carbohydrate reserves at mortality, indicating that evidence supporting carbon starvation was not universal. Reduced non-structural carbohydrates were more common for gymnosperms than angiosperms, associated with xylem hydraulic vulnerability, and may have a role in reducing hydraulic function. Our finding that hydraulic failure at drought-induced mortality was persistent across species indicates that substantial improvement in vegetation modelling can be achieved using thresholds in hydraulic function.

Increasing forest mortality from global change has been observed in all forested biomes[1,2] and will have profound implications for future energy and element fluxes[3-5]. Predictions of vegetation responses to future climate are uncertain due to the lack of realistic mortality mechanisms in vegetation models[3,6-9]. Recent research supports at least two tightly inter-related

115 physiological mechanisms associated with tree mortality by drought: (a) hydraulic failure
116 through partial or complete loss of xylem function from embolism that inhibits water transport
117 through the vasculature, leading to tissue desiccation; and (b) carbon starvation via imbalance
118 between carbohydrate demand and supply that may lead to an inability to meet osmotic,
119 metabolic, and defensive carbon requirements[3,6,7,10-15]. Hydraulic failure is most typically
120 assessed via percent loss of xylem conductivity (PLC), and carbon starvation via changes in
121 tissue non-structural carbohydrate (NSC) concentrations[12-16]. There has been significant debate
122 over these co-occurring mechanisms of mortality, particularly regarding the prevalence of carbon
123 starvation and whether reduced carbohydrate reserves can be lethal during drought[11,17-22].
124 Though a number of studies on the mechanism of drought-induced mortality in trees have
125 been conducted for a variety of tree species over the last decade, the prevalence of these
126 mechanisms at a global scale remains uncertain. Differences in approach, variables measured,
127 and species and life stage studied have limited global assessment of drought-induced tree
128 mortality mechanism. Here, we provide the first cross-species synthesis of tree drought
129 mortality mechanisms. We used a standardized physiological framework to analyze drought-
130 induced tree mortality across species and assessed hydraulic function as PLC, and carbohydrate
131 status as NSC normalized relative to controls. We examined data from 19 recent experimental
132 and observational studies on 26 species from around the globe. Most tree species were assessed
133 in only one study, but for several species, data were available from more than one study,
134 resulting in 34 cases (species-study combinations). However, data were not available for all
135 analyses from all cases: more cases had NSC data (31 cases from 24 species) than PLC data (14
136 cases from 9 species) which could be used to compare NSC and PLC at mortality with that of
137 surviving control trees (see Methods below, Supplementary Table 1). In order to make our

138 synthesis comprehensive, we worked with all of the data that were available, including data from
139 studies on a range of tree sizes and ontogenetic life stages (i.e. seedlings, saplings, and large
140 trees), conducted in a variety of settings, including potted plants in greenhouses or growth
141 chambers, and trees grown in the field (Supplementary Tables 1, 2). Given the diversity of
142 studies synthesized, these data were not ideal for a statistical meta-analysis; therefore, we limited
143 our analyses to a standard comparison within each case between plants that died and plants that
144 remained healthy (Supplementary Methods). We also compared differences in degree of
145 embolism and carbohydrate concentrations between plants at mortality and control plants to
146 differences in functional traits[3,24,25]. For each species, we obtained available data for traits that
147 are easily measured, widely available, and likely relevant for drought tolerance, including wood
148 density and specific leaf area[26]. We also obtained data for hydraulic traits that are directly related
149 to drought tolerance, but harder to measure, including xylem water potential at 50% loss of
150 hydraulic conductivity (Ψ_{50}), point of embolism entry (Ψ_e), and corresponding hydraulic safety
151 margins[24,27] (Supplementary Methods). We used this dataset to address the following
152 hypotheses: 1) given the potential role of NSC in the maintenance of water transport during
153 drought[6, 28], both high PLC and reduced NSC reserves are common at tree death from drought,
154 and 2) among species, species-level functional traits that have been positively related to drought
155 tolerance (e.g. low xylem vulnerability to embolism, low SLA, high wood density) are associated
156 with high NSC at tree death. According to this hypothesis we expect that for species with greater
157 xylem vulnerability (quantified by Ψ_{50}, Ψ_e, and hydraulic safety margin), NSC at death will be
158 relatively lower. This hypothesis is based on prior proposals that drought-sensitive trees which
159 close their stomata earlier during drought would be more likely to show a reduction in NSC
160 associated with carbon starvation[3,25,29,30].

Results.

For the cases where PLC data at mortality were available (Supplementary Methods), PLC was 60% or higher (Figure 1A), demonstrating that a high degree of xylem embolism at drought-induced death was a universal aspect of mortality physiology in these species. Mean PLC was 84.3% at mortality, and PLC was significantly higher at mortality than for control trees in every case ($p < 0.05$, Student's t-test). For NSC, we focused our analysis on differences in NSC concentration between trees that died from drought and controls which did not die, measured at the same point in time for both groups, although we also considered differences over time for trees that died (Supplementary Discussion). Reductions in NSC at mortality were common among species, but not universal, and no common NSC threshold for mortality was identified. For 48% of cases and 38% of species with available data, NSCs were significantly lower at mortality in dying trees compared to surviving or control trees (for observational and experimental studies, respectively) in at least one tissue ($p < 0.05$, ANOVA; Figure 1B-D). Among all species, mean NSCs at mortality for leaves, above-ground woody tissues (bole, branch, stem, or twig), and roots were 13, 17, and 35% lower in dying trees than control measurements.

For boreal and temperate angiosperms, lower NSCs at mortality relative to control trees were observed in 56% of cases and 63% of the species for at least one tissue, and NSC reductions exceeded 50% in approximately 33% of these cases and 38% of these species (Figure 1B). Higher NSCs at mortality relative to controls were common for tropical angiosperm seedlings[31], more than 100% higher in some cases, and reduced NSCs were not observed in this group, suggesting different physiological responses to severe drought in non-tropical and tropical

tree species (Figure 1B, C). In a similar seedling study with the same tropical species, however, lower pre-drought NSCs were consistently correlated with a shorter time to mortality though NSCs did not decline during drought[14]. Lower NSCs at mortality relative to controls were most common in root tissues[32], and typically resulted from lower starch concentrations, consistent with a starch to sugar conversion to meet metabolic and osmoregulatory demands during drought stress[6] (Supplementary Figure 1). Notably, only a few cases exhibited the hypothesized time-series trend in NSCs of initial small increase and then a more pronounced decrease in NSCs over time[28] (Supplementary Figures 2, 3, 4).

Reductions in NSCs at mortality were more prevalent for gymnosperms than angiosperms (Figure 1, Supplementary Figures 2, 3, 4). Among gymnosperms, 83% of cases and 67% of species had lower NSC at mortality relative to controls for at least one tissue (Figure 1D). This occurred in at least one tissue for all four species of the Pinaceae, but not for the two species in the Cupressaceae, which is consistent with divergent evolutionary pathways for stomatal control between these families[33]. Relative reductions in NSCs were also generally greater in gymnosperms than angiosperms, e.g. *Pinus sylvestris* had NSC reductions of >80% in some tissues prior to mortality (Figure 1D).

Functional traits related to xylem embolism resistance and stomatal control have been suggested as useful predictors of the physiological causes of drought-induced mortality[3,25,30,34]. For all species, the deviation of NSCs in trees at mortality from their controls was not significantly associated with wood density or specific leaf area ($p > 0.05$, linear regression), regardless of whether the relationships were assessed for angiosperms, gymnosperms, or all species together. For gymnosperms, reduced NSCs at mortality in aboveground woody tissues (bole, branch, stem, or twig) were associated with lower resistance to xylem embolism (i.e.

higher Ψ_{50} and Ψ_e; $r^2 = 0.88$ and 0.91, respectively, $p < 0.001$, linear regression; Figure 2), indicating that hydraulic features in gymnosperms associated with drought resistance were related to NSC dynamics during lethal drought. Normalized NSCs in other tissues were positively correlated with embolism resistance at mortality (leaf NSC with Ψ_{50}, root NSC with Ψ_e; $p < 0.05$, linear regression), and normalized NSCs in aboveground woody tissue and roots at mortality were also positively correlated with the Ψ_{50} hydraulic safety margin for gymnosperms ($p < 0.001$, linear regression; Supplementary Figure 5), but these relationships were strongly influenced by one species, *Callitris rhomboidea* (Supplementary Methods). Variation in PLC at mortality was not related to any functional traits assessed ($p > 0.05$, linear regression).

Discussion.

We found that tree mortality from drought was always associated with substantial loss of hydraulic function, and that lower NSCs at mortality were common but not universal (Figure 1). Our findings for PLC at mortality (Figure 1A) are close to modeling and theoretical predictions of a stem PLC mortality threshold near or above 60%[7,10,35-37]. In all cases, we found that PLC at mortality was at least 60%, but values were much higher in a number of cases. The studies in our synthesis were not designed to quantify lethal PLC thresholds, which deserve future investigation to determine the duration and intensity of drought required to trigger mortality and the mechanisms underlying such a threshold. The physiological effects of a particular level of PLC likely vary among species, mediated by traits such as the capacity to refill embolism and replace conducting area via new growth[6,38]. Nonetheless, a sustained stem PLC at or above 60% provides a generally supported starting point for modeling vegetation response across spatial scales, a point beyond which the probability of mortality increases[7,10,36,37].

For the cases where both NSC and PLC data were available at mortality, all trees died with high PLC (100% of cases), but only 62% of cases also had low NSCs at mortality relative to controls (Figure 3). This suggests that trees died from either hydraulic failure alone, or hydraulic failure in combination with reduced NSCs. This finding should help lay to rest the misconception of a dichotomy between hydraulic failure and carbon starvation, which are often mistakenly thought to represent mutually exclusive mechanisms[15]. Clearly, our results underscore the importance of maintaining a functional plant hydraulic system for survival, while suggesting a relationship between hydraulic failure and carbon starvation mechanisms in this process. The majority of studies included in our analysis were not designed to distinguish the drivers of mortality from the non-causative symptoms of dying. Thus, it is not possible with our data to conclusively determine if changes in either NSC or PLC facilitated death or were the result of the mortality process (Supplementary Discussion). Results from studies in which light and CO_2 concentration were manipulated to regulate carbon fixation do suggest a role for NSC as a survival mechanism against mortality via hydraulic failure during drought, even when NSC does not decline during drought or is not reduced below control values[12-16] (Supplementary Discussion).

