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RESEARCH ARTICLE

Reducing plant-derived ethylene enhances crop growth and soil functions under drought stress in subtropical agroecosystems

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Abstract
Aims The increasing frequency of future drought events will negatively impact agroecosystem functions, such as inhibiting crop growth and reducing soil functions. Previous studies have shown that plant-derived ethylene plays an important role in responses to drought, but its effects on crop growth and soil functions in agroecosystems have not been validated.
Methods We reduced the concentration of ethylene released from crops under drought stress by adding an ethylene inhibitor, aminoethoxyvinylglycine (AVG), and investigated the effects of AVG on the growth and soil functions of *Brassica oleracea var. capitata* Linnaeus, a common crop in subtropical agriculture, for one growing season. We measured soil respiration, soil extractable carbon, nitrogen content, and soil microbial activity to characterize soil functions, and also observed changes in soil microbial community structure.
Results Drought caused significant negative effects on crop growth and soil functions, whereas reducing the concentration of plant-derived ethylene significantly mitigated the adverse effects of drought on agroecosystem functions, thereby promoting crop growth and soil functions. The underlying microbial mechanisms include the application of AVG under drought conditions, which remodels the soil microbial community structure. This lead to an increase in the relative abundance of Gram-negative bacteria, such as Aspergillus, which has a significant correlation with crop growth and soil function.
Conclusions This study demonstrates that reducing plant-derived ethylene under drought can alleviate its detrimental effects on crop growth and soil functions in agroecosystems. This provides a scientific foundation for sustainable management of agriculture in the face of climate change in the future.

Keywords Drought · Ethylene inhibitor · Soil function · Agriculture productivity

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Introduction

Agro-ecosystems cover about one-third of the Earth's land area, which provides ecosystem functions such as crop growth and soil function which are of great significance for maintaining global agricultural productivity and soil fertility (Sato et al. 2024). In recent years, drought has become the primary environmental factor to reduce the function of agroecosystems (Haile et al. 2019) with consequences for food security and sustainable agricultural development under future climate change scenarios (Piao et al. 2019). Model predictions suggest that the frequency and intensity of drought events will persist in increasing, further exacerbating the serious threats to agroecosystem function (Zhao and Running 2010). Despite this, our understanding of the specific mechanisms through which drought impacts agroecosystem function remains limited.

Drought can inhibit crop growth, leading to a decline in both crop yield and quality (Hu et al. 2021; Xiong et al. 2022). Studies indicate that plant growth and development under drought stress are usually regulated by ethylene (Zhang et al. 2016; Dubois et al. 2018). When drought occurs, plants rapidly produce large amounts of ethylene to ensure survival, but this response can suppress growth to some extent, resulting in reduced biomass (Trejo et al. 1995; Bray 1997; Dodd and Ryan 2016). Consequently, numerous studies have focused on promoting plant growth under drought stress by reducing the concentration of ethylene from plant sources. Moreover, researchers are increasingly recognize that ethylene from plant may be another important way through which drought impacts agro-ecosystems (Zhou et al. 2013; Liu et al. 2019). However, the current understanding of the regulatory role of plant-derived ethylene under drought stress mainly centers on molecular-scale processes within individual plants (Chavoushi et al. 2019; Rossi and Huang 2023). Far less is known about how ethylene regulates plant-soil-microbe interactions on larger scales.

Soil function is vital for maintaining soil fertility and ensuring crop growth (Miltner et al. 2012; Bouma 2014). Under drought conditions, changes in soil functions, such as soil soluble organic carbon, nitrogen content, and soil microbial activity, are highly sensitive and can effectively reflect soil health within agroecosystems, serving as key indicators of soil functions (Zvomuya et al. 2008; Kaisermann et al. 2013; Bardgett and van der Putten 2014). Soil microbial community is a major driver of soil function and a critical indicator of changes in soil microenvironment (Falkowski et al. 2008). Drought directly affects soil microbial communities through changes in soil moisture, while alterations in substrate availability indirectly affect their composition and diversity, thereby impacting soil nutrient cycling, and ultimately crop growth (Hartmann and Six 2023). Some studies conducted in other natural ecosystems have shown that plant-derived ethylene significantly affects key functions such as soil respiration in temperate semi-arid grassland ecosystems, due to its influence on plant growth (Gu et al. 2022). Given the increasing negative impacts of drought on agroecosystem functioning, there has been limited research confirming the importance of ethylene in these systems through the application of ethylene inhibitors. This gap hinders our understanding of how plant-soil-microbe systems respond to drought conditions.

In order to fill the above knowledge gap, we conducted an experiment in subtropical arid ecosystem where an ethylene inhibitor, aminoethoxyvinylglycine (AVG), was used to reduce the concentration of plant-derived ethylene in a growing season of *Brassica oleracea var. capitata* Linnaeus, a common crop in this region. We measured yield, net photosynthetic rate, and chlorophyll content as indicators of crop growth, and soil respiration, soil microbial activity, dissolved organic carbon, and nitrogen content as parameters to reflect soil functionality. We also used metagenomic techniques to assess changes in soil microbial community structure. With this information, the objectives of this study were to: (1) investigate the effects of drought and AVG addition on crop growth and soil functions in agroecosystems and (2) uncover the microbial mechanism underlying these processes. We hypothesized that ethylene inhibitors would relieve the negative effects of drought on agroecosystem function.

Materials and methods

Sample site information and experimental setup

The experimental sample plot was located in a crop-growing area in Fengxian District, Shanghai, an eastern city in China (30°52 N, 121°34 E). The area has a typical subtropical monsoