



Research Paper

Interactive effects of air and nutrient solution temperature and CO₂ concentration on growth, yield, and quality of fresh-cut culinary herbsSeth W. Benjamin , Roberto G. Lopez ^{*} 

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ABSTRACT

Basil (*Ocimum basilicum*), cilantro (*Coriandrum sativum*), parsley (*Petroselinum crispum*), and sage (*Salvia officinalis*) are among the most popular fresh-cut herbs; however, there is limited information available on how to maximize their growth and development in controlled environments. Given that cut herbs are sold by weight, the goal is to maximize harvestable fresh mass while minimizing production time, space, and energy inputs. Our objective was to determine the most effective nutrient solution temperature (NST), carbon dioxide (CO₂) concentration, and air average daily temperature (ADT) to maximize yield. NST, CO₂, and ADT setpoints of 24, 28, or 32 °C, 450 or 900 μmol•mol⁻¹, and 20 or 23 °C respectively, were utilized. ADT contributed the most to the accumulation of shoot fresh mass (SFM) in basil, sage, and parsley. Increasing ADT from 20 to 23 °C increased SFM of parsley, sage, and basil by 46, 100, and 180%, respectively. Increasing CO₂ from 450 to 900 μmol•mol⁻¹ increased SFM of parsley and cilantro by 13 and 14% but decreased basil SFM by 12%. Increasing the NST from 24 to 28 °C increased the SFM of cilantro by 9%, and the SFM of sage was greatest when the NST was 24 or 28 °C. We conclude that SFM can be maximized by maintaining a 23 °C ADT, 28 °C NST, and 450 μmol•mol⁻¹ CO₂ for basil and sage, a 23 °C ADT, 24 °C NST, and 900 μmol•mol⁻¹ CO₂ for parsley, and a 20 °C ADT, 28 °C NST, and 450 μmol•mol⁻¹ CO₂ for cilantro.

List of abbreviations

ADT	average daily temperature
CF	chlorophyll fluorescence
CO ₂	carbon dioxide
DI	deionized
DLI	daily light integral
DWC	deep-water culture
EC	electrical conductivity
GI	growth index
LAR	leaf-area ratio
LED	light-emitting diodes
NST	nutrient solution temperature
pH	potential hydrogen
RDM	root dry mass
SDM	shoot dry mass
SFM	shoot fresh mass
TPFD	total photon flux density

1. Introduction

From 1998 to 2022, the value of fresh-cut culinary herbs produced in the United States (U.S.) has increased from \$31 to \$65 million (USDA, National Agricultural Statistics Service, 2019; Walters et al., 2020). This makes herbs the third-most valuable food crop under protection behind tomato (*Solanum lycopersicum*) and lettuce (*Lactuca sativa*). In total, 16.6 million kg of fresh-cut herbs were produced in 2019. Of this, 3.7 million kg (22 %) were grown in hydroponic systems (USDA, National Agricultural Statistics Service, 2019). Similarly, the number of controlled environment agriculture (CEA) production facilities, including greenhouses and indoor farms growing herbs and specialty crops, is expanding. From 2014 to 2019, the number of fresh-cut culinary herb operations increased by 34 % from 524 to 700 operations, respectively (USDA, National Agricultural Statistics Service, 2019).

However, recently, the indoor and greenhouse CEA industry has been plagued by a series of vertical farm and greenhouse bankruptcy filings by large domestic operations, including AeroFarms, AppHarvest, Bowery, Kalera, Planted Detroit, Plenty, and Square Roots Urban Farms,

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while Fifth Season suspended its operations (Moss, 2023; McGowan et al., 2024; Strailey, 2025). As of July 2025, it appears that AeroFarms, Planted Detroit, Plenty, and Square Roots Urban Farms have reopened after restructuring or acquiring financing (Brooker, 2024; Hall, 2025; Funk, 2025). High capital inputs and low revenues have been identified as the fundamental issues for these companies, with high utility costs being among the industry's key challenges (Moss, 2023).

To improve the economic viability of the industry, the high rate of energy consumption needs to be addressed. Not only is energy use costly to producers, but it also causes harm to the environment through increased greenhouse gas emissions. In recent years, the introduction and use of light-emitting diode (LED) fixtures have reduced energy use. As such, electricity for lighting in vertical farms and greenhouses accounts for 17 % and 3 % of operating costs, respectively, the second and sixth most significant operating costs (Eaves and Eaves, 2018). One less-explored area to reduce energy costs is through the manipulation of the nutrient solution temperature (NST) in hydroponic systems to determine if lowering the air temperature can reduce overall energy use.

The type of production facility affects the operational energy costs. For example, in a study between similar-sized greenhouse and vertical farm facilities in Quebec, Canada, energy accounted for 20 and 26 % of total operating costs, respectively. In the greenhouse, nearly 13 % of the operating costs were due to natural gas heating alone, accounting for almost 62 % of the total energy cost (Eaves and Eaves, 2018). In Michigan, an estimated 88 % of the energy costs for a greenhouse are attributed to heating the air, and an additional 11 % is due to heating water (Lindberg et al., 2021). Additionally, the short winter days and cloudy skies limit the amount of heat greenhouses can capture from solar radiation. A simple solution could be to lower the air temperature to conserve fuel. However, the rate of plant development is directly influenced by the average daily temperature (ADT). If the ADT is lowered, the rate of development decreases and production times increase, so simply reducing the setpoint would not necessarily decrease fuel costs (Runkle, 2023).

In hydroponic CEA production, plants are grown with their roots submerged or in contact with a thin layer of nutrient solution in deep-water culture (DWC) tanks or in nutrient film technique (NFT) channels, respectively (Miller, 2020). The NST is often not controlled and is similar to the ambient air temperature. Hendrickson and Dunn grew 17 basil cultivars in an NFT system with three different NSTs of 23, 27.5, and 31 °C. They reported shoot fresh mass (SFM) increased by 44 and 67 % as the NST was raised from 23 to 27.5 and 27.5 to 31 °C, respectively. Of the 17 cultivars tested, only the purple basil and a few of the large leaf basil cultivars were unaffected by the different NSTs used (Hendrickson and Dunn, 2022). This means that for the vast majority of cultivars tested, increasing the NST was beneficial to the growth and development of basil plants.

According to Hurd (1983), reducing the heating load by 2.5 °C can reduce fuel consumption by 19 %. Additionally, the NST in a DWC tank is a closed system that can be insulated to minimize heat loss, unlike the air temperature in a greenhouse, which infiltration, exfiltration, glazing materials, and venting can influence. Therefore, creating NST and ADT guidelines could help growers reduce their energy costs.

Reducing crop timing and increasing the number of crop cycles per year can lead to increased revenue. One strategy to reduce production time could be by increasing the carbon dioxide (CO₂) concentration in the growing environment. CO₂ is an essential chemical compound in photosynthesis and is often a limiting factor in plant growth and yield. During the winter months in a tightly sealed greenhouse, CO₂ concentrations can drop as low as 100 to 200 μmol·mol⁻¹ (De Pascale and Maggio, 2005). This is less than half the ambient average CO₂ concentration of 419 μmol·mol⁻¹ (Lindsey, 2024) and well below the optimum CO₂ range of 800–1000 μmol·mol⁻¹ for plant growth of many crops (Wang et al., 2022).

Most of the benefits of CO₂ enrichment are in the 600 to 900 μmol·mol⁻¹ range, while some greenhouses using CO₂ enrichment

target 1000 μmol·mol⁻¹ (Lopez et al., 2017). For basil, increasing the CO₂ concentration from 420 to 720 μmol·mol⁻¹ can boost shoot dry mass (SDM) by 56.5, 28.5, and 21 % when grown at ADTs of 20, 26, and 32 °C, respectively, suggesting CO₂ concentration has a greater influence at lower ADTs (Barickman et al., 2021).

Research is needed to explore the most effective combinations of NST and CO₂ concentrations that reduce energy costs and maximize yield for individual herb species. Therefore, our objective was to determine effective combinations of NST, air ADT, and CO₂ concentrations for hydroponically grown basil (*Ocimum basilicum*), sage (*Salvia officinalis*), parsley (*Petroselinum crispum*), and cilantro (*Coriandrum sativum*). We hypothesize that 1) growing culinary herbs at a higher NST and lower air ADT will result in high-quality fresh-cut herbs without compromising yield, and 2) that increasing the concentration of CO₂, combined with higher NST, will increase the overall yield of culinary herbs within the same time span.

2. Materials and methods

2.1. Plant material and propagation conditions

Trays of 200-cell (2.5 cm × 2.5 cm) rockwool plugs (AO 25/40 Starter Plugs; Grodan, Milton, ON, Canada) were presoaked for 20 min. in deionized (DI) water with a pH of 4.4 to 4.5. The pH was measured using a pH and electrical conductivity (EC) probe and adjusted using diluted (1:31) 95 to 98 % sulfuric acid (J.Y. Baker, Inc.; Phillipsburg, NJ). After presoaking the rockwool, the pH-adjusted DI water was drained.

Seeds of basil 'Nufar,' cilantro 'Santo,' parsley 'Giant of Italy,' and sage were obtained from commercial distributors (Johnny's Selected Seeds, Fairfield, ME, and Ball Seed Company, Chicago, IL). Two to three seeds were sown into each presoaked rockwool cell and were sub-irrigated with DI water supplemented with Jack's 12N-4P-16 K (JR Peters, Inc) water-soluble fertilizer providing the following (in mg·L⁻¹):

Basil and Sage (Target EC: 1.3 mS/cm):

141 N, 20.5 P, 156 K, 82.3 Ca, 23.5 Mg, 1.76 Fe, 0.588 Mn, 0.411 Zn, 0.235 Cu, 0.0118 Mo, and 0.235 B

Parsley and Cilantro (Target EC: 1.6 mS/cm):

174 N, 25.3 P, 192 K, 101 Ca, 29 Mg, 2.17 Fe, 0.725 Mn, 0.507 Zn, 0.29 Cu, 0.0145 Mo, 0.29 B

The seedling trays of basil and sage, and parsley and cilantro, were grown at an air ADT and standard deviation of 30.0 ± 4.7 °C and 27.7 ± 4.0 °C, respectively. For all plants, LED fixtures 40 W T8 LED lights (Barrina Lighting, Paris, France) provided a light ratio of 29:31:37:3 blue (400–499 nm):green (500–599 nm):red (600–699 nm):far red (700–800 nm) (B:G:R:FR) and a total photon flux density (TPFD) of 210 ± 5.6 μmol·m⁻²·s⁻¹ for 16 h·d⁻¹ to achieve a daily light integral (DLI) of 12.0 ± 0.4 mol·m⁻²·d⁻¹.