Given the diversity of NSC responses found at mortality, there is an obvious need to develop frameworks for the sensitivity of plant metabolism to changes in NSC levels, including the potential for lethal thresholds[22,39]. Specific NSC thresholds for survival or mortality during drought are not well-resolved in our data, nor yet in the literature. Such survival thresholds likely vary with factors including tree species, ontogeny, tree tissue, canopy position, seasonality, environmental conditions, and interactions with other organisms, but empirical investigation of these thresholds is needed[22,40,41]. Determination of these thresholds is hampered

253 by an incomplete understanding of the role of NSC storage in plant function, and its regulatory
254 mechanism[22,39]. However, significantly lower NSCs at mortality were relatively common for a
255 variety of species in our analysis, such that reduced NSCs can no longer be considered a rare or
256 atypical response during tree death.

257 Our finding that reduced NSCs at mortality were more common for gymnosperms, than
258 for angiosperms (Figure 1, Supplementary Figures 2, 3, 4), is consistent with the wider hydraulic
259 safety margins of gymnosperms relative to angiosperms[24,42]. For gymnosperms, our functional
260 trait analysis revealed that species with greater xylem embolism resistance had higher NSC at
261 mortality in boles, branches, stems, or twigs than surviving controls, indicating that species'
262 hydraulic traits can affect C balance during lethal drought (Figure 2). As embolism resistance is
263 often associated with an ability to keep stomata open at lower water potentials[30,43], our results
264 suggest that tree species which can maintain stomatal conductance and photosynthesis at higher
265 xylem tension during drought are less likely to have reduced NSC at mortality[29]. These resistant
266 tree species would be more likely to die from hydraulic failure alone without reduced NSC —
267 consistent with hypotheses that stomatal regulation and hydraulic transport strategies influence
268 the contribution of carbon starvation and hydraulic failure to mortality mechanism among
269 species[3,25,30]. Caution, however, should be used in assuming stomatal regulation is highly
270 coupled with water potential regulation and hydraulic strategy[44]. Importantly, we did not find a
271 relationship between NSC reduction and embolism resistance for angiosperms, nor did any other
272 trait predict mortality physiology in these species.

273 Our synthesis of data from multiple studies on the physiology of drought-induced tree
274 mortality exposes several key knowledge gaps in the field. Our dataset of only 26 species under-
275 represents the enormous diversity of tree species found in forests globally, particularly so for

276 tropical forests, where drought-induced mortality can have substantial implications for the global
277 carbon cycle[9]. *Pinus* was relatively over-represented in this synthesis (nine cases from three
278 species), although it is widely distributed and has been widely affected by forest die-off on
279 multiple continents[1]. Also, our dataset is dominated by data from seedlings and saplings, often
280 from studies conducted with potted plants, which may be predisposed to die quickly from
281 hydraulic failure due to limited rooting volume and lack of access to deeper soil water pools
282 (Supplementary Tables 1, 2). Data at mortality for more than one life stage were available for
283 only three species (Figure 1), and the consistency of NSC and PLC responses at mortality across
284 a gradient of size and ontogeny varied in these species. Clearly, more research on the physiology
285 of mortality in large trees in the field and the effect of size and ontogeny on the mortality process
286 is needed. Nonetheless, our overall observation that hydraulic failure was universal, and NSC
287 reduction was not, does not change if we only consider data for each life stage separately. In all
288 cases for which PLC data were available, mean PLC was 60% or greater at mortality,
289 irrespective of life stage (Figure 1A). Our finding that normalized NSC at mortality varied
290 among cases and species also holds when seedlings, saplings, and trees are considered separately
291 (Figure 1B-D, Supplementary Table 1).

292 Determining whether forests will continue to act as a global carbon sink or transition to a
293 carbon source is a critical uncertainty for the carbon cycle with large ramifications for society
294 and climate policy[8,9,23]. Such a shift largely depends on tree mortality responses which could be
295 anticipated by resolving the relative roles of hydraulic and carbohydrate mechanisms in causing
296 tree death[7,10,45]. We found that hydraulic failure was ubiquitous among the studies we compared,
297 that PLC at mortality in all cases with such data was at least 60%. These results affirm that
298 simulating hydraulic function should be a first priority for development of mechanistic tree

mortality algorithms in climate-vegetation models to improve projections of the future terrestrial carbon budget. Hydraulic models that capture drought damage at tree and landscape scales are rapidly developing[7,10,36,37,45-47] and substantial improvement in vegetation model projections may be possible with simulation of hydraulic-driven mortality, whether tree carbohydrate status is represented or not. Reduced NSC in tree species dying from drought was common in gymnosperms, but not angiosperms, suggesting an influence of NSC on hydraulic deterioration in some trees that requires further investigation. Yet, the diversity of NSC responses among only 26 species and the design limitations of past studies in determining causality demonstrate that we need to further assess the influence of carbon metabolism and storage on mortality[39]. Ultimately, an improved representation of the physiology of drought-induced tree mortality that includes both water and carbon relations will be crucial for forecasting the fate of forests in a changing climate.

Methods

Data Synthesis. We used literature search and extensive discussion with colleagues to identify data from 19 experimental and observational studies on 26 species, for a total of 34 cases (study and species combinations). Literature search terms included "non-structural carbohydrates", "water potential", "tree mortality", and "drought". Our synthesis was not limited to an objective literature search, as we sought to include all published data that fit our criteria for inclusion. Criteria for inclusion were that studies included data on: 1) tree mortality from drought; 2) NSC concentrations of at least one tissue, and/or PLC of aboveground woody tissue, either measured directly, or estimated from plant water potential (Ψ_p) measured at mortality, or modeled from hydraulic conductance[48,49] (Supplementary Methods); and 3) that data were either: a)

322 concurrently collected for trees that died (either at or near mortality) and from trees that either
323 survived the drought or were in a paired control treatment, and/or: b) available prior to drought
324 or pre-treatment from the same trees that later died. We obtained data from each study directly
325 from contributors. Details on the specific studies synthesized can be found in Supplementary
326 Table 1. Determination of the point of mortality in dying trees was defined in each original
327 study, as detailed in Supplementary Table 3, and we relied on data contributors to provide the
328 appropriate data for at- (or near-) mortality assessments.

329 NSC measurements are methodologically challenging and comparisons of absolute
330 concentrations can be problematic across studies due to issues of standards, NSC technique, and
331 lab protocol disagreement[50,51]. However, relative differences (treatment vs. control and changes
332 over time assessed with the same technique in the same laboratory) provide robust estimates of
333 NSC dynamics within studies[50,51]. We limited all statistical analyses of absolute NSC data to
334 within each case (detailed below) and we only present relative differences in NSC in figures.
335 For studies where data were concurrently available for trees that died and control or surviving
336 trees, we calculated a normalized NSC deviation from the difference between values at or near
337 mortality and those for control or surviving trees divided by the control or surviving tree value.
338 For studies where data were available prior to the drought for the same trees that later died (or
339 seedlings in the same treatment harvested at measurement), normalized values were also
340 calculated as the difference between values at or near mortality and initial pre-treatment or pre-
341 drought values divided by the initial or pre-drought values. In both cases, normalized values
342 were expressed as a percent. For comparison of time series trends in NSC, we also calculated
343 normalized, proportional NSCs in trees that died by scaling values relative to the maximum
344 value in each time series, which was defined as a normalized value of 1. When possible,

345 normalizations were calculated for individual trees, and specifically for each tissue sampled. For
346 studies 3 and 9 (Supplementary Table 1), only means and standard errors for species and tissues
347 were available, so normalized values were calculated from these metrics.
348 Note that all types of data were not available for all cases in our synthesis. Among the 34
349 cases in our dataset, PLC measured at mortality was available for nine cases (eight species), PLC
350 was estimated in five cases (two species), NSC deviation from control/surviving trees at
351 mortality was available for 31 cases (24 species), and percent change in NSC was available for
352 28 cases (22 species). Sample sizes for PLC and NSC data are available in Supplementary
353 Tables 4 and 5. Because PLC values are already normalized to the maximum conductivity per
354 sample, no further normalization was conducted with these data. We also acknowledge that
355 direct measurements of PLC and generation of hydraulic vulnerability curves can be challenging,
356 and that method artifacts can effect results[52,53]. Although the majority of hydraulic data we
357 report were collected following recommended practices (Supplementary Methods,
358 Supplementary Table 5), we cannot rule out the possibility of such artifacts influencing our data.
359 To compare physiological mortality indicators to tree species traits, we obtained trait data
360 for the species in this synthesis from a variety of sources. We investigated the relationships
361 between physiology at mortality and traits related to drought tolerance that are easily measured
362 and widely available, such as wood density and specific leaf area (SLA). We also included
363 hydraulic traits more directly related to drought tolerance that were measured with more-
364 challenging hydraulic vulnerability curve methods. Wood density data for most species were
365 obtained from the Global Wood Density database[54,55] available through the DRYAD digital
366 repository (www.datadryad.org). We obtained SLA data from the TRY database (www.try-
367 db.org)[56-58], for nearly all non-tropical species. We calculated species means for SLA from all

368 data available for each species of interest for our analysis. Data for *Acer pseudoplatanus* were
369 available from the mortality study population[16]. For *Callitris rhomboidea* and *Eucalyptus*
370 *smithii*, SLA data were not available. Additional sources of wood density data are detailed in
371 Supplementary Methods. Hydraulic trait data for the stem water potential at 50 PLC (Ψ_{50}) and
372 hydraulic safety margin (Ψ_{50} – minimum Ψ)[24,27], were obtained from multiple sources
373 (Supplementary Table 5, Supplementary Methods). Data for the embolism entry point (Ψ_e) were
374 not available in the literature, so we calculated Ψ_e from relevant hydraulic vulnerability curve for
375 each case by applying a Weibull fit to the data, and determining the x-intercept of the line
376 tangent to Ψ_{50} (Supplementary Table 5)[27,59]. Hydraulic trait data were unavailable for
377 *Eucalyptus radiata*, *Eucalyptus smithii*, and *Nothofagus nitida*. No trait data were available for
378 the tropical angiosperm species from study 7 (Supplementary Table 1) for any of the traits we
379 assessed[31].

380 The majority of datasets generated and analyzed during the current study are available
381 from the corresponding author on reasonable request. Trait data obtained for the current study
382 from the TRY Database were used under license and as restrictions apply to the availability of
383 these data, these are not available from the corresponding author, but can be requested from the
384 TRY Database (www.try-db.org).

385

386 **Statistical Analyses.** We used MATLAB R2012a (The Mathworks, Inc., Natick, MA, USA) for
387 all statistical analyses, with $\alpha = 0.05$. All NSC and PLC comparisons were performed using
388 ANOVA or Student's t-test individually for each case, between dead (or dying) and
389 control/surviving trees or between post-drought dead and corresponding pre-drought values, with
390 tissue as a factor for analysis of NSC. Since our NSC normalization could affect tissue

comparisons within the same case, these analyses were performed on non-normalized NSC data to maintain the correct ratio among tissues, a conservative approach. Our within-individual case analysis on relative differences in non-normalized NSC does not bear the risk of error introduced by different NSC techniques or labs, or uncertainty in standards for determining absolute NSC, and furthermore the inferences are based on large effect sizes compared to possible measurement error[50,51]. In experimental cases that included temperature or CO_2 concentration treatments in addition to drought, we included these factors in ANOVA tests to determine if PLC and NSC should be pooled or split among levels of these factors (Supplementary Table 1). For NSC, these analyses also included tissue as a factor. Functional trait relationships with normalized NSC data at mortality were analyzed with linear regression. Cook's distance was calculated for all points in significant linear regressions, and a value greater than three times the mean of the Cook's distance was used to identify outliers for exclusion.

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Competing financial interests. The authors declare they have no competing financial interests.

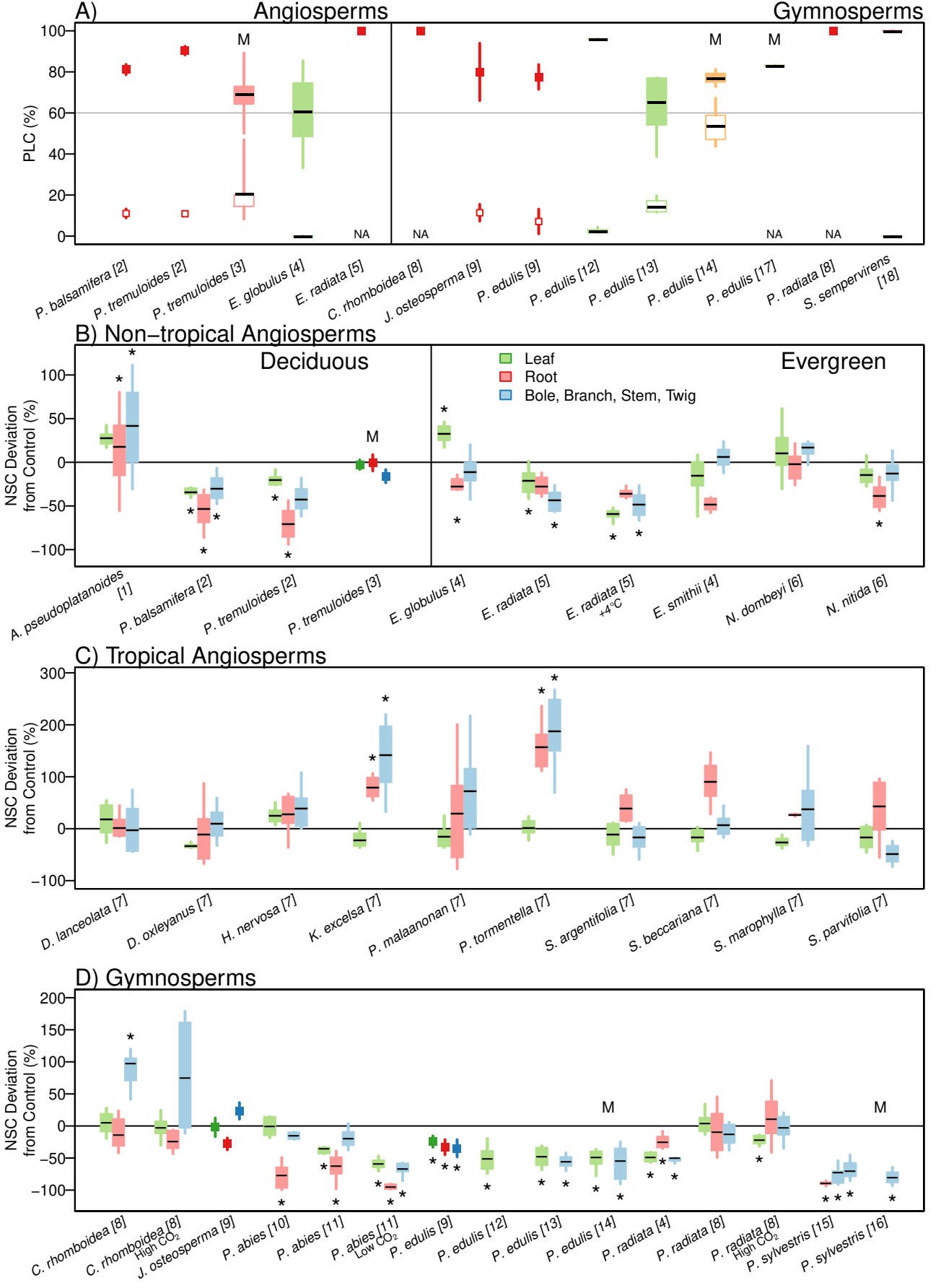
Figure Legends

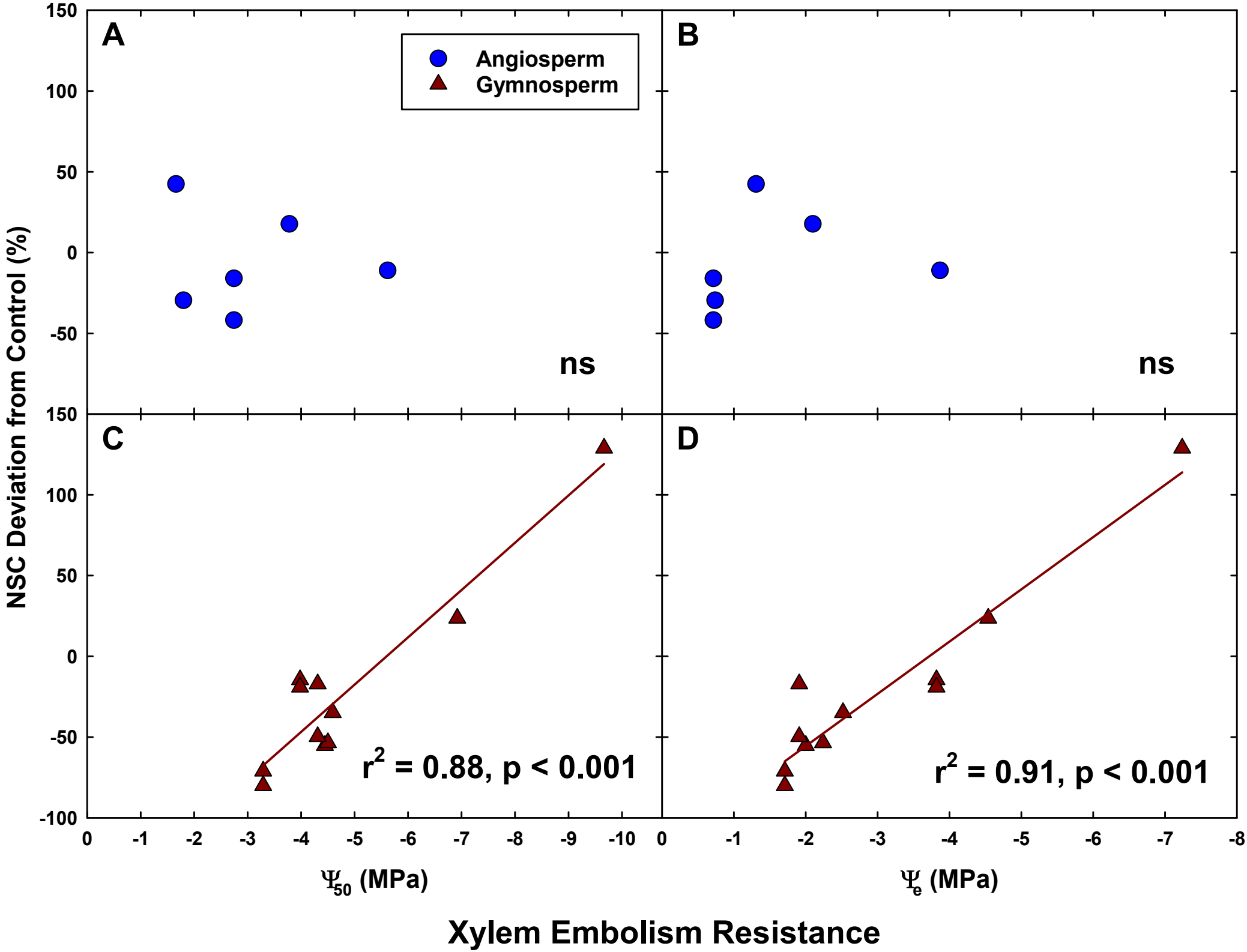
Figure 1. Physiological responses at, or prior to, mortality from drought for multiple tree species. Percent loss of hydraulic conductivity (PLC) for ambient moisture, control, or surviving trees and concurrently at mortality from drought is shown for both angiosperm and gymnosperm species (A). PLC was either measured directly (red) for control (open symbols) and dying (closed symbols) trees or estimated from either water potential with a hydraulic vulnerability curve (green) for control (open) and dying (closed) trees, or modeled from hydraulic conductance (orange) for control (open), and dying (closed) trees. An "NA" indicates that control PLC data were not available. In all panels for cases where individual data were available, boxes indicate the 25% and 75% quartiles, whiskers indicate the extent of data, and black bars indicate the mean. For cases where only means and a measure of variability were

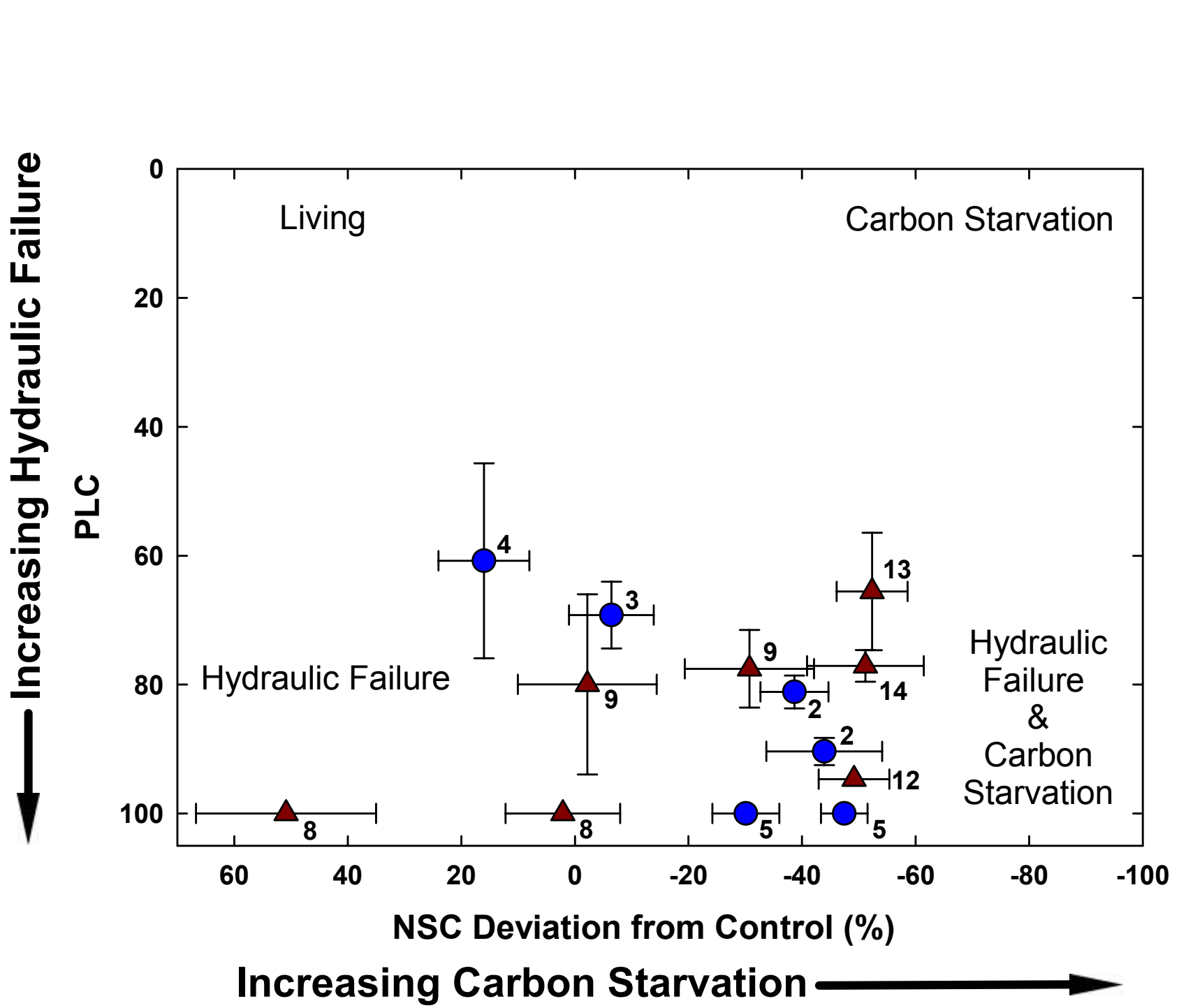
609 available, means are indicated with squares and error bars are one standard error. For each case
610 in A where control and dying tree data were available, PLC was significantly higher at mortality
611 than for controls concurrently ($p < 0.05$, Student's t-test). A potential threshold for hydraulic
612 failure is indicated by a line at 60%. Non-structural carbohydrate concentration (NSC) at
613 mortality, normalized as the percent deviation from concurrent measurements of ambient,
614 control, or unaffected trees in each study for each plant tissue, is shown for deciduous and
615 evergreen non-tropical angiosperm (B), evergreen tropical angiosperm (C), and evergreen
616 gymnosperm (D) species. Significant differences for each tree tissue between drought trees at
617 mortality (black bar or square) and ambient, control, or surviving trees (0% line) are indicated
618 with an asterisk ($p < 0.05$, ANOVA). Note that the absolute values in NSC concentration used in
619 statistical analysis varied for each tissue in each case, such that distances between the mean and
620 zero in B-D are not a consistent indicator of statistical significance among cases or for tissues
621 within a case. An "M" indicates data from a study on mature trees; all other data are from studies
622 of seedlings, saplings, and small trees (Supplementary Tables 1, 2). Numbers after species
623 names in all panels designate original studies (Supplementary Table 1). Sample size for all data
624 analyzed for Figure 1 are shown in Supplementary Table 4.
625
626 **Figure 2.** The relationship between the tree hydraulic traits related to xylem embolism resistance
627 and normalized non-structural carbohydrates (NSC) in aboveground woody tissue at, or prior to,
628 mortality from drought, expressed as a deviation from concurrent measurements of surviving
629 control trees, for angiosperm (blue circles; A, B) and gymnosperm (red triangles; C, D) species.
630 Tree hydraulic traits related to embolism resistance are the water potential at 50% loss of
631 hydraulic conductivity (Ψ_{50}; A, C) and point of xylem embolism entry (Ψ_e; B, D). Xylem

embolism resistance increases to the right. NSC data shown are means for aboveground woody tissue (bole, branch, stem, or twig), normalized as a percent of ambient moisture, control, or surviving trees in each case. Significant linear regressions were found for gymnosperms (C, D) but not angiosperms (A, B). Values for *Callitris rhomboidea* (upper right in C, D) were identified as potential outliers, but both relationships remain statistically significant ($p < 0.01$, linear regression) for the remaining data with the removal of these points (Supplementary Methods).

Figure 3. Physiological responses associated with hydraulic failure and carbon starvation, as defined by PLC and NSC deviation from control in 13 cases (study × species combinations) for which both data were available. Among these cases, trees either died with high PLC and low NSCs (8/13 cases), or with only high PLC (5/13 cases). NSC data are means for all sampled tissues available for each case and normalized as a percent of difference from concurrent measurements of control trees. PLC data are those shown in Figure 1A. NSC and PLC at mortality for angiosperm (blue circles) and gymnosperm (red triangles) species are shown relative to hypothesized drought mortality mechanisms. Numbers near points designate original studies (Supplementary Table 1). Error bars are one standard error.


A)
Angiosperms
Gymnosperms
PLC (%)
M
NA
P. balsamifera [2]
P. tremuloides [2]
P. tremuloides [3]
E. globulus [4]
E. radiata [5]
C. rhomboidea [8]
J. osteosperma [9]
P. edulis [9]
P. edulis [12]
P. edulis [13]
P. edulis [14]
P. edulis [17]
P. radiata [8]
S. sempervirens [18]
B) Non−tropical Angiosperms
Deciduous
Evergreen
Leaf
Root
Bole, Branch, Stem, Twig
NSC Deviation from Control (%)
A. pseudoplatanoides [1]
P. balsamifera [2]
P. tremuloides [2]
P. tremuloides [3]
E. globulus [4]
E. radiata [5]
E. radiata [5] +4°C
E. smithii [4]
N. dombeyi [6]
N. nitida [6]
C) Tropical Angiosperms
D. lanceolata [7]
D. oxleyanus [7]
H. nervosa [7]
K. excelsa [7]
P. malaanonan [7]
P. tormentella [7]
S. argentifolia [7]
S. beccariana [7]
S. marophylla [7]
S. parvifolia [7]
D) Gymnosperms
C. rhomboidea [8]
C. rhomboidea [8] High CO2
J. osteosperma [9]
P. abies [10]
P. abies [11]
P. abies [11] Low CO2
P. edulis [9]
P. edulis [12]
P. edulis [13]
P. edulis [14]
P. radiata [4]
P. radiata [8]
P. radiata [8] High CO2
P. sylvestris [15]
P. sylvestris [16]


A
B
C
D
Angiosperm
Gymnosperm
ns
ns
r^2 = 0.88, p < 0.001
r^2 = 0.91, p < 0.001
NSC Deviation from Control (%)
Ψ_{50} (MPa)
Ψ_e (MPa)
Xylem Embolism Resistance


Increasing Hydraulic Failure
PLC
0
20
40
60
80
100
Living
Carbon Starvation
Hydraulic Failure
Hydraulic Failure & Carbon Starvation
4
3
9
8
8
9
13
14
2
2
12
5
5
60
40
20
0
-20
-40
-60
-80
-100
NSC Deviation from Control (%)
Increasing Carbon Starvation