

Early growth, development and allometry of glyphosate-resistant and susceptible *Amaranthus palmeri* in response to current and elevated temperature and CO₂

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Abstract

This study aimed to evaluate the main factor(s) influencing *Amaranthus palmeri* (Palmer amaranth) biotypes growth, development, and what parameters were affected. Seeds of two glyphosate resistant (GA2017 and GA2020) and one susceptible (GA2005) Palmer amaranth biotypes were collected in Georgia, US during those growing seasons. These seed were used to grow plants and then evaluate response to scenarios of normal and elevated CO₂ (410± 25 ppm and 750± 25 ppm) and temperature (23/33°C and 26/36°C). CO₂ was the main factor affecting Palmer amaranth growth and differences among biotypes were also observed. Plants grown under elevated CO₂ showed increases in height (cm), leaf area (cm²), stem dry matter (g) and plant volume (m³) while among susceptible and resistant biotypes, GA2005 had greater number of leaves, height (cm) and plant volume (m³) compared to glyphosate-resistant biotypes. Shoot to root ratio of the biotypes was isomeric, despite the allometry observed at 14 and 28 days after transplant (DAT) with respect to shoot development. The data indicate that Palmer amaranth may perceive and adapt its above-ground development in response to changes in the surrounding environment. These findings have important implications for the management of this weed species under climate change scenarios, since it is estimated that CO₂ levels and temperatures will continue to rise throughout the century.

Introduction

Climate change is one of the most significant environmental challenges facing the world today, and it is already having a profound impact on ecosystems and agriculture around the globe. Elevated temperature, rising carbon dioxide (CO₂), salinity, and drought affect plant growth and are a growing threat to sustainable agriculture and can lead to changes in the plant community structure and composition [1]. According to IPCC [2], the rise in global average temperature tends to obscure the notable temperature differences between land and sea, and between high and low latitudes. In high latitudes, there is a high likelihood of precipitation increases, while in most of the tropics and subtropical land regions, precipitation decreases are expected. Carbon dioxide (CO₂) is known as a primary contributor to the greenhouse effect and subsequent temperature increase, and it is also a vital component for plant photosynthesis. While atmospheric CO₂ levels rise, photosynthesis rates increase mainly in C3 plants, leading to a phenomenon known as CO₂ fertilization [3]. CO₂ fertilization could counterbalance the effects of temperature increase, particularly in regions where plant growth is constrained by water availability [4]. This may alter the competitive balance between species that differ in their photosynthetic pathways, rooting depths, and other effects [4].

Because of environmental changes, plant communities can be affected by shifts in the geographic range of plant species and face changes in their allometric growth. First, in some regions, warmer temperatures have allowed plants to move to higher elevations or latitudes where they previously could not survive [5]. An increase of 1°C in temperature can move ecological zones by 160 km, and in the northern hemisphere,

increases up to 4°C will move species up to 500 km^[6]. At the same time, other plant species could reduce in abundance or disappear altogether due to changes in their habitat conditions^[7]. Overall, the capacity of various species to cope with climate change will mainly rely on their ability to follow the changing climate by migrating to new areas or adjusting their physiology to acclimate to the new surroundings^[8].

Allometry is the scientific investigation of how biological organisms grow in proportion to each other^[9]. This concept is commonly used to analyze various organs' size, shape, and function and estimate different metabolic parameters. The idea of allometry was initially proposed to explain how the relative growth rate of organs is linked to body size through a power law function $Y = aM^\beta$, where Y is a morphological or physiological trait that can be predicted by the individual mass M , a constant a and the allometric exponent β ^[10]. Allometric growth is based on the allocation of species-specific biomass and is primarily governed by genetics^[11]. Additionally, allometric growth can be influenced by phenotypic traits. Variations in the size of plants of the same species can contribute to differences in phenotypic traits, and are not only environmental resources alone^{[9][12]}. Thus, allometric relationships can be used to forecast plant growth and ecosystem processes, and serve as a measure of plant plasticity in response to changing environmental conditions^[13].

In the context of the climate change, herbicide-resistant weeds poses a significant threat as they spread across agricultural production regions. Palmer amaranth's (*Amaranthus palmeri*) ability to adjust to environmental variations is one reason for its successful introduction and rapid distribution. This weed exhibits a remarkable level of plasticity to various environmental factors, including light, temperature, water availability, and human management practices^[14]. Palmer amaranth is a dioecious C4 summer annual native to the Sonoran Desert regions of northern Mexico and the southwestern United States^[15]. It began spreading beyond its original habitat in the early 1900s because of human-mediated seed dispersal and the creation of new habitats through agricultural expansion^{[14][16]}.

Palmer amaranth exhibits wind pollination and a prolonged germination period that extends throughout the growing season^[16], with optimal germination and dry matter production occurring at day and night temperatures of 35/30°C^{[17][18]}. The emergence of Palmer amaranth can be influenced by management practices such as tillage and herbicides, and could potentially lead to population shifts extensively reported in the literature, such as reported in *Bassia scoparia*^[19]; horseweed (*Conyza canadensis*)^[20] and common waterhemp (*Amaranthus tuberculatus*)^[21]. Under drought stress, Palmer amaranth survived and produced at least 14,000 seeds plant⁻¹^[22]. Palmer amaranth seeds grown under limited water conditions demonstrated increased weight, reduced dormancy, and high germination rates^[23]. In addition, the sex dimorphism and flowering pattern of Palmer amaranth can be influenced by a range of growing conditions and management practices^{[24][25][26][27]}.

Furthermore, the selection pressure imposed by the recurrent use of herbicides with the same mode of action (MoA) resulted in the evolution of herbicide-resistant weeds. Palmer amaranth is one species that has evolved resistance to multiple modes of action^[14]. Following the HRAC^[28] mode of action

classification, these include inhibitors of the acetolactate synthase (ALS – 2), microtubule assembly (3), auxin mimics (4), PSII inhibitors (5), enolpyruvyl shikimate phosphate synthase (EPSP – 9), glutamine synthetase (10), protoporphyrinogen oxidase (PPO – 14), very long-chain fatty acid synthesis (15), and hydroxyphenyl pyruvate dioxygenase (27) were related to herbicide-resistance in Palmer amaranth populations worldwide^[29]. Models of the evolution of resistance often assume that there is a fitness cost associated with resistance as a result of the genetic variability found within populations. This assumption was confirmed for triazine-resistant weeds with the Gly-264 psbA gene^[30]. However, no resistance cost was detected in glyphosate-resistant Palmer amaranth^[31]. Fitness costs are not always observed in herbicide resistant weed populations^[32]. Furthermore, in cases where fitness costs are present, they have been demonstrated to be influenced by the genetic background of the population^[33]. The fitness cost of an adaptive allele can manifest as a direct cost due to the pleiotropic effect of the resistance allele, and via ecological trade-offs in traits such as plant growth, development, and resource partitioning^[34], height, and flowering time^[35]. These trade-offs can ultimately lead to a direct fitness cost in an environment with limited resources^[32].

The rise of atmospheric CO₂ levels and higher temperatures caused by global climate change is expected to expand Palmer amaranth range, increasing the challenge to manage these populations and its adverse impacts on the agriculture practices^[36]. We hypothesized that the Palmer amaranth biotypes will respond differently to CO₂ and temperatures variations, and its allometric shoot to root relationship will be affected due to its plasticity. Thus, this study was conducted to evaluate the growth and development of herbicide-resistant and susceptible Palmer amaranth under variable CO₂ and temperature regimes.

Materials and Methods

Dose-response assessment. Three biotypes of Palmer amaranth were collected in Georgia, US, in 2005 (GA2005), 2017 (GA2017), and 2020 (GA2020) during those growing seasons. Seed were and then stored under dry and cold conditions until use^[37]. These biotypes were submitted to a dose-response screening to determine the ED50 of glyphosate, flumioxazin, atrazine, and imazapic (data not shown). These herbicides were chosen based on their use in crops grown in Georgia, US. The experiment was repeated three times in a complete randomized design, and the methodology adapted^[38] to include doses ranging from 1/16X to 16X times the recommended dose for all herbicides tested. The resistance was confirmed to glyphosate, with the following ED50: GA2005 = 272 a.e. g/ha, GA2017 = 1180 a.e. g/ha, and GA2020 = 3603 a.e. g/ha, based on the recommended dose of 832 g a.e. g/ha. Among the biotypes tested, there is one susceptible (GA2000) and two glyphosate-resistant (GA2017 and GA2020).

Plant material. The seeds of Palmer amaranth GA2005, GA2017, and GA2020 were sown in trays filled with potting media (Pro-Mix®, BX, Quebec, Canada) and allowed to grow in a greenhouse (daily temp and light conditions, does not have to be exact.) until they reached 8 to 10 cm tall. Irrigation was scheduled twice daily, and supplemental light delivering 600 µmol/m²/s was used. After achieving the desired height (8 to 10 cm), the seedlings were transplanted into a 5-L container filled with potting media (Pro-Mix®, BX,

Quebec, Canada). Fertilizer Osmocote Blend, 18-5-12 (ICL® Specialty Fertilizers, Holland) was added, and the containers were placed inside walk-in growth chambers (model CG72, Conviron®, Winnipeg, Canada) located at the Georgia Envirotron, Griffin Campus, GA.

Study design. Replicated randomized complete block design. The factors analyzed were a combination of temperature and CO₂: 1 – 23/33C, 410 ± 25 ppm; 2- 23/33C, 750± 25 ppm; 3- 26/36C, 410± 25 ppm and 4- 26/36C, 750± 25 ppm, performed in 2021 and 2022. Three replications per block were used, and harvests were performed, beginning at 14 DAT (days after transplant), 21 DAT, and 28 DAT. There were 216 plants in total, combining the two years of experiment.

Growth chambers setup: The growth chambers were scheduled to operate under four different scenarios. They were low/high temperatures (23/33 and 26/36 C; night/day) and low and high CO₂ concentrations (410 and 750 ppm) combined. Lights were set to deliver 700 µmol/m²/s on a 16/8 h (day/night) photoperiod. The temperatures and CO₂ levels evaluated in this study were derived from projected future scenarios outlined by the Intergovernmental Panel on Climate Change ^[2].

Data collection (growth parameters). At each harvest date, the height (cm), widest horizontal and vertical diameters (cm), stem diameter (mm), number of leaves, leaf area (cm²), leaf dry matter (g), stem matter (g), root dry matter (g) and plant volume (cm³) were recorded. The plant volume is calculated considering horizontal plant diameters in the widest direction, at 90° and 180° to the widest direction ^[39].

For each plant, leaves, stems, and roots were separated. The number of leaves was counted, and the foliar area (cm²) measured using the LI-3100C area meter (LI-COR®, Lincoln, NE). Roots were hand washed carefully, and the plant parts were placed in separated paper bags. The samples were then placed in oven with forced air circulation (60 °C) until constant dry matter was achieved and then weighed to determine the final dry matter (g). Above-ground dry matter (stems and leaves) and root dry matter were further used to analyze plant allometry under the scenarios tested.

Data analysis. Table 1 displays the experimental factors and their levels. Preliminary univariate analyses were carried out to identify any non-normality and non-constant variance in each response variable. Corrective log or square-root transformations were applied as necessary. The resulting eight response variables were then analyzed jointly by fitting a multivariate analysis of variance model appropriate for the study design ^[40]. This model incorporated main effects and all interactions among the experimental factors, with the main effects of year, the blocking factor, and all interactions involving year treated as random. The model was simultaneously fitted to all eight responses, assuming normal errors that were independent across distinct experimental units but with an unstructured 8 by 8 covariance matrix for the vector-valued response on each unit.

The interactions and main effects from the multivariate model were of primary interest, but secondary univariate analyses were also conducted to detect significant main effects and interactions for individual response variables. Due to the repeated testing of these effects on eight responses, a Bonferroni

correction was applied to all tests conducted in the univariate analyses. The significance levels for these tests were all divided by eight. Significant interactions were evaluated via interaction plots. For factors that were not involved in significant interactions but had significant main effects, pairwise contrasts were tested. In the case of DAT, all pairwise contrasts were tested with Tukey HSD-corrected p-values, and for biotype, pairwise contrasts with the susceptible biotype were tested with a Dunnett correction. No multiplicity correction was necessary for two-level factors CO₂ and temperature. All multiplicity-adjusted p-values were compared to the Bonferroni-corrected significance level of 0.0062 to determine statistical significance. The analyses were done in R using the nlme^[41], lme4^[42], lmerTest^[43], and car^[44] packages. Large sample Wald tests are reported for the multivariate analysis. Kenward-Roger adjusted approximate F tests are reported for univariate analyses.