2.2. Hydroponics systems

Two 250 L, vol. 0.9-m-wide by 1.8-m-long, DWC hydroponic systems (Active Aqua premium high-rise flood table; Hydrofarm, Petaluma, CA) were prepared within each of three walk-in refrigerated growth chambers (Hotpack environmental room UWP 2614-3; SP Scientific). All six DWC tanks were covered with a floating 4-cm-thick extruded polystyrene foam sheet (Foamular, Owens Corning, Toledo, OH). The foam sheets had twenty-four 4-cm diameter holes to accommodate plastic net baskets that held the rockwool cubes in contact with the nutrient solution.

After two (basil and cilantro), three (parsley), and four weeks (sage), the seedlings were transplanted into the DWC systems and placed within the plastic net pots. Each species was grown within the DWC system until harvest 3 (basil) or 4 weeks (parsley, sage, and cilantro) after

transplant. Basil and sage were grown with an EC of 1.3 and a pH of 5.7, and cilantro and parsley were grown with an EC of 1.6 and a pH of 5.7. The EC and pH were adjusted daily. The EC was adjusted by adding additional nutrient solution or DI water, and the pH was adjusted by adding potassium bicarbonate or sulfuric acid, respectively. The average horizontal air velocity was approximately $0.4 \text{ m}\cdot\text{s}^{-1}$, which was measured with an anemometer (HHF803; Omega Engineering, Norwalk, CT), and the average dissolved oxygen content was approximately $5.9 \text{ mg}\cdot\text{L}^{-1} \pm 0.4 \text{ mg}\cdot\text{L}^{-1}$.

2.3. Environmental conditions

Two ADTs of either 20 or 23 °C, three NSTs of 24, 28, or 32 °C, and CO₂ concentrations of 450 or 900 $\mu\text{mol}\cdot\text{mol}^{-1}$ were created in the walk-in growth chambers (Table 1). Air temperature was measured every 5 s by a resistance temperature detector (Platinum RTD RBBJL-GW05A-00-M 36B; SensorTec, Inc., Fort Wayne, IN) and logged by a C6 controller (Environmental Growth Chambers, Chagrin Falls, OH). The elevated CO₂ concentration was maintained with a CO₂ sensor (GM86P; Vaisala, Helsinki, Finland) via compressed CO₂ injection and logged by a C6 Controller (Environmental Growth Chambers) every 5 s. NSTs were maintained with water heaters (EcoPlus Aqua Heat Titanium Heater 300 Watt; Hawthorn Gardening Company, Romulus, MI).

A TPF of 260 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and light ratio of 31:31:38:1 B:G:R:FR was provided for 16 h·d⁻¹ by LED fixtures (GreenPower LED production module 3.0; Phillips, Amsterdam, Netherlands) to achieve a DLI of 15 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$.

NST, leaf temperature, and TPF were monitored using thermistors (ST-100; Apogee Instruments, Logan, UT), infrared thermocouples (OS36-01-T-80F; Omega Engineering, INC. Norwalk, CT), and quantum sensors (LI-190R; LI-COR Biosciences, Lincoln, NE) placed in the center of each crop, respectively. The data were measured every 15 s, and means were logged each hour by a CR-1000 datalogger (Campbell Scientific, Logan, UT).

2.4. Growth data collection and analysis

To provide a measurement of plant size, growth index (GI) was calculated by measuring the horizontal width (dia_1) of each plant from leaf tip to leaf tip, the width perpendicular to the first width (dia_2), and the height (ht) from the base of the foam boards to the tallest point on each plant using a ruler (Krug et al., 2010). The equation used to calculate GI is as follows:

$$GI = \frac{\frac{(dia_1 + dia_2)}{2} + ht}{2} \quad (1)$$

Chlorophyll fluorescence (CF) was measured (F_v/F_m), averaged, and recorded on five plants per treatment chosen using a random number generator. The most recently unfolded leaf from each plant was dark acclimated for >15 min using manufacturer-supplied clips. The leaves were then exposed to 3500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ of R light (peak at 650 nm) to achieve saturation of photosystem II with a portable CF meter (Handy Plant Efficiency Analyzer; Hanstech Instruments Ltd., Norfolk, U.K.). Shoot fresh mass (SFM) was recorded for each plant by separating the shoot from the roots at the rockwool cube surface and weighing the samples on a scale (A&D GR-200 Balance scale; A&D Company, Wood Dale, IL). SDM and root dry mass (RDM) were recorded following a minimum of 5 d in a forced-air dryer at 70 °C. The leaf area of each plant was determined by destructively harvesting all plants in each treatment, which involved removing the leaves from the stems and sending the leaves through an LI-3100 Area Meter (LI-COR Inc., Lincoln, NE). Leaf-area ratio (LAR) was calculated with the following equation:

$$LAR = x/\text{SDM} \quad (2)$$

where x is the measured leaf area of each plant and is divided by the

SDM of each plant.

The experiment was organized in a split-plot design with two air temperatures as the main factor and two CO₂ concentrations and three root-zone temperatures as the sub-factors. The experiment was repeated over time, resulting in each ADT treatment being paired with each NST and CO₂ treatment. All data, except for chlorophyll fluorescence, were collected from all 12 plants from both replications per treatment, providing a total of 24 plants sampled per treatment (Benjamin, 2025).

Treatments were blocked by air ADT (two levels), NST (three levels), and CO₂ concentration (two levels), with 12 plants per treatment combination. Each treatment combination was replicated twice. Data were analyzed separately by genus, and analysis of variance was performed using SAS version 9.4 (SAS Institute, Inc., Cary, NC) mixed model procedure (PROC MIXED). JMP (version 12.0.1, SAS Institute Inc., Cary, NC). When interactions between replications were not significant, data were pooled. Linear and quadratic regression analyses were conducted using SigmaPlot (version 14.0, Systat Software Inc., San Jose, CA).

3. Results

3.1. Basil growth

There were main effects of ADT, NST, and CO₂ on the height and GI of basil, but there were also some interactive effects (Table 2). Air ADT had the greatest impact on height and GI. For example, increasing the air ADT from 20 to 23 °C increased height and GI by 103 and 60 %, respectively (Fig. 1A–B). Increasing the NST from 24 to 28 °C resulted in a height and GI reduction of 7 and 8 %, respectively. Increasing the NST from 28 to 32 °C resulted in a height and a GI reduction of 5 and 1 %, respectively. Similarly, the height and GI of basil decreased by 10 and 7 % as CO₂ increased from 450 to 900 $\mu\text{mol}\cdot\text{mol}^{-1}$. Regardless of NST, the tallest basil plants (17.8 cm) were those grown at an ADT of 23 °C and a CO₂ concentration of 450 $\mu\text{mol}\cdot\text{mol}^{-1}$ (Fig. 1A). In contrast, the shortest plants (7.5 cm) and plants with the smallest GI (9.9 to 10.1) were those grown with an ADT of 20 °C and an NST of 32 °C, regardless of CO₂ concentration (Fig. 1A–B).

Basil SDM was individually influenced by ADT and by the interaction of ADT and NST. RDM was only influenced individually by ADT and NST. SFM was affected individually by ADT and CO₂, as well as by the interaction of ADT and CO₂, and ADT and NST (Table 2). At an ADT of 23 °C, plants had 183, 157, and 93 % greater SFM, SDM, and RDM, respectively, than those grown at an ADT of 20 °C (Fig. 1C–D). In contrast, as NST increased from 24 to 28 °C, RDM decreased by 11 %. Increasing CO₂ from 450 to 900 $\mu\text{mol}\cdot\text{mol}^{-1}$ resulted in a 13 % decrease in SFM. For example, the SFM of plants grown at an ADT of 23 °C and a CO₂ concentration of 450 $\mu\text{mol}\cdot\text{mol}^{-1}$ and an ADT of 23 °C and a CO₂ concentration of 900 $\mu\text{mol}\cdot\text{mol}^{-1}$ were 69.8 and 59.9 g, respectively.

ADT, NST, and CO₂ interactively impacted the LA and LAR of basil (Table 2). Plants grown with an ADT of 23 °C, a CO₂ concentration of 450 $\mu\text{mol}\cdot\text{mol}^{-1}$, and NST of 24 or 28 °C had the greatest LA (Fig. 1G). CO₂ concentration had the greatest impact on LAR (Fig. 1H). Increasing the CO₂ concentration from 450 to 900 $\mu\text{mol}\cdot\text{mol}^{-1}$ resulted in a 12% decrease in the LAR of basil.

3.2. Basil chlorophyll fluorescence

CF was influenced by ADT, NST, CO₂, and all interactions (Table 2). The plants with the highest CF were those grown under an ADT of 23 °C, NST of 24 °C, and a CO₂ concentration of 450 $\mu\text{mol}\cdot\text{mol}^{-1}$ (Fig. 1F). Plants with the lowest CF were grown under an ADT of 20 °C, NST of 32 °C, and a CO₂ concentration of 900 $\mu\text{mol}\cdot\text{mol}^{-1}$ indicating a greater level of stress.

3.3. Sage growth

There were main effects of ADT and NST and some interactive effects

for height and GI of sage (Table 2; Fig. 5). CO₂ concentration had no impact on height or GI, but increasing the ADT from 20 to 23 °C increased the average height and GI of sage by 56 and 47 %, respectively (Fig. 2A–B). Additionally, when NST increased from 24 to 32 °C, the height of sage was 8 % lower. The tallest plants (23.1 cm) were grown at an ADT of 23 °C, NST of 28 °C, and CO₂ concentration of 450 μmol•mol⁻¹, while the shortest plants (12.8 to 14 cm) were all grown at an ADT of 20 °C. Plants with the largest GI (30) were grown at an ADT of 23 °C, NST of 28 or 32 °C, and 450 μmol•mol⁻¹ CO₂ or an ADT of 23 °C, NST of 24 °C, and 900 μmol•mol⁻¹ CO₂. As with height, all sage grown at an ADT of 20 °C had the smallest GI (17.3 to 20.9).

SDM and RDM of sage were influenced by the interactive effects of ADT and NST, ADT and CO₂, and CO₂ and NST. Individually, ADT and NST, and ADT and CO₂ influenced SDM and RDM, respectively (Table 2). For instance, the SFM, SDM, and RDM were 91, 89, and 43 % greater, respectively, at an ADT of 23 °C than those grown at an ADT of 20 °C (Fig. 2C–E). Plants growing above an NST of 28 °C experienced a 29 % and 18 % reduction of SFM and SDM, respectively, while RDM was not affected. Plants with the greatest SDM (9.7 g) and RDM (2.2 g) were grown at an ADT of 23 °C, an NST of 28 °C, and a CO₂ concentration of 450 μmol•mol⁻¹, and an ADT of 23 °C, an NST of 24 °C, and a CO₂ concentration of 900 μmol•mol⁻¹, respectively. NST did not affect RDM, but doubling the CO₂ concentration or increasing the ADT from 20 to 23 °C resulted in a 20 and 42 % increase in RDM, respectively. Sage SFM was affected by ADT, NST, and all interactions (Table 2). Additionally, the SFM of plants grown at an ADT of 23 °C and NST of 28 °C, and an ADT of 20 °C and NST of 32 °C was 61.1 and 22.3 g, respectively.

Sage LA and LAR were influenced by the main effects of ADT, NST, and all interactive effects, but only LAR was influenced by CO₂ (Table 2). CO₂ had no impact on LA, but plants under the 23 °C ADT had an 83 % larger leaf area than plants under the 20 °C ADT (Fig. 2G). LA was reduced by 22 % for plants grown at an NST of 32 °C. Plants with the lowest LAR (106.2 cm²/g) were grown with an ADT of 23 °C, an NST of 32 °C, and a CO₂ concentration of 900 μmol•mol⁻¹, while an ADT of 20 °C, NST of 24 °C, and a CO₂ concentration of 450 μmol•mol⁻¹ had the highest LAR at 134.6 cm²/g (Fig. 2H).

3.4. Sage chlorophyll fluorescence

There were no significant differences in CF among ADTs, NSTs, or CO₂ concentrations (Table 2) (Fig. 2F).

3.5. Cilantro growth

Height and GI of cilantro were influenced by all main and interactive effects (Table 2). NST had the most significant impact on height and GI with a reduction of 40 and 40 % as NST was increased from 28 to 32 °C (Fig. 3A–B). The greatest height (18.7 cm) and GI (24.6) were observed when plants were grown under an ADT of 23 °C, NST of 24 °C, and a CO₂ of 450 μmol•mol⁻¹. The shortest plants (7.6 cm) were grown with an ADT of 23 °C, NST of 32 °C, and CO₂ of 450 μmol•mol⁻¹, while the plants with the smallest GI (12.2 to 13.4) were all grown with an NST of 32 °C.

SDM and RDM of cilantro were influenced by all the main and interactive effects (Table 2). The SDM and RDM of plants grown at an NST of 28 °C were 86 and 441 % greater, respectively, than those grown with an NST of 32 °C (Fig. 3D–E). Plants with the highest SDM (6.1 g) were grown with an ADT of 23 °C, NST of 28 °C, and 900 μmol•mol⁻¹ CO₂. Increasing the NST from 28 to 32 °C at an ADT of 20 °C and 450 μmol•mol⁻¹ CO₂ resulted in the SDM decrease from 5.6 to 2.1 g, respectively. The greatest and lowest RDM of 1.5 and 0.2 g were recorded for plants grown under an ADT of 23 °C, NST of 24 °C, and 450 μmol•mol⁻¹ CO₂, and an ADT of 20 °C, NST of 32 °C, and 450 μmol•mol⁻¹ CO₂, respectively.

Cilantro SFM was influenced by NST, CO₂ concentration, and all interactive effects (Table 2). At a CO₂ concentration of 450 μmol•mol⁻¹,

increasing the ADT from 20 to 23 °C and the NST from 28 to 32 °C resulted in the SFM of cilantro decreasing from 49.1 to 7.8 g (Fig. 3C).

Cilantro LA and LAR were both influenced by ADT, NST, and interactive effects, while only LAR was influenced by CO₂ concentrations (Table 2). Plants with the greatest LA (786.3 cm²) and LAR (150.2 cm²/g) were grown at an ADT of 23 °C, NST of 24 °C, and a CO₂ of 450 μmol•mol⁻¹ (Fig. 3G–H). LA was lowest (180 cm²) for plants grown under an ADT of 23 °C, NST of 32 °C, and 450 μmol•mol⁻¹ CO₂. LAR was lowest (83.9 cm²/g) for plants grown under an ADT of 20 °C, NST of 32 °C, and 900 μmol•mol⁻¹ CO₂.

3.6. Cilantro chlorophyll fluorescence

ADT, CO₂ concentration, and some interactive effects affected the CF of cilantro (Table 2). CF was highest (0.83 F_v/F_m) for plants grown under an ADT of 23 °C, NST of 24 °C, and 900 μmol•mol⁻¹ CO₂ (Fig. 3F). CF was lowest (0.78 F_v/F_m) for plants grown under an ADT of 23 °C, NST of 24 °C, and 450 μmol•mol⁻¹ CO₂.

3.7. Parsley growth

The height and GI of parsley were impacted by the main effects of ADT and NST, and all other interactive effects (Table 2; Fig. 6). For example, plants with the greatest height (18.7 cm) and largest GI (24.5) were recorded at an ADT of 23 °C, NST of 24 °C, and a CO₂ concentration of 450 or 900 μmol•mol⁻¹ (Fig. 4A–B). Regardless of ADT or CO₂ concentration, at an NST of 32 °C, parsley plants were 50 % shorter than those grown at an NST of 24 °C. Height and GI of parsley plants were reduced by 18 and 12 %, respectively, when the ADT was reduced from 23 to 20 °C. Additionally, height and GI of parsley plants were reduced by 8 and 5 % when NST was increased from 24 to 28 °C, and a further 46 and 38 % reduction, respectively, when NST was increased from 28 to 32 °C.

SDM and SFM were both influenced by the main effects of ADT, NST, CO₂ concentration, and all interactive effects (Table 2). ADT, NST, and all interactive effects influenced Parsley RDM. The SDM and RDM of parsley plants were reduced by 5 and 10 % as NST increased from 24 to 28 °C, and both were reduced by a further 53 and 73 %, respectively, as NST was increased from 28 to 32 °C (Fig. 4D–E). Plants with the greatest SDM (6.9 g) and SFM (49.9 g) (Fig. 4C) were grown under an ADT of 23 °C, NST of 24 °C, and 900 μmol•mol⁻¹ CO₂. Plants with the lowest SDM (2.1 to 2.6 g) and SFM (8.0 to 9.4 g) were all grown at an NST of 32 °C regardless of ADT or CO₂. CO₂ did not affect RDM (Table 2). RDM was reduced by 10 and 77 % as NST decreased to 24 °C or increased to 32 °C from 28 °C, respectively. Plants had the largest RDM (1.7 g) when grown with an ADT of 23 °C, NST of 28 °C, and CO₂ of 900 μmol•mol⁻¹.

NST and various interactive effects influenced LA and LAR of parsley, but only LA was influenced by ADT (Table 2). LA and LAR of plants grown at an NST of 32 °C were 67 and 30 % lower when compared to plants grown with an NST of 28 °C (Fig. 4G–H). The greatest leaf area (911.6 cm²) was recorded on plants grown at an ADT of 23 °C, NST of 24 °C, and CO₂ of 900 μmol•mol⁻¹.

3.8. Parsley chlorophyll fluorescence

Parsley CF was influenced by ADT, CO₂ concentration, and various interactive effects (Table 2). CF of parsley increased by 5 % as CO₂ was increased from 450 to 900 μmol•mol⁻¹ and increased by 4 % as the ADT was increased from 20 to 23 °C (Fig. 4F). The lowest CF (0.71 and 0.74 F_v/F_m) was observed on plants grown at an ADT of 20 °C, NST of 28 or 32 °C, and CO₂ of 450 μmol•mol⁻¹.

4. Discussion

This study reports the morphological responses of four culinary herbs to the environmental parameters of ADT, NST, and CO₂. As fresh-cut

herbs are sold by weight, any changes in environmental conditions must lead to increased biomass accumulation to maximize production and grower revenue. However, increasing production inputs has the potential to increase production costs, which may outweigh any economic returns incurred from greater biomass accumulation.

In many studies, increasing CO₂ generally had a positive influence on biomass accumulation (Barickman et al., 2021; Gómez et al., 2019). Singh et al. (2020) evaluated basil 'Cardinal', lettuce 'Auvona', and Swiss chard 'Magenta Sunset' (*Beta vulgaris*) grown at air ADT of 21/18 °C and under a DLI of 12 to 14 mol·m⁻²·d⁻¹ and two CO₂ concentrations of 410 (ambient) and 800 μmol·mol⁻¹ (elevated) in a greenhouse. At the elevated concentration, shoot fresh mass increased by 25, 29, and 39 % for lettuce, basil, and Swiss chard, respectively, and dry mass increased by 21, 34, and 40 %, respectively, compared to ambient CO₂. Similarly, Tarr and Lopez (2025) reported that SFM of lettuce 'Rouxai' and 'Rex' increased by 33 and 16 %, respectively, as CO₂ increased from 500 to 800 μmol·mol⁻¹. However, as CO₂ increased further to 1200 μmol·mol⁻¹, SFM of 'Rouxai' and 'Rex' decreased and plateaued, respectively (Tarr and Lopez, 2025).

In contrast, in our study, parsley and cilantro were the only species where a doubling of CO₂ increased the SFM, and it was by a modest 14 and 13 %, respectively. CO₂ did not affect the SFM of sage, and the SFM of basil decreased by 12 %. After accounting for the interactive effects of ADT, NST, and CO₂, only the SFM of cilantro increased in response to an elevated CO₂ concentration of 900 μmol·mol⁻¹. For basil, sage, and parsley, the greatest SFM was recorded when the CO₂ concentration was 450 μmol·mol⁻¹, indicating that another environmental parameter such as light intensity or ADT were limiting. Similar to Tarr and Lopez (2025), testing an intermediate CO₂ level between 450 and 900 μmol·mol⁻¹ may better elucidate the optimal CO₂ level to maximize basil and sage SFM.

Singh et al. (2020) found that Swiss chard and basil were 6 and 14 % wider, respectively, and both were 9 % taller under elevated CO₂. This contrasts with the current study as basil 'Nufar' and cilantro 'Santo' exposed to 900 μmol·mol⁻¹ CO₂ were up to 5 and 7 % narrower, 8 and 11 % shorter, and had a GI 7 and 8 % lower, respectively, than those under 450 μmol·mol⁻¹ CO₂ conditions. CO₂ did not affect the width, height, or GI of sage and parsley.

Walters et al. (2023) reported that SFM of sage 'Extrakta' was highest under an ADT of 22.8 °C and a DLI of 18.3 mol·m⁻²·d⁻¹. This was similar to the ADT in this study, but their DLI was approximately 3.5 mol·m⁻²·d⁻¹ greater. This contrasts with basil 'Nufar' as SFM was greatest under a DLI of 13.2 mol·m⁻²·d⁻¹ and an ADT of 35.7 °C (Walters et al., 2023). This is slightly lower and much higher than the DLI and ADT in his study, respectively. Although time and space were limited for this study, future research should expand the ADT and DLI ranges and tailor these factors to individual crops, rather than optimizing them for two different crops grown concurrently.

Sakamoto and Suzuki (2015) grew red-leaf lettuce 'Red Wave' hydroponically at an air ADT of 20 °C and at NSTs of 10, 20, 25, and 30 °C. The stem length and diameter of lettuce grown at an NST of 10 °C were 16 % and 23 % lower than those at an NST of 25 °C. Additionally, those plants grown with an NST >20 °C had no difference in fresh and dry shoot and root mass. However, these plants contained significantly higher levels of secondary metabolites, such as anthocyanins and phenolics. Total sugars measured in Brix were also greatest at the lowest NST. This suggests that plant growth was reduced because the NST was suboptimal, and resources were allocated to secondary metabolite production to increase environmental stress tolerance. Due to this, an NST of 32 °C was supraoptimal and had a negative impact on growth and development.

All crops experienced a significant reduction in SFM at an NST of 32

°C, except for basil (Figs. 3.5–3.8). Under low ADT treatments, the SFM of basil decreased with increasing NST, whereas under high ADT treatments, the SFM of basil increased or remained unchanged as NST increased.

While lowering the ADT and increasing NST generally had a detrimental effect on the growth of basil, sage, and parsley, there were promising results for cilantro. For example, cilantro plants grown at an ADT of 20 °C, CO₂ of 450 μmol·mol⁻¹, and NST of 28 °C had an SFM 21 % greater than those grown at an ADT of 23 °C, 450 μmol·mol⁻¹ CO₂, and NST of 24 °C. Nguyen et al. (2019) reported similar results, where cilantro had the highest stem and leaf fresh mass when grown at an ADT of 22 °C, 400 μmol·mol⁻¹ CO₂, and 25 °C NST. Once the NST was increased to 30 °C, the stem and leaf fresh mass decreased by nearly 50 %. In addition, fresh mass increased linearly at an NST of 25 °C as PPFD increased from 100 to 300 μmol·m⁻²·s⁻¹, suggesting that the light saturation point may not have been reached. However, when the NST was increased to 30 °C, both leaf and stem fresh mass increased as the PPFD increased from 100 to 200 μmol·m⁻²·s⁻¹, but decreased or plateaued, respectively, as PPFD increased to 300 μmol·m⁻²·s⁻¹ (Nguyen et al., 2019). This suggests that higher NSTs interact negatively with a high PPFD, resulting in a reduced light saturation point.

5. Conclusion

The environmental conditions tested, which resulted in the greatest SFM for basil and sage, were an ADT of 23 °C, a CO₂ concentration of 450 μmol·mol⁻¹, and an NST of 24 °C. For parsley and cilantro, an ADT of 23 °C, CO₂ concentration of 900 μmol·mol⁻¹, and NST of 24 °C, and an ADT of 20 °C, CO₂ concentration of 450 μmol·mol⁻¹, and NST of 28 °C, achieved the greatest SFM, respectively. Knowing this, fresh-cut herb growers could reduce their use of CO₂ supplementation within their greenhouse or vertical farm growing environments. Additionally, if growers could produce cilantro in a separate area during the winter months, they could lower the air temperature while slightly heating their nutrient solution, potentially saving on heating costs and boosting profit margins.

Data availability

The data have been published and are available in Mendeley Data (Benjamin, 2025).

CRedit authorship contribution statement

Seth W. Benjamin: Writing – original draft, Visualization, Validation, Project administration, Investigation, Data curation. **Roberto G. Lopez:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare no known competing interests.

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Appendix

Table 1

Target and actual carbon dioxide (CO₂), daily light integral (DLI), air, plant, and root-zone temperatures (mean ± SD).

Target			Actual				
Air temperature (°C)	CO ₂ (μmol·mol ⁻¹)	Root-zone Temperature (°C)	CO ₂ (μmol·mol ⁻¹)	DLI (mol·m ⁻² ·d ⁻¹)	Temperature (°C)		
					Air	Plant	Root-zone
<i>Basil</i>							
20	450	24	468.9 ± 33.2	15.0 ± 0.2	20.1 ± 0.6	23.9 ± 1.3	24.1 ± 0.4
		28	469.0 ± 33.3	14.5 ± 0.4	20.1 ± 0.6	24.6 ± 1.1	27.7 ± 0.6
		32	479.0 ± 33.4	^z	20.0 ± 0.2	^z	31.6 ± 0.4
	900	24	883.4 ± 60.1	14.9 ± 0.4	20.0 ± 0.4	23.8 ± 1.3	24.0 ± 0.4
		28	909.9 ± 52.6	14.7 ± 0.2	20.1 ± 0.6	24.6 ± 1.1	28.0 ± 0.3
		32	904.3 ± 13.1	14.3 ± 0.8	20.0 ± 0.3	30.2 ± 0.8	31.7 ± 0.2
23	450	24	472.7 ± 48.0	14.3 ± 0.6	23.0 ± 0.4	25.9 ± 1.2	24.0 ± 0.3
		28	503.7 ± 66.3	14.5 ± 0.4	23.1 ± 0.6	26.7 ± 1.1	27.8 ± 0.5
		32	^z	14.3 ± 0.9	^z	32.3 ± 1.2	31.6 ± 0.4
	900	24	885.8 ± 78.3	14.4 ± 1.8	23.0 ± 0.5	26.4 ± 1.0	24.4 ± 0.6
		28	926.5 ± 73.2	14.4 ± 1.7	23.2 ± 0.6	27.1 ± 1.2	28.1 ± 0.6
		32	^z	14.9 ± 2.1	^z	32.4 ± 1.0	31.3 ± 0.8
<i>Sage</i>							
20	450	24	468.9 ± 33.2	14.5 ± 0.8	20.1 ± 0.6	23.6 ± 0.9	24.1 ± 0.4
		28	469.0 ± 33.3	14.9 ± 0.4	20.1 ± 0.6	23.4 ± 0.8	27.7 ± 0.6
		32	479.0 ± 33.4	^z	20.0 ± 0.2	^z	31.6 ± 0.4
	900	24	883.4 ± 60.1	14.6 ± 0.3	20.0 ± 0.4	23.6 ± 1.1	24.0 ± 0.4
		28	909.9 ± 52.6	14.8 ± 1.1	20.1 ± 0.6	23.5 ± 0.9	28.0 ± 0.3
		32	904.3 ± 13.1	14.3 ± 0.8	20.0 ± 0.3	25.1 ± 0.6	31.7 ± 0.2
23	450	24	472.7 ± 48.0	14.5 ± 0.5	23.0 ± 0.4	26.1 ± 0.8	24.0 ± 0.3
		28	503.7 ± 66.3	14.4 ± 0.9	23.1 ± 0.6	26.3 ± 0.8	27.8 ± 0.5
		32	479.0 ± 33.4	^z	20.0 ± 0.2	^z	31.6 ± 0.4
	900	24	885.8 ± 78.3	14.5 ± 1.6	23.0 ± 0.5	25.8 ± 1.1	24.4 ± 0.6
		28	926.5 ± 73.2	14.6 ± 2.0	23.2 ± 0.6	26.1 ± 0.7	28.1 ± 0.6
		32	^z	14.9 ± 2.1	^z	28.2 ± 0.6	31.3 ± 0.8
<i>Parsley</i>							
20	450	24	477.8 ± 39.1	14.1 ± 2.0	20.0 ± 0.2	25.6 ± 1.0	23.9 ± 0.6
		28	476.6 ± 42.7	14.5 ± 1.5	20.0 ± 0.4	26.3 ± 0.9	27.9 ± 0.4
		32	484.1 ± 43.3	14.4 ± 1.4	20.0 ± 0.6	28.4 ± 0.9	31.6 ± 0.5
	900	24	891.7 ± 84.2	14.4 ± 1.3	20.0 ± 0.2	25.8 ± 1.3	24.0 ± 0.4
		28	905.5 ± 23.8	14.4 ± 1.0	20.0 ± 0.2	26.0 ± 0.8	28.0 ± 0.5
		32	894.5 ± 77.2	14.2 ± 2.4	20.0 ± 0.5	28.9 ± 0.4	31.9 ± 0.7
23	450	24	477.8 ± 39.1	14.1 ± 2.0	23.2 ± 1.4	25.6 ± 1.0	23.9 ± 0.6
		28	476.6 ± 42.7	14.5 ± 1.5	23.0 ± 0.5	26.3 ± 0.9	27.9 ± 0.4
		32	484.1 ± 43.3	14.4 ± 1.4	23.0 ± 0.6	28.4 ± 0.9	31.6 ± 0.5
	900	24	891.7 ± 84.2	14.4 ± 1.3	23.2 ± 0.7	25.8 ± 1.3	24.0 ± 0.4
		28	897.8 ± 78.8	14.9 ± 1.4	23.0 ± 0.4	24.2 ± 1.0	28.0 ± 0.5
		32	899.3 ± 67.4	14.9 ± 0.9	23.0 ± 0.5	25.2 ± 0.8	31.4 ± 0.7
<i>Cilantro</i>							
20	450	24	477.8 ± 39.1	14.7 ± 1.0	20.0 ± 0.2	25.7 ± 1.4	23.9 ± 0.6
		28	476.6 ± 42.7	14.3 ± 1.9	20.0 ± 0.4	26.3 ± 1.7	27.9 ± 0.4
		32	484.1 ± 43.3	14.4 ± 1.4	20.0 ± 0.6	34.6 ± 1.4	31.6 ± 0.5
	900	24	891.7 ± 84.2	14.7 ± 1.2	20.0 ± 0.2	25.5 ± 1.6	24.0 ± 0.4
		28	905.5 ± 23.8	14.5 ± 2.0	20.0 ± 0.2	26.3 ± 1.4	28.0 ± 0.5
		32	894.5 ± 77.2	14.2 ± 2.4	20.0 ± 0.5	35.1 ± 0.5	31.9 ± 0.7
23	450	24	473.7 ± 43.2	14.5 ± 1.6	23.2 ± 1.4	24.5 ± 3.3	24.2 ± 0.7
		28	487.2 ± 58.1	14.6 ± 1.6	23.0 ± 0.5	23.9 ± 1.5	28.0 ± 0.8
		32	496.9 ± 55.8	14.0 ± 3.0	23.0 ± 0.6	31.7 ± 1.3	31.5 ± 0.6
	900	24	894.1 ± 80.9	14.9 ± 0.8	23.2 ± 0.7	23.4 ± 1.5	24.2 ± 0.6
		28	897.8 ± 78.8	15.0 ± 0.2	23.0 ± 0.4	24.6 ± 1.7	28.0 ± 0.5
		32	899.3 ± 67.4	14.9 ± 0.9	23.0 ± 0.5	32.3 ± 1.0	31.4 ± 0.7

^z Data not available.

Table 2

Analyses of variance for the effects of air average daily temperature (ADT), carbon dioxide (CO₂ concentration), and nutrient solution temperature (NST) and their influence on height, width 1, width 2, growth index, chlorophyll fluorescence, shoot dry and fresh mass, root dry mass, leaf area, and leaf-area ratio.

	Height	Width 1	Width 2	Growth index	Chlorophyll fluorescence	Shoot dry mass	Shoot fresh mass	Root dry mass	Leaf area	Leaf-area ratio
<i>Basil</i>										
Air ADT (A)	***	***	***	***	***	***	***	***	***	***
CO ₂ (C)	***	***	**	***	**	NS	***	NS	***	***
Nut. sol. temp. (N)	***	*	NS	**	***	NS	NS	**	**	*
A × C	***	**	NS	***	NS	NS	**	NS	***	NS

(continued on next page)

Table 2 (continued)

	Height	Width 1	Width 2	Growth index	Chlorophyll fluorescence	Shoot dry mass	Shoot fresh mass	Root dry mass	Leaf area	Leaf-area ratio
<i>A × N</i>	NS	NS	**	*	NS	**	**	NS	*	***
<i>C × N</i>	NS	NS	NS	NS	NS	NS	NS	NS	NS	*
<i>A × C × N</i>	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
<i>Sage</i>										
Air ADT (A)	***	***	***	***	NS	***	***	***	***	*
CO ₂ (C)	NS	NS	NS	NS	NS	NS	NS	**	NS	**
Nut. sol. temp. (N)	*	***	***	*	NS	***	***	NS	***	***
<i>A × C</i>	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
<i>A × N</i>	NS	NS	NS	*	NS	NS	*	NS	NS	NS
<i>C × N</i>	NS	NS	NS	**	*	NS	NS	NS	NS	NS
<i>A × C × N</i>	NS	NS	NS	***	NS	NS	NS	NS	NS	NS
<i>Parsley</i>										
Air ADT (A)	***	***	***	***	***	***	***	*	***	NS
CO ₂ (C)	NS	NS	NS	NS	***	***	***	NS	NS	NS
Nut. sol. temp. (N)	***	***	***	***	NS	***	***	***	***	***
<i>A × C</i>	NS	NS	NS	*	NS	***	***	***	**	NS
<i>A × N</i>	***	**	**	***	NS	***	***	NS	***	*
<i>C × N</i>	NS	NS	NS	NS	*	**	**	NS	NS	NS
<i>A × C × N</i>	NS	NS	NS	NS	**	***	***	NS	NS	NS
<i>Cilantro</i>										
Air ADT (A)	***	**	***	***	**	NS	NS	***	**	***
CO ₂ (C)	***	**	**	***	***	*	***	***	NS	***
Table 2. (cont'd)										
Nut. sol. temp. (N)	NS	***	***	***	NS	***	***	***	***	***
<i>A × C</i>	***	NS	NS	NS	***	***	***	**	NS	NS
<i>A × N</i>	***	NS	**	***	NS	*	***	***	**	***
<i>C × N</i>	***	NS	NS	***	NS	NS	*	***	**	***
<i>A × C × N</i>	NS	NS	NS	NS	NS	NS	NS	NS	*	***

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05, 0.01, \text{ and } 0.001$, respectively.

Table 3

Regression analysis equations for R^2 or r^2 for height, chlorophyll fluorescence (CF), shoot fresh mass (SFM), shoot dry mass (SDM), root dry mass (RDM) growth index (GI), leaf area (LA), and leaf-area ratio (LAR) in response to nutrient solution temperature (NST) (24, 28, and 32 °C), average daily temperature (ADT) (20 and 23 °C), and CO₂ concentrations (450 and 900 $\mu\text{mol}\cdot\text{mol}^{-1}$) for basil, sage, cilantro and parsley. All models are in the form of: $f = y_0 + a\cdot\text{NST} + b\cdot\text{NST}^2$.

Parameter	ADT	CO ₂	y_0	(a) NST	(b) NST ²	R ² or r ²
<i>Basil</i>						
Height	20	**	41.12 ^I	-2.16	3.48E-2	0.305
			9.57 ^{IV}	69.1E-2	1.23E-2	
	23	450	15.23	0.24	5.20E-3	0.005
			31.22	2.25	4.02E-2	
CF	20	**	44.60	-2.07	3.58E-2	0.020
			28.58	2.06	3.68E-2	
	23	**	1.80	-6.98E-2	1.10E-3	0.151
			0.63	4.54E-2	8.00E-4	
SFM	20	**	1.07	-1.65E-2	3.00E-4	0.132
			24.96E-2	1.80E-2	3.00E-4	
	23	450	186.82	-10.84	0.18	0.249
			50.31	3.63	6.48E-2	
SDM	20	**	49.54E-2	4.65	-7.66E-2	0.007
			185.77	13.42	23.94E-2	
	23	**	293.98	-17.42	31.93E-2	0.006
			187.12	13.51	24.11E-2	
RDM	20	**	17.10	-1.02	1.68E-2	0.234
			4.26	30.78E-2	5.50E-3	
	23	**	7.41	20.50E-2	4.30E-3	0.009
			10.52	0.76	1.36E-2	
GI	20	**	2.42	-11.20E-2	1.90E-3	0.005
			1.76	12.75E-2	2.30E-3	
	23	**	2.86	-16.57E-2	2.70E-3	0.142
			92.23E-2	6.66E-2	1.20E-3	
LA	20	**	33.32	-1.47	2.32E-2	0.274
			8.00	57.76E-2	1.03E-2	
	23	450	10.64	56.36E-2	-1.07E-2	0.006
			23.16	1.67	2.98E-2	
LAR	20	**	50.30	-2.47	4.40E-2	0.007
			21.51	1.55	2.77E-2	
	23	450	3148.43	-174.49	2.78	0.236
			980.62	70.82	1.26	
23	450	1408.95	-4.70	-8.60E-3	0.005	
		2938.93	212.25	3.78		

(continued on next page)

Table 3 (continued)

Parameter	ADT	CO ₂	y ₀	(a) NST	(b) NST ²	R ² or r ²	
LAR	20	900	7133.18	-444.88	8.02	0.031	
			3045.85	219.97	3.92		
		450	60.61	15.72	-31.02E-2	0.046	
	23	900	257.81	18.62	33.22E-2		
			-550.96	55.38	-97.37E-2	0.099	
		450	253.56	18.31	32.67E-2		
		900	689.00	-29.74	48.96E-2	0.219	
			182.04	13.15	23.46E-2		
		900	707.16	-34.66	59.98E-2	0.101	
Height	20	**	182.96	13.21	23.58E-2		
				<i>Sage</i>			
			42.39	-2.02	3.50E-2	0.013	
	23	**	24.57	1.77	3.17E-2		
			16.55	0.68	-1.79E-2	0.034	
			40.61	2.93	5.23E-2		
CF	*	**	73.99E-2	6.90E-3	-1.00E-4	0.022	
			7.51E-2	5.40E-3	9.70E-5		
SFM	20	**	-22.75	4.82	-10.68E-2	0.109	
			90.64	6.55	11.68E-2		
SDM	20	**	-340.07	30.96	-59.41E-2	0.150	
			176.87	12.78	22.81E-2		
			1.17	35.10E-2	8.40E-3	0.051	
23	**	13.26	95.78E-2	1.71E-2			
		-37.31	3.49	-6.59E-2	0.053		
		26.82	1.93	3.46E-2			
RDM	20	450	4.69	-23.02E-2	3.60E-3	0.044	
			900	3.98	28.76E-2	5.10E-3	
			4.40	-20.60E-2	3.60E-3	0.002	
23	450	9.32	67.32E-2	1.20E-2			
		-11.29	96.30E-2	-1.75E-2	0.004		
		9.78	70.71E-2	1.26E-2			
900		3.02	-2.66E-2	-4.00E-4	0.012		
		9.53	68.81E-2	1.23E-2			
		8.70	1.11	-2.60E-2	0.109		
GI	20	**	27.15	1.96	3.5E-2		
			-47.09	5.43	-9.68E-2	0.005	
LA	20	**	45.41	3.28	5.85E-2		
			242.46	43.00	-1.15	0.111	
			1631.20	117.84	2.10		
23	**	-2049.55	262.40	-5.44	0.137		
		3021.75	218.32	3.40			
		-52.48	15.05	-30.26E-2	0.157		
LAR	20	450	170.15	12.29	21.92E-2		
			139.00	72.68E-2	-4.78E-2	0.136	
			181.20	13.09	23.35E-2		
23	450	319.77	-12.22	18.17E-2	0.109		
		211.39	15.27	27.24E-2			
		-58.43	15.43	-32.13E-2	0.199		
900		199.05	14.38	25.65E-2			
		<i>Cilantro</i>					
		-128.92	10.74	-20.18E-2	0.510		
Height	20	450	27.45	1.98	3.54E-2		
			900	-83.04	7.04	-13.09E-2	0.264
			26.08	1.88	3.36E-2		
	23	450	-135.21	12.26	-24.35E-2	0.721	
			36.01	2.60	4.64E-2		
			-96.00	8.55	-16.41E-2	0.335	
900		39.94	2.88	5.15E-2			
		78.41E-2	3.20E-3	-6.70E-5	0.015		
		16.94E-2	1.22E-2	2.00E-4			
CF	23	450	75.32E-2	1.80E-3	-2.19E-5	0.003	
			57.47E-2	4.15E-2	7.00E-4		
			-925.42	72.63	-1.35	0.948	
SFM	20	450	39.79	2.87	5.13E-2		
			-785.61	61.15	-1.13	0.812	
			60.59	4.38	7.81E-2		
23	450	-295.75	27.61	-56.64E-2	0.606		
		134.51	9.71	17.33E-2			
		-605.88	50.00	-95.12E-2	0.535		
SDM	20	450	141.91	10.25	18.29E-2		
			-72.77	5.86	-10.92E-2	0.383	
			17.51	1.26	2.26E-2		
*	**		-48.77	4.10	-7.77E-2	0.342	
			11.98	86.53E-2	1.54E-2		
			-64.74	5.32	-9.98E-2	0.285	
23	900	20.90	1.51	2.69E-2			

(continued on next page)

Table 3 (continued)

Parameter	ADT	CO ₂	y ₀	(a) NST	(b) NST ²	R ² or r ²
RDM	20	900	-24.17	1.87	-3.45E-2	0.648
			2.95	21.28E-2	3.80E-3	
			* -22.48	1.79	-3.39E-2	0.765
GI	20	900	2.01	14.51E-2	2.60E-3	
			** -18.13	1.55	-3.06E-2	0.899
			2.27	16.40E-2	2.90E-3	
LA	20	900	-166.39	13.81	-25.70E-2	0.485
			* 32.94	2.37	4.24E-2	
			** -175.79	15.02	-28.53E-2	0.577
LAR	20	900	27.50	1.99	3.54E-2	
			** -135.17	12.77	-25.46E-2	0.705
			40.22	2.90	5.18E-2	
Height	20	450	-13,921.71	1084.60	-20.04	0.540
			2131.39	153.93	2.75	
			-8773.61	690.00	-12.73	0.368
CF	20	900	1865.08	134.70	2.40	
			** -8180.58	689.10	-13.31	0.427
			2039.71	147.31	2.63	
SFM	20	450	-1123.44	92.05	-1.69	0.503
			* 177.01	12.78	22.81E-2	
			900	46.75	-88.01E-2	0.202
SDM	20	900	174.77	12.62	22.52E-2	
			** -534.06	55.80	-1.14	0.714
			204.28	14.75	26.32E-2	
Height	20	450	<i>Parsley</i>			
			** -64.40	6.28	-12.51E-2	0.469
			23.22	1.68	2.99E-2	
CF	20	450	-125.99	11.55	-23.01E-2	0.656
			** 28.88	2.09	3.72E-2	
			1.44	-4.11E-2	6.00E-4	0.445
SFM	20	900	28.36E-2	4.21E-2	8.00E-4	
			** 21.46E-2	4.10E-2	-7.00E-4	0.002
			47.71E-2	3.45E-2	6.00E-4	
SDM	20	450	75.32E-2	1.80E-3	-2.18E-5	0.003
			** 57.47E-2	4.15E-2	7.00E-4	
			38.66E-2	3.15E-2	-6.00E-4	0.052
SFM	20	900	40.05E-2	2.89E-2	5.00E-4	
			** -259.88	22.84	-45.13E-2	0.753
			42.39	3.06	5.46E-2	
SDM	20	450	-301.17	27.70	-56.38E-2	0.898
			** 53.58	3.87	6.90E-2	
			900	51.97	-1.02	0.956
SDM	20	450	46.94	3.39	6.05E-2	
			** -68.96	5.50	-10.24E-2	0.623
			10.14	73.26E-2	1.31E-2	
RDM	20	450	-8.85	1.12	-2.42E-2	0.680
			** 6.37	46.02E-2	8.20E-3	
			6.37	46.02E-2	8.20E-3	
RDM	20	450	-32.79	3.07	-6.18E-2	0.858
			** 6.62	47.78E-2	8.50E-3	
			5.13	-10.12E-2	-10.12E-2	0.938
RDM	20	450	5.86	42.30E-2	7.50E-3	
			** -22.24	1.82	-3.49E-2	0.501
			6.04	43.66E-2	7.80E-3	
RDM	20	900	-24.74	1.97	-3.72E-2	0.785
			** 2.85	20.61E-2	3.70E-3	
			2.85	20.61E-2	3.70E-3	
RDM	20	450	-24.34	1.97	-3.75E-2	0.874
			** 2.30	16.64E-2	3.00E-3	
			2.30	16.64E-2	3.00E-3	
RDM	20	900	-33.78	2.66	-4.98E-2	0.874
			** 2.55	18.42E-2	3.30E-3	
			-88.61	8.57	-16.85E-2	0.554
GI	20	900	23.64	1.7	3.05E-2	
			** -139.51	13.05	-25.91E-2	0.672
			30.49	2.20	3.93E-2	
LA	20	900	-4635.06	407.30	-7.99	0.473
			** 1302.79	94.10	1.68	
			1302.79	94.10	1.68	
LA	20	450	-5700.90	529.80	-10.81	0.606
			** 2491.87	179.96	3.21	
			2491.87	179.96	3.21	
LAR	20	900	-10,125.92	870.21	-17.10	0.569
			** 3219.04	232.48	4.15	
			3219.04	232.48	4.15	
LAR	20	900	-467.29	48.21	-96.22E-2	0.206
			** 234.02	16.90	30.16E-2	
			234.02	16.90	30.16E-2	

* ADT not significant.

** CO₂ not significant.^y Coefficients for model equations were used to generate Figs. 1–4.^w Standard error (se).

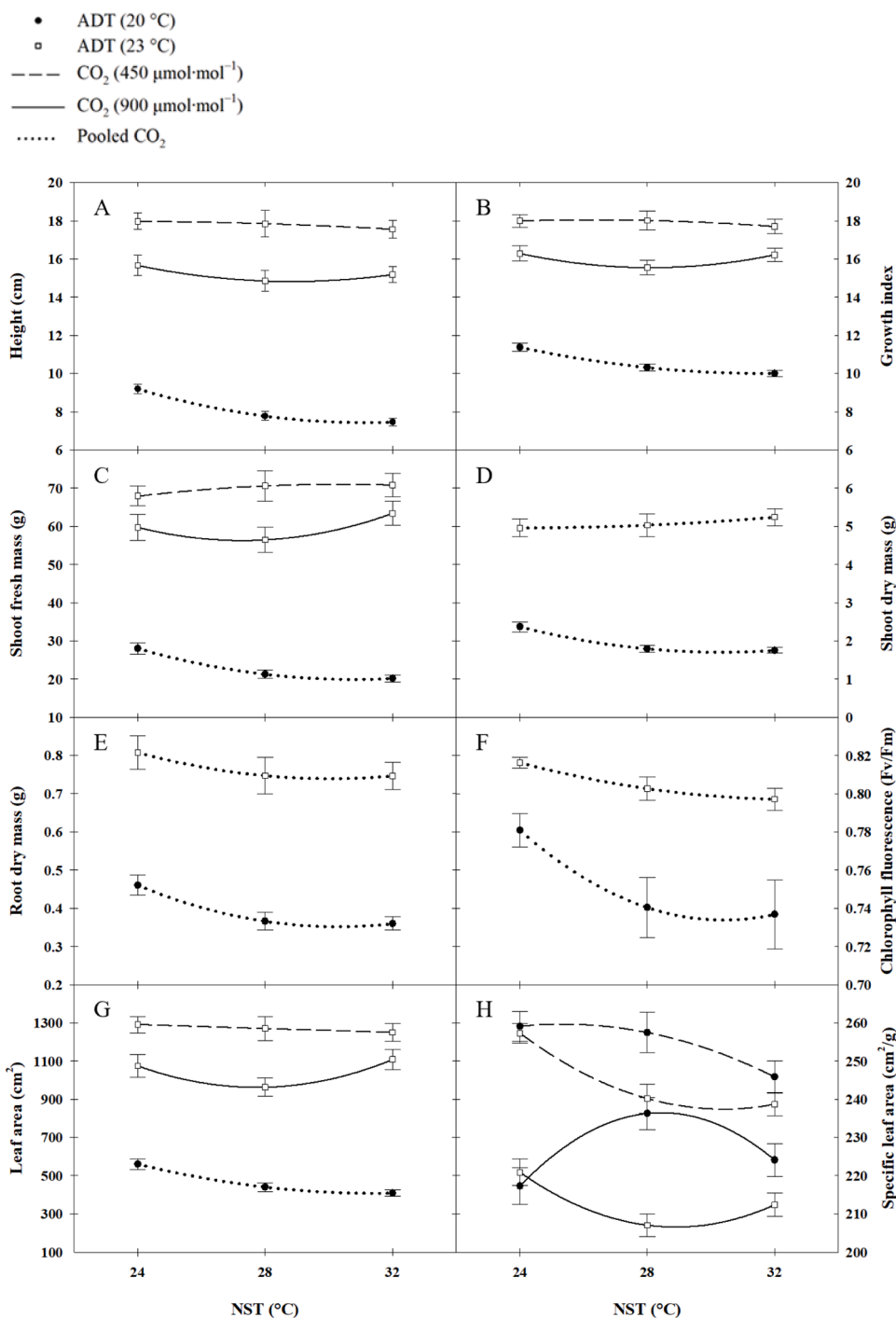


Fig. 1. Plant height, growth index, shoot dry mass, shoot fresh mass, root dry mass, chlorophyll fluorescence, leaf area, and leaf-area ratio of basil 'Nufar' grown under different average daily temperatures (ADT) and nutrient solution temperatures (NST) and carbon dioxide (CO₂) concentrations. Model predictions are represented by lines; error bars represent standard errors; coefficients are in Table 3.

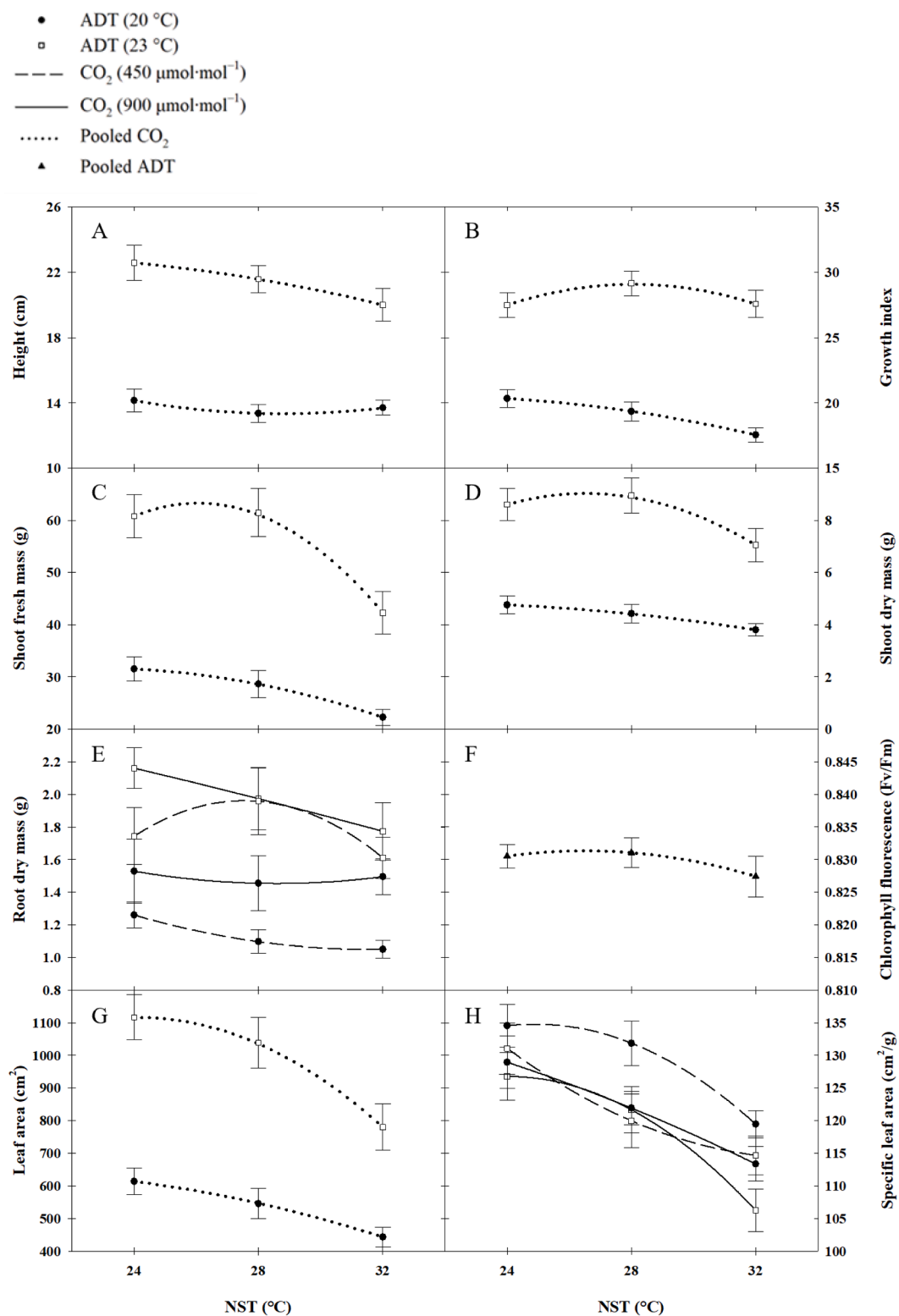


Fig. 2. Plant height, growth index, shoot dry mass, shoot fresh mass, root dry mass, chlorophyll fluorescence, leaf area, and leaf-area ratio of sage grown under different average daily temperatures (ADT) and nutrient solution temperatures (NST) and carbon dioxide (CO₂) concentrations. Model predictions are represented by lines; error bars represent standard errors; coefficients are in Table 3.

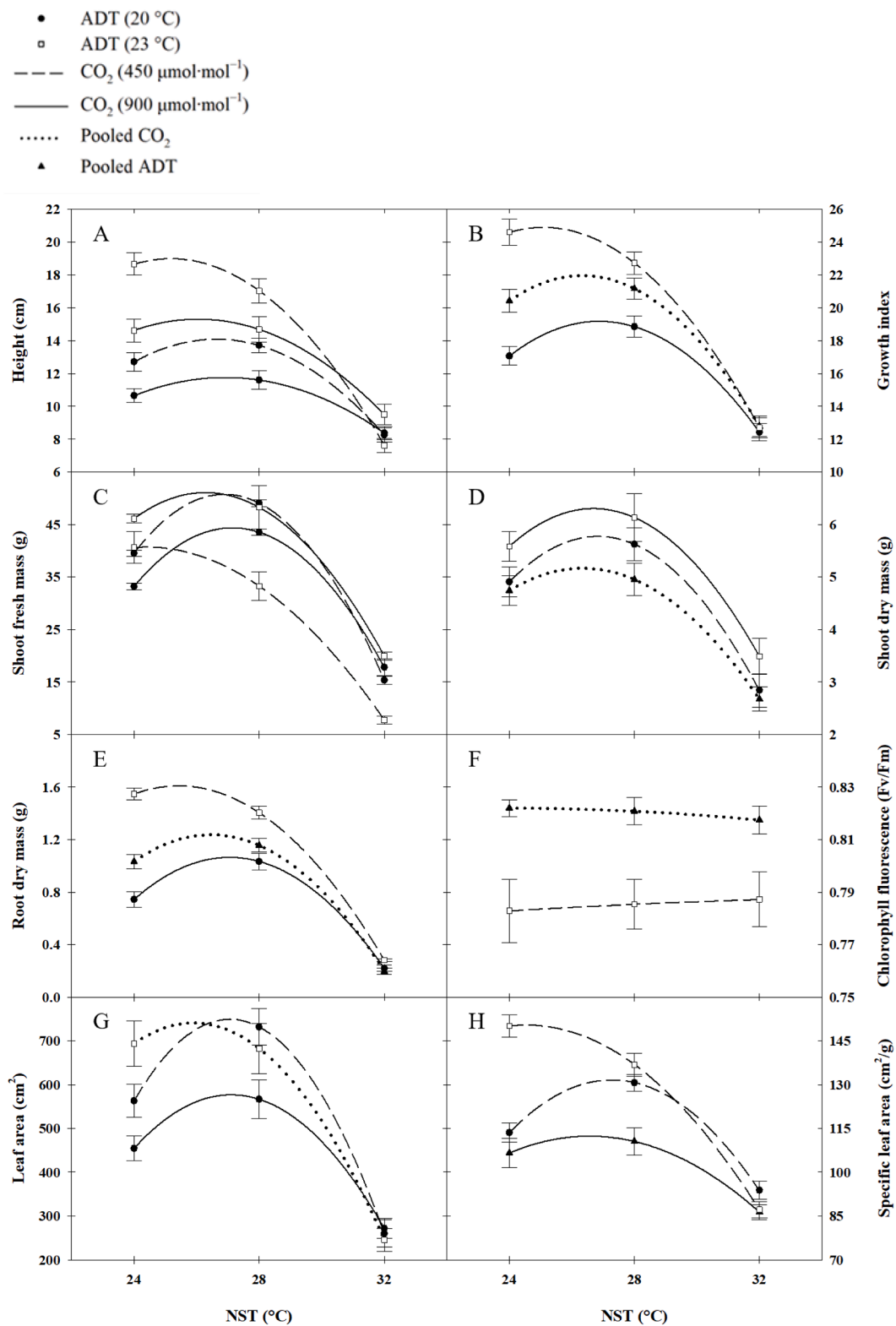


Fig. 3. Plant height, growth index, shoot dry mass, shoot fresh mass, root dry mass, chlorophyll fluorescence, leaf area, and leaf-area ratio of cilantro 'Santo' grown under different average daily temperatures (ADT) and nutrient solution temperatures (NST) and carbon dioxide (CO₂) concentrations. Model predictions are represented by lines; error bars represent standard errors; coefficients are in Table 3.