Next, the allometric relationships between shoots (leaves plus stem) (y) and roots (x) dry matter (g) were tested for all biotypes and every treatment factor. Linear regression aims to minimize the distance between the observed values and the regression line in the y-direction. As such, it is well-suited for predicting the value of one variable based on another variable. However, since measurement errors can occur in x and y, minimizing the sum of squared deviations in the y-direction is not ideal. In contrast, the standardized major axis (SMA) estimation method determines the minimum distance between the observed values and the regression line while considering the deviations in both x and y directions, as well as the slope of the variables. This makes SMA more appropriate for estimating the slope of the allometric scaling equation. The SMA regression was utilized to establish the correlation between log-transformed shoot and root dry matter. The allometric relationship was represented by the equation $\log y = \log b + a * \log x$, where 'a' denotes the scaling exponent (slope) and 'b' represents the allometric coefficient or "scaling factor" (y-intercept/elevation). The standardized major axis regression (SMA), also known as reduced major axis (RMA), was utilized to evaluate differences in shifts of the slope and elevation of slopes (y-intercept). The 'smatr' package^[45] in R was used to obtain the SMA slopes, intercepts, and its confidence interval (95%). The allometric analysis was used to mainly verify whether or not the biomass partitioning (shoot to root ratio) changes among biotypes under the treatment factors tested.

Permissions required

The authors collected GA2005 and GA2020 seeds used, and Dr. Stanley Culpepper, UGA Tifton, collected GA2017. All seeds were gathered from experimental fields at the University of Georgia.

Guidelines required

The collection of Palmer amaranth seed used in this study complies with the institutional guidelines.

Results

According to the multivariate model, the results indicated that CO₂ levels, biotype, and DAT (p<0.001) were significant among the treatment factors tested, whereas temperature did not show significant effects. No interaction among the treatment factors were observed (Table 2).

Palmer amaranth is assumed to be insensitive to higher CO₂ levels due to the mechanism of CO₂ accumulation on the leaves, resulting in high CO₂ concentrations near Rubisco. However, as observed, not only the photosynthesis pathway can be used to evaluate plant responses to CO₂, being necessary to consider the overall carbon assimilation, genetic response to stress, and metabolism. In addition, the response to CO₂ could be specie/specific.

After evaluating the global tests from the multivariate model, univariate analyses were conducted to understand how the treatment factors affect the response variables of height (cm), diameter (cm), number of leaves, leaf area (cm²), leaf, stem, roots dry matter (g) and plant volume (m³) (Table 3). Data related to DAT can be found in the supplementary information section.

CO₂ levels

The study revealed noteworthy primary effects of CO₂ on plant characteristics including mean plant height (cm), leaf area (cm²), stem dry matter (g) and plant volume (m³). Specifically, plants cultivated under 750 ppm displayed a 15.5% increase in height, a 10% increase in leaf area, an 18% increase in stem dry matter, and a 28.4% increase in volume compared to those grown under 410 ppm (Table 4).

It is worth examining the effect of CO₂ on the phenology of Palmer amaranth at the early stages of growth. Plants were transplanted at the 3 to 4 leaf stage and moved to the growth chambers. At the first harvest date (14 DAT), mean height (cm) and leaf area (cm²) were 46.3 cm and 1947 cm², respectively. Rapid growth during the seedling phase, which is the period of greatest herbicide sensitivity, was observed. This is an important observation since it has an implication on herbicide efficacy, affecting the timing for weed management.

Biotypes

GA2005 was taller, with 72.4 cm, while GA2017 and GA2020 was 59.2 cm and 62.6 cm, respectively. This represents a decrease of 18% and 15.5% in height for both resistant biotypes. The number of leaves for GA2005 was 217, representing an increase of 27% in comparison to both glyphosate-resistant biotypes. Additionally, the plant volume, which measures the plant's overall architecture, decreased by 35.6% (0.1298 m³) and 23.8% (0.1537 m³) for GA2017 and GA2020, respectively. The average volume for GA2005 was 0.2017 m³ (Table 5).

To evaluate the differences in biotype response (Table 5), the Dunnett-adjusted pairwise contrasts with GA2005 were conducted. GA2017 ($p < 0.0062$) exhibited statistically differences in plant height (cm) and volume (m³) compared to GA2005. While GA2020 also showed significance, it did not meet the significance threshold ($p\text{-value} = 0.0062$). These findings indicate variations among resistant biotypes, possibly linked to Palmer amaranth's populations plasticity and glyphosate resistance mechanism.

According to the results, comparing glyphosate-resistant and susceptible Palmer amaranth biotypes, different responses were observed in terms of plant development. The biotypes were collected from

different counties in the state of Georgia, US, as previously mentioned and it reflects the weed management programs adopted, their population genetics structure, as well as the local environmental characteristics. Because of that, the existence of Palmer amaranth ecotypes, varying on the morphological traits and between resistant biotypes can result make their management more challenging under climate change scenarios.

Allometry

To test the hypothesis of changes between shoot and root ratio among biotypes and across CO₂, temperature, and DAT, an allometric analysis was performed.

Biotypes and CO₂

Shoot to root biomass was positively correlated to CO₂ levels and biotypes tested ($P < 0.001$) (table 6). The SMA slopes for CO₂ of 410 ppm and 750 ppm were not significantly different to 1 ($P > 0.05$) for biotypes, indicating allometric growth.

Biotypes and DAT

Shoot to root biomass was positively correlated with DAT (table 7) for all biotypes tested (R^2 , $P < 0.001$). The SMA slopes for 14 DAT and 21 DAT were significantly different to 1 ($P < 0.05$) for biotypes, indicating allometric growth. Whereas at 28 DAT, all biotypes showed isometric growth $P > 0.05$. During 14 DAT and 21 DAT, plants invested more biomass on shoot development, with common slopes of 0.5186 and 0.7590, respectively.

Biotypes and temperature

Dry matter of shoot to root ratio was positively correlated for all biotypes at 23/33°C and 26/36°C and SMA slopes were not statistically different from 1 ($P > 0.05$), with an isometric growth under both temperatures (table 8). Overall, no differences among biotypes were detected and the treatment factors did not affect the allometric/isometric relationship on Palmer amaranth.

Discussion

This study aimed to investigate the early growth and development of both glyphosate resistant and susceptible Palmer amaranth biotypes in varying CO₂ and temperature conditions. Additionally, we explored the allometric relationships between the biotypes and the treatment factors, CO₂, temperature, as well as the DAT. These analyses can provide valuable insights into how biotypes adapt to various environmental stresses [9].

Height (cm), leaf area (cm²), stem dry matter and plant volume (m³) were the variables mostly impacted by the increase in CO₂. Plants can detect a change in atmospheric CO₂ levels mainly through tissues that are exposed to the open air, which are mostly limited to the plant's photosynthetic organs. The protective

layer covering these organs, known as the cuticle, restricts direct exposure of the guard cells of stomata and the mesophyll to changes in atmospheric CO₂^[46]. One of the hypotheses that explains why C4 plants responds to increases in CO₂ levels in a short term is related to their water use efficiency (WUE). For C4 plants, the water loss is costly for the carbon balance in the plant, so species tend to operate at a low transpiration rate (E) preventing hydraulic failure^[47]. In addition, under elevated CO₂, the WUE is explained by a decrease in 20% of stomatal conductance^[46].

There has been a suggestion that elevated CO₂ could enhance the WUE of C4 species by reducing their transpiration rate and boosting their CO₂ assimilation rate^[48]. Conversely, in C4 species, the benefits of increased CO₂ on photosynthesis could be particularly significant during times of drought. Because of how the C4 cycle operates, it is possible to correlate the increase in some above ground features and stem dry matter, observed in this study, under elevated CO₂ to improved water use.

Other studies reported no changes in plant height while aboveground biomass of winter wheat, a C3 plant, increased under 712 µmol mol⁻¹ of CO₂^{[48][49]}. Whereas for maize and sorghum, C4 plants, grown under well-watered conditions, plant height, leaf area, and biomass of leaf, stem and total above-ground were not affected by elevated CO₂ at 720 µmol mol⁻¹^[50]. The response to elevated CO₂ varies substantially more within C4 plants^[48]. Other studies showed an increase in biomass of C4 plants, leading to a conclusion that not only the photosynthetic mechanism can explain the response under elevated CO₂^[51]. In terms of leaf area, the increase observed could be related to cell expansion, due to the increased carbohydrate substrate availability^{[52][53][54][55]}.

Among biotypes, there were differences between the susceptible (GA2005) and the resistant's (GA2017 and GA2020) even though little is known about intraspecific differences. Height (cm), plant volume (m³) and number of leaves were significantly greater on the susceptible GA2005. Researchers have observed that herbicide-resistant plants display stunted growth or diminished growth rates, as well as altered leaf canopy shape, across different C4 species under actual levels of CO₂^{[56][57]}. However, under increased CO₂, temperature, and other environmental stressors, it remains unknown the specific mechanisms and how herbicide resistant and susceptible traits behave. What is known is that herbicide resistance mutations can sometimes modify the morphology, development, or phenology of weeds without directly affecting plant fitness^[58]. These alterations in traits can be attributed to changes in life history characteristics that arise due to subtle pleiotropic effects of resistance mutations or the coevolution of resistance with non-resistance traits^{[32][59][60][61][62]} in response to diverse selective pressures in agroecosystems. It means that under certain environmental conditions, changes in life history traits not always will be expressed. The genetic background of the populations from this study will be evaluate and available as a follow up of the present study.

The allometry analysis shows that besides the allometric growth observed at 14 and 28 DAT, the isomeric growth recorded demonstrate no differences in terms of carbon portioning among biotypes when

compared to CO₂, temperature, and DAT. In some studies, the below growth can be enhanced by CO₂^[62]^[63], but neither root biomass nor shoot to root ratios were affected by CO₂ in this study. Even though biotypes demonstrated differences related to above ground characteristics, shoot to root ratio was not affected by whether glyphosate resistance is involved or not.

In conclusion, this study investigated the early growth and development of glyphosate resistant and susceptible Palmer amaranth biotypes under varying CO₂ and temperature conditions. The results showed that CO₂ had the most significant impact on plant height, leaf area, stem dry matter, and plant volume, with C4 plants exhibiting a response in their water use efficiency. There were also differences between the susceptible and resistant biotypes, with the former showing greater height, plant volume, and number of leaves. Nevertheless, it is crucial to note that elevated CO₂ levels can lead to a shorter seedling phase, reducing weed susceptibility to herbicides. However, the specific mechanisms of how herbicide resistance and susceptibility traits behave under different environmental stressors remain unknown. Allometry analysis showed no differences in terms of carbon partitioning among biotypes when compared to CO₂, temperature, and DAT. The findings of this study provide valuable insights into how biotypes adapt to various environmental stresses and can provide background information for future studies exploring the weed population dynamics under environmental changes.

Declarations

Author contributions

J.S.R. designed, performed experiments, analyzed data, and prepared the manuscript; T.G. designed and supervised experiments; J.S.R. and S.B. performed experiments, evaluated and collected data; J.S.R., T.G. and V.T. designed experiments; J.S.R., D.S. and T.G. wrote the paper; S.D. and D.H. wrote code, ran the model, and analyzed output data; J.S.R., S.D. and D.H analyzed data and proofread the paper.

Data availability statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Additional Information

Competing Interests Statement

The author(s) declare no competing interests.

References

1. Zandalinas, S.I., et al. The impact of multifactorial stress combination on plant growth and survival. *New Phytol.* **230**, 1034-1048; doi.org/10.1111/nph.17232 (2021).

2. IPCC, Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3–33 (2022).
3. Still, C. J., Berry, J. A., Collatz, G. J., & Defries, R. S. Global distribution of C3 and C4 vegetation: Carbon cycle implications. *Global Biogeochemical Cycles* **17**, 6-1-6-14; doi.org/10.1029/2001GB001807 (2003).
4. Haverd, V., et al. Higher than expected CO2 fertilization inferred from leaf to global observations. *Glob Change Biol.* **26**, 2390– 2402; doi.org/10.1111/gcb.14950 (2020).
5. Hoegh-Guldberg, O., et al. Impacts of 1.5°C Global Warming on Natural and Human Systems. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S.
6. Thuiller, W. Climate change and the ecologist. *Nature* **448**, 550–552; doi.org/10.1038/448550a (2007).
7. Bellard, C., et al. Vulnerability of biodiversity hotspots to global change. *Global Ecology and Biogeography* **23**, 1376-1386; doi.org/10.1111/geb.12228 (2014).
8. Valiente-Banuet, A., et al. Beyond species loss: the extinction of ecological interactions in a changing world. *Funct Ecol.* **29**, 299-307; doi.org/10.1111/1365-2435.12356 (2015).
9. Weiner, J. Allocation, plasticity and allometry in plants. *Perspectives in Plant Ecology, Evolution and Systematics* **6**, 207-215; doi.org/10.1078/1433-8319-00083 (2004).
10. Huxley, J. Constant Differential Growth-Ratios and their Significance. *Nature* **114**, 895–896; doi.org/10.1038/114895a0 (1924).
11. Paul, K.I., et al. Testing the generality of above-ground biomass allometry across plant functional types at the continent scale. *Global Change Biology* **22**, 2106-2124; doi.org/10.1111/gcb.13201 (2015).
12. Vasseur, F., Violle, C., Enquist, B J., & Vile, D. Genetic variability and plasticity of plant allometry. *Functional Ecology* **00**, 1– 11; doi.org/10.1111/1365-2435.14281 (2023).
13. Packard, G.C. Multiplicative by nature: Why logarithmic transformation is necessary in allometry. *Journal of Theoretical Biology* **257**, 519–521; 10.1002/jez.b.22570 (2009).
14. Roberts, J. & Florentine, S. A review of the biology, distribution patterns and management of the invasive species *Amaranthus palmeri* S. Watson (Palmer amaranth): Current and future management challenges. *Weed Research* **62**, 113– 122; doi.org/10.1111/wre.12520 (2022).
15. Sauer, J.D. Recent migration and evolution of the dioecious amaranths. *Evolution* **11**, 11–31; doi.org/10.2307/2405808 (1957).

16. Ward, S.M. et al. Palmer Amaranth (*Amaranthus palmeri*): A Review. *Weed Technology* **27**, 12-27; 10.1614/WT-D-12-00113.1 (2013).
17. Jha, P., Norsworthy, J., Riley, M., & Bridges, W. Annual Changes in Temperature and Light Requirements for Germination of Palmer Amaranth (*Amaranthus palmeri*) Seeds Retrieved from Soil. *Weed Sci.* **58**, 426-432; 10.1614/WS-D-09-00038.1 (2010).
18. Guo, P.G. & Al-Khatib, L. Temperature effects on germination and growth of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*). *Weed Sci.* **51**, 869–875; 10.1614/P2002-127 (2003).
19. Sbatella, G. M & Wilson, R. G. Isoxaflutole shifts Kochia (*Kochia scoparia*) populations in continuous corn. *Weed Technol.* **24**, 392–396; 10.1614/WT-D-09-00023.1 (2010).
20. Buhler, D.D. & Owen, M.D.K. Emergence and survival of horseweed (*Conyza canadensis*). *Weed Sci* **45**, 98–101; 10.1017/S0043174500092535 (1997).
21. Smith, D.A. & Hallett, S.G. Variable response of common waterhemp (*Amaranthus rudis*) populations and individuals to glyphosate. *Weed Tech* **20**, 466–471; 10.1614/WT-05-068R1.1 (2006).
22. Chahal, P. S., Irmak, S., Jugulam, M., & Jhala, A. J. Evaluating effect of degree of water stress on growth and fecundity of Palmer amaranth (*Amaranthus palmeri*) using soil moisture sensors. *Weed Sci.* **66**, 738–745; 0.1017/wsc.2018.47 (2018).
23. Matzrafi, M., Osipitan, O. A., Ohadi, S. & Mesgaran, M. B. Under pressure: maternal effects promote drought tolerance in progeny seed of Palmer amaranth (*Amaranthus palmeri*). *Weed Sci.* **69**, 31–38; doi.org/10.1017/wsc.2020.75 (2021).
24. Liu, M., Korpelainen & Li, C. Sexual differences and sex ratios of dioecious plants under stressful environments. *Journal of Plant Ecology* **14**, 920-933; doi.org/10.1093/jpe/rtab038 (2021).
25. Mesgaran, M.B., Matzrafi, M. & Ohadi, S. Sex dimorphism in dioecious Palmer amaranth (*Amaranthus palmeri*) in response to water stress. *Planta* **254**, 17; 10.1007/s00425-021-03664-7 (2021).
26. Rumpa, M. M., Krausz, R. F., Gibson, D. J., & Gage, K. L. Effect of PPO-inhibiting herbicides on the growth and sex ratio of a dioecious weed species *Amaranthus palmeri* (Palmer Amaranth). *Agronomy* **9**, 275; doi.org/10.3390/agronomy9060275 (2019).
27. HRAC- Herbicide Resistance Action Committee. <https://hracglobal.com> (2022).
28. Korres, N. E., Norsworthy, J. K., FitzSimons, T., Roberts, T. L., & Oosterhuis, D. M. Differential response of Palmer Amaranth (*Amaranthus palmeri*) gender to abiotic stress. *Weed Sci.* **65**, 213–227; doi.org/10.1017/wsc.2016.34 (2017).
29. Heap, I. The International Herbicide-Resistant Weed Database. Online. Wednesday, March 8, 2023. Available at www.weedscience.org
30. Gronwald, JW (1994) Resistance to photosystem II inhibiting herbicides. Pages 27–60 in Powles SB, Holtum JAM, eds. *Herbicide Resistance in Plants: Biology and Biochemistry*. Boca Raton, FL: CRC Press
31. Giacomini, D., Westra, P., Ward, S.M. Impact of genetic background in fitness cost studies: an example from glyphosate-resistant Palmer amaranth. *Weed Sci.* **62**, 29–37; doi.org/10.1614/WS-D-13-00066.1