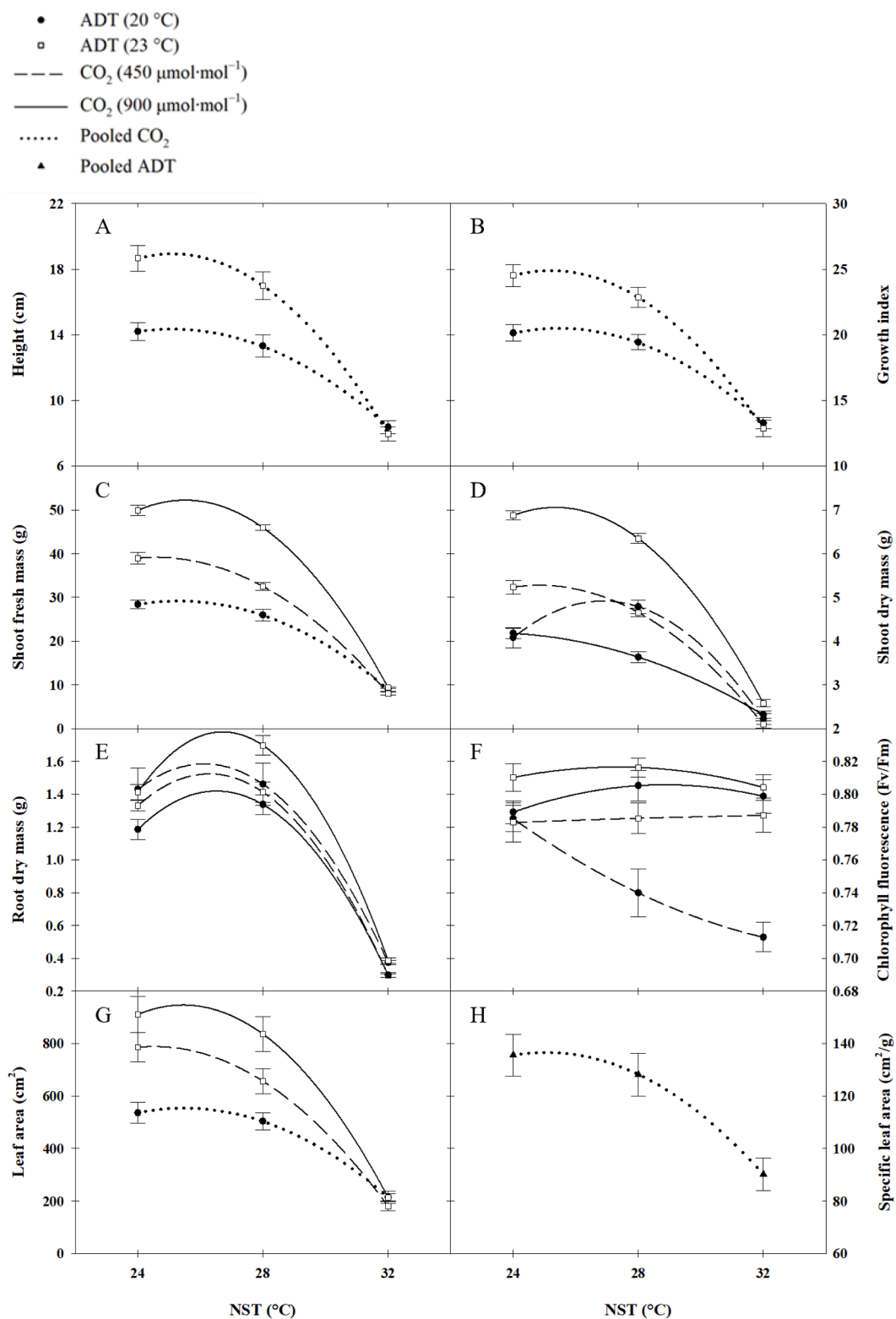


Fig. 4. Plant height, growth index, shoot dry mass, shoot fresh mass, root dry mass, chlorophyll fluorescence, leaf area, and leaf-area ratio of parsley ‘Giant of Italy’ grown under different average daily temperatures (ADT) and nutrient solution temperatures (NST) and carbon dioxide (CO₂) concentrations. Model predictions are represented by lines; error bars represent standard errors; coefficients are in Table 3.

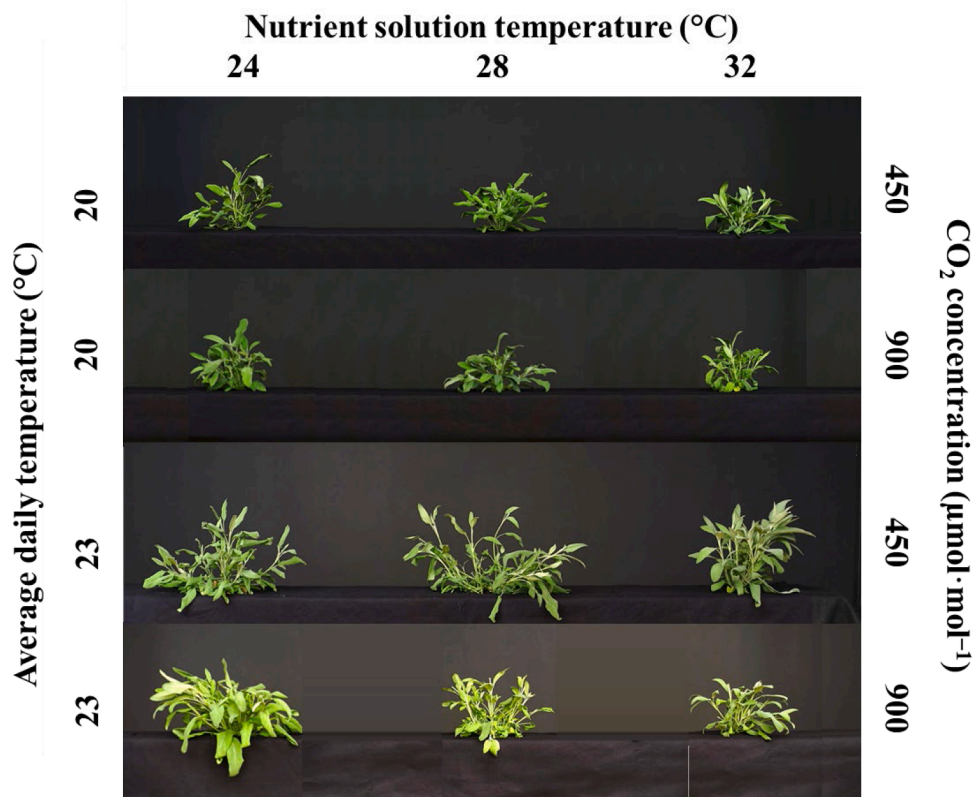


Fig. 5. Average daily temperature (ADT), nutrient solution temperature (NST), and carbon dioxide (CO₂) concentration effects on sage (Rep. 1). Images depict representatives of plants measured.

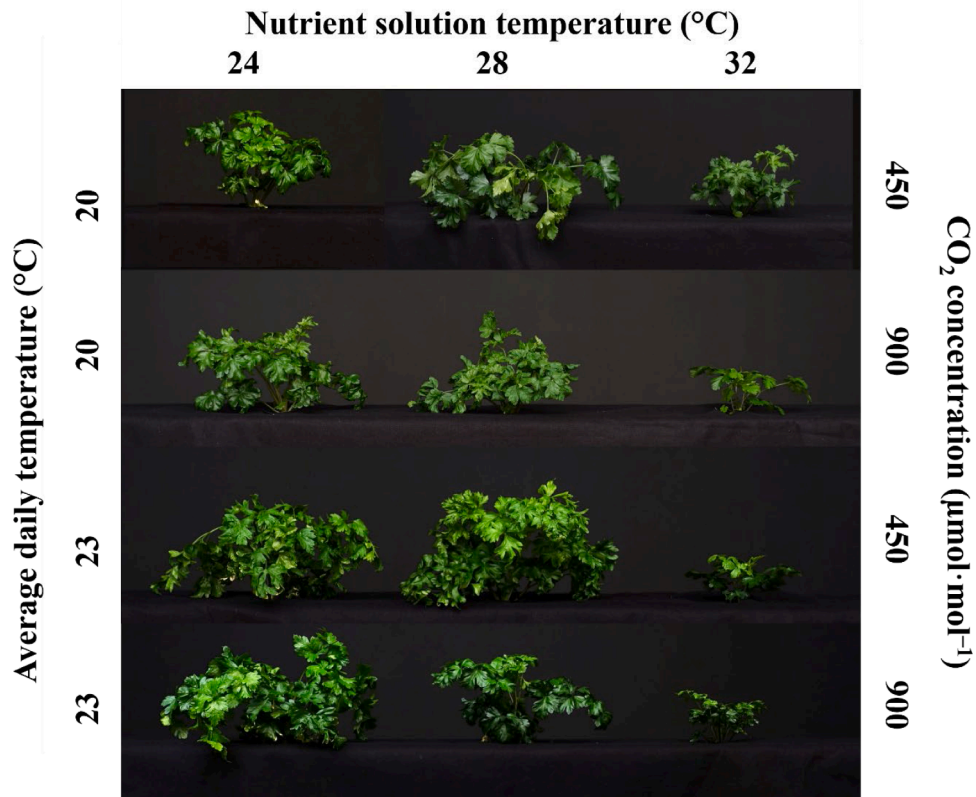


Fig. 6. Average daily temperature (ADT), nutrient solution temperature (NST), and carbon dioxide (CO₂) concentration effects on parsley 'Giant of Italy' (Rep. 1). Images depict representatives of plants measured.

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