- (2014).
32. Délye, C., Jasieniuk, M., & Le Corre, V. Deciphering the evolution of herbicide resistance in weeds. *Trends Genet.* **29**, 649–658; 10.1016/j.tig.2013.06.001 (2013).
 33. Vila-Aiub, M.M. Fitness of Herbicide-Resistant Weeds: Current Knowledge and Implications for Management. *Plants*, **8**, 469; doi.org/10.3390/plants8110469 (2019).
 34. Comont, D., et al. Alterations in Life-History Associated With Non-target-site Herbicide Resistance in *Alopecurus myosuroides*. *Front Plant Sci.* **10**, 837; 10.3389/fpls.2019.00837 (2019).
 35. Roux, F., Matejcek, A., & Reboud, X. Response of *Arabidopsis thaliana* to 22 ALS inhibitors: baseline toxicity and cross-resistance of *csr1-1* and *csr1-2* resistant mutants. *Weed Res.* **45**, 220–227; 10.1111/j.1365-3180.2005.00450.x (2005).
 36. Kistner, E.J. & Hatfield, J.L. (2018) Potential geographic distribution of Palmer amaranth under current and future climates. *Agricultural and Environmental Letters* **3**, 170044; doi.org/10.2134/ael2017.12.0044 (2018).
 37. Webster, T.M. & Grey, T.L. Glyphosate-resistant Palmer amaranth morphology, growth, and seed production in Georgia. *Weed Sci* **63**:264-272; 10.1614/WS-D-14-00051.1 (2015).
 38. Culpepper, A.S., et al. Glyphosate-Resistant Palmer Amaranth (*Amaranthus palmeri*) Confirmed in Georgia. *Weed Science*, **54**, 620-626; 10.1614/WS-06-001R.1 (2006).
 39. Horak, M.J. & Loughin, T.M. Growth Analysis of Four *Amaranthus* Species. *Weed Sci.* **48**, 347-355; 10.1614/0043-1745(2000)048[0347:GAOFAS]2.0.CO;2 (2000).
 40. Snijders, T.A.B., & Bosker, R.J. Multilevel analysis: an introduction to basic and advanced multilevel modeling 282-289 (Sage, 2012).
 41. Pinheiro, J. & Bates, D. nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-162; (2023).
 42. Bates, D., Mächler, M., Bolker, B., Walker, S. "Fitting Linear Mixed-Effects Models Using lme4." *Journal of Statistical Software* **67**, 1–48; 10.18637/jss.v067.i01 (2015).
 43. Kuznetsova, A., Brockhoff, P.B., Christensen, R.H.B. "lmerTest Package: Tests in Linear Mixed Effects Models." *Journal of Statistical Software* **82**, 1–26; doi.org/10.18637/jss.v082.i13 (2017).
 44. Fox J, Weisberg S (2019). An R Companion to Applied Regression. Third edition. (Sage, 2019).
 45. Warton, D.I., Duursma, R.A., Falster, D.S. & Taskinen, S. smatr 3– an R package for estimation and inference about allometric lines. *Methods in Ecology and Evolution* **3**, 257-259; doi.org/10.1111/j.2041-210X.2011.00153.x (2011).
 46. Long, S.P., et al. Rising Atmospheric Carbon Dioxide: Plants FACE the Future. *Annual Review of Plant Biology* **55**, 591-628; 10.1146/annurev.arplant.55.031903.141610 (2004).
 47. Way, D.A., et al. Increasing water use efficiency along the C3 to C4 evolutionary pathway: a stomatal optimization perspective. *Journal of Experimental Botany* **65**, 3683–3693; doi.org/10.1093/jxb/eru205 (2014).

48. Wang, J., et al. Changes in plant nutrient status following combined elevated [CO₂] and canopy warming in winter wheat. *Front Plant Sci.* **14**, 1132414; doi.org/10.3389/fpls.2023.1132414 (2023).
49. Qiao, Y., et al. Effects of elevated CO₂ concentration on growth and water use efficiency of winter wheat under two soil water regimes. *Agricultural Water Management* **97**, 1742-1748; /doi.org/10.1016/j.agwat.2010.06.007 (2010).
50. Allen, L.H., et al. Elevated CO₂ increases water use efficiency by sustaining photosynthesis of water-limited maize and sorghum. *Journal of Plant Physiology* **168**, 1909-1918; doi.org/10.1016/j.jplph.2011.05.005 (2011).
51. Robinson, E.A., Ryan, G.D. & Newman, J.A. A meta-analytical review of the effects of elevated CO₂ on plant-arthropod interactions highlights the importance of interacting environmental and biological variables. *New Phytol.* **194**, 321–36; 10.1111/j.1469-8137.2012.04074.x (2012).
52. Hager, H.A., et al. Effects of elevated CO₂ on photosynthetic traits of native and invasive C₃ and C₄ grasses. *BMC Ecol.* **16**, 28; doi.org/10.1186/s12898-016-0082-z (2016).
53. Ayub, G., et al. Impacts of drought on leaf respiration in darkness and light in *Eucalyptus saligna* exposed to industrial-age atmospheric CO₂ and growth temperature. *New Phytol.* **190**, 1003–1018; 10.1111/j.1469-8137.2011.03673.x (2011).
54. Logan, B.A., et al. Examination of pre-industrial and future CO₂ reveals the temperature-dependent CO₂ sensitivity of light energy partitioning at PSII in eucalypts. *Funct Plant Biol.* **37**, 1041–1049; 10.1071/FP10113 (2010).
55. Tissue, D.T. & Lewis, J.D. Photosynthetic responses of cottonwood seedlings grown in glacial through future atmospheric CO₂ vary with phosphorus supply. *Tree Physiol.* **30**, 1361–72; doi.org/10.1093/treephys/tpq077 (2010).
56. Pritchard, S.G., et al. Elevated atmospheric CO₂ differentially affects needle chloroplast ultrastructure and phloem anatomy in *Pinus palustris*: interactions with soil resource availability. *Plant Cell Environ.* **20**, 461–471; doi.org/10.1046/j.1365-3040.1997.d01-92.x (1997).
57. Bravo W., et al. Differentiation of life-history traits among palmer amaranth populations (*Amaranthus palmeri*) and its relation to cropping systems and glyphosate sensitivity. *Weed Science* **65**, 339– 349; doi.org/10.1017/wsc.2017.14 (2017).
58. Van Etten M.L., Kuester A., Chang S.M., & Baucom R.S. Fitness costs of herbicide resistance across natural populations of the common morning glory, *Ipomoea purpurea*. *Evolution* **70**, 2199– 2210; doi.org/10.1111/evo.13016 (2016).
59. Neve,P, Vila-Aiub, M., & Roux, F. Evolutionary-thinking in agricultural weed management. *New Phytologist* **184**, 783–793; 10.1111/j.1469-8137.2009.03034.x (2009).
60. Baucom, R.S. Evolutionary and ecological insights from herbicide-resistant weeds: what have we learned about plant adaptation, and what is left to uncover? *New Phytologist* **223**, 68–82; 10.1111/nph.15723 (2019).

61. Leon, R.G., Dunne, J.C. & Gould, F. The role of population and quantitative genetics and modern sequencing technologies to understand evolved herbicide resistance and weed fitness. *Pest Manag. Sci.* **77**, 12-21; doi.org/10.1002/ps.5988 (2021).
62. Ziska, L. Evaluation of the growth response of six invasive species to past, present and future atmospheric carbon dioxide. *Journal of Experimental Botany* **54**, 395–404; 10.1093/jxb/erg027 (2003).
63. Bernsten, G.N. & Woodward, F.I. The root system architecture and development of *Senecio vulgaris* in elevated CO₂ and drought. *Functional Ecology* **6**, 324–33; doi.org/10.2307/2389524 (1992).

Tables

Table 1. Combination of treatment factors temperature, CO₂, biotype, days after transplant (DAT) and year tested for Palmer amaranth, and their respective levels. Year was considered a blocking factor on the statistical analysis.

<i>Factors</i>	<i>Levels</i>
Temperature	22/33°.C and 26/36°.C (night/day).
CO ₂	410 and 750 ppm.
Biotype	GA2005, GA2017 and GA2020.
DAT	14, 21 and 28.
Year	2021 and 2022.

Table 2. Results from the fitted multivariate model, showing the CO₂, biotypes, and days after transplant (DAT) as main effects on the growth and development of Palmer amaranth.

<i>Treatment factors</i>	<i>Df</i>	<i>Chisq</i>	<i>Pr (>Chisq)</i>
Temperature	8	9.22	0.3238
CO ₂	8	35.2	< 0.001
Biotype	16	46.64	< 0.001
Days after transplant (DAT)	16	1171.27	< 0.001
Temperature * CO ₂	8	12.37	0.1351
Temperature * Biotype	16	12.83	0.6851
Temperature * DAT	16	19.43	0.2469
CO ₂ * Biotype	16	12.90	0.6801
CO ₂ * DAT	16	17.04	0.3830
Biotype * DAT	32	21.32	0.9243
Temperature * CO ₂ * Biotype	16	9.72	0.8805
Temperature * CO ₂ * DAT	16	21.35	0.1653
Temperature * Biotype * DAT	32	22.61	0.8903
CO ₂ * Biotype * DAT	32	22.72	0.8869
Temperature * CO ₂ * Biotype * DAT	32	12.53	0.9992

Table 3. P-values of the ANOVA test for the eight response variables tested. The Bonferroni adjusted level of significance considered is <0.0062. The interactions observed for diameter (cm) (Temperature*CO₂), number of leaves (CO₂*biotype and Temperature*CO₂*DAT), roots dry matter (CO₂*biotype*DAT), as well the main effects with p-value less than 0.05 were not considered statistically significant because we used a Bonferroni-adjusted threshold of 0.05/8=0.0062. Signif. codes: '***' 0.001 '**' 0.01 '*' 0.05.

<i>Treatment factors</i>	<i>Height (cm)</i>	<i>Diameter (cm)</i>	<i>Number of leaves</i>	<i>Leaf area (cm²)</i>	<i>Leaf dry matter (g)</i>	<i>Stem dry matter (g)</i>	<i>Roots dry matter (g)</i>	<i>Plant volume (m³)</i>
<i>p-value</i>								
Temperature	0.4136	0.6994	0.1078	0.0338*	0.7675	0.3881	0.8635	0.1450
CO ₂	< 0.0062	0.0104*	0.0090**	< 0.0062	0.1254	< 0.0062	0.1711	< 0.0062
Biotype	< 0.0062	0.7602	< 0.0062	0.8200	0.4767	0.0159*	0.9686	< 0.0062
Days after transplant (DAT)	< 0.0062	< 0.0062	< 0.0062	< 0.0062	< 0.0062	< 0.0062	< 0.0062	< 0.0062
Temperature * CO ₂	0.1252	0.0189*	0.8121	0.5741	0.5798	0.0557	0.0623	0.1245
Temperature * Biotype	0.6948	0.7638	0.3445	0.0823	0.6772	0.8058	0.6146	0.7088
Temperature * DAT	0.8738	0.9527	0.3444	0.4308	0.6063	0.9315	0.4344	0.9571
CO ₂ * Biotype	0.5471	0.6345	0.0169*	0.4281	0.3803	0.6518	0.5251	0.3425
CO ₂ * DAT	0.8948	0.5812	0.9140	0.5639	0.1356	0.4466	0.1936	0.3770
Biotype * DAT	0.4466	0.9083	0.3966	0.5232	0.6404	0.9215	0.1955	0.4013
Temperature * CO ₂ * Biotype	0.6466	0.6179	0.3778	0.6380	0.2822	0.9402	0.9863	0.5520
Temperature * CO ₂ * DAT	0.3368	0.6638	0.0499*	0.5465	0.4779	0.9313	0.1452	0.5299
Temperature * Biotype * DAT	0.6780	0.6115	0.6473	0.9649	0.5231	0.4712	0.8875	0.4610
CO ₂ * Biotype * DAT	0.9282	0.8378	0.9544	0.2930	0.5476	0.7406	0.0869	0.7350
Temperature * CO ₂ * Biotype * DAT	0.9290	0.9684	0.9122	0.8625	0.5571	0.9434	0.5880	0.9719

Table 4. Marginal means and significant effects of CO₂ in height (cm), leaf area (cm²), stem dry matter (g) and plant volume (m³) in Palmer amaranth. Bonferroni-adjusted intervals statistically significant at a p-value of 0.0062 were used. SE: standard error.

Response variables	CO ₂ level (ppm)	Response	SE	p-value
Height (cm)	410	60.0	±3.12	<i>0.0011</i>
	750	69.3	±3.60	
Leaf area (cm ²)	410	2216	±532	<i>0.0057</i>
	750	2432	±584	
Stem dry matter (g)	410	13.9	±2.93	<i>0.0014</i>
	750	16.4	±3.45	
Plant volume (m ³)	410	0.1346	±0.0092	<i><.0001</i>
	750	0.1879	±0.0130	

Table 5. Marginal means for biotypes (GA2005, GA2017 and GA2020) in height (cm), number of leaves, and plant volume (m³) in Palmer amaranth. Bonferroni-adjusted intervals statistically significant at a p-value of 0.0062 were used. The table also shows the results of the Dunnett pairwise contrasts of Palmer amaranth biotypes (GA2005, GA2017, GA2020) for height (cm), number of leaves and plant volume (m³). Bonferroni-adjusted intervals statistically significant at a p-value of 0.0062 were used, on the log scale. SE: standard error.

Response variables	Biotypes	Response	SE	Pairwise comparison (Dunnett correction)	p-value
Height (cm)	GA2005	72.4	±4.09	GA2017 vs. GA2005	0.0005
	GA2017	59.2	±3.39		
	GA2020	62.6	±3.53	GA2020 vs. GA2005	>.00062
Number of leaves	GA2005	217	±13.9	GA2017 vs. GA2005	0.0002
	GA2017	171	±11.0		
	GA2020	172	±11.0	GA2020 vs. GA2005	0.0003
Plant volume (m ³)	GA2005	0.2017	±0.0160	GA2017 vs. GA2005	<.0001
	GA2017	0.1298	±0.0103		
	GA2020	0.1537	±0.0132	GA2020 vs. GA2005	>.00062

Table 6. R², standardized major axis (SMA) slope, P (p-value regarding the biomass allocation relationship, being significant indicating allometric growth $\neq 1$ or not significant, isometric growth =1), common slope and elevation (interception) of biotypes compared between 410 and 750 ppm of CO₂ and the Palmer amaranth biotypes tested ** indicate significant differences among biotypes with P<0.001.

CO ₂ level	Biotype	R ²	SMA slope + (95% ci)	P (H0 : slope =1.0)	Common slope	Elevation + (95% ci)
410 ppm	GA2005	0.70**	0.8659 (0.7214 - 1.0394)	0.153	0.9044	0.3230 (0.2037 - 0.4422)
	GA2017	0.86**	0.9028 (0.7892 - 1.0328)			0.2939 (0.1846 - 0.4031)
	GA2020	0.76**	0.9358 (0.7854 - 1.1151)			0.3503 (0.2384 - 0.4622)
750 ppm	GA2005	0.64**	1.0749 (0.8882 - 1.3007)	0.303	0.9601	0.3168 (0.2066 - 0.4270)
	GA2017	0.80**	0.8986 (0.7877 - 1.0251)			0.2575 (0.1536 - 0.3615)
	GA2020	0.82**	0.9621 (0.8613 - 1.0746)			0.2725 (0.1726 - 0.3724)

Table 7. R², standardized major axis (SMA) slope, P (p-value regarding the dry matter allocation relationship, being significant indicating allometric growth $\neq 1$ or not significant, isometric growth =1), common slope and elevation (interception) of biotypes compared between days after transplant (DAT) and Palmer amaranth biotypes tested ** indicate significant differences among biotypes with P<0.001.

DAT	Biotype	R ²	SMA slope + (95% ci)	P (H0 : slope =1.0)	Common slope	Elevation + (95% ci)
14	GA2005	0.52**	0.5516 (0.3957 - 0.7689)	0.0000	0.5196	0.6775 (0.5714 - 0.7837)
	GA2017	0.39**	0.4351 (0.2849 - 0.6647)			0.6492 (0.5455 - 0.7529)
	GA2020	0.54**	0.5522 (0.3984 - 0.7653)			0.6542 (0.5470 - 0.7614)
21	GA2005	0.35**	0.9703 (0.7021 - 1.3408)	0.0026	0.7590	0.5019 (0.3279 - 0.6758)
	GA2017	0.68**	0.8399 (0.6316 - 1.1169)			0.4694 (0.3059 - 0.6329)
	GA2020	0.75**	0.6307 (0.4996 - 0.7963)			0.5124 (0.3568 - 0.6680)
28	GA2005	0.70**	1.1175 (0.7211 - 1.7319)	0.54374	1.1271	0.09272 (-0.2817 - 0.4672)
	GA2017	0.51**	1.2772 (0.8969 - 1.8188)			0.0032 (-0.3758 - 0.3824)
	GA2020	0.36**	0.9971 (0.7138 - 1.3929)			0.0706 (-0.3031 - 0.4444)

Table 8. R², standardized major axis (SMA) slope, P (p-value regarding the biomass allocation relationship, being significant indicating allometric growth $\neq 1$ or not significant, isometric growth =1), common slope and elevation (interception) of biotypes compared between 23/33°C and 26/36°C and Palmer amaranth biotypes tested. ** indicate significant differences among biotypes with P<0.001.

Temperature	Biotype	R ²	SMA slope + (95% ci)	P(H0 : slope =1.0)	Common slope	Elevation + (95% ci)
23/33°C	GA2005	0.63**	1.0609 (0.8715- 1.2915)	0.1086	0.9069	0.3627 (0.2486 - 0.4769)
	GA2017	0.84**	0.8396 (0.7537- 0.9353)			0.3204 (0.2240- 0.4167)
	GA2020	0.76**	0.9322 (0.8114 - 1.0711)			0.3358 (0.2394- 0.4322)
26/36°C	GA2005	0.69**	0.9069 (0.7678- 1.0712)	0.3629	0.9811	0.2458 (0.1219- 0.3697)
	GA2017	0.83**	1.0330 (0.8863- 1.2040)			0.1993 (0.0799- 0.3187)
	GA2020	0.80**	0.9842 (0.8473- 1.1434)			0.9842 (0.1421- 0.3773)

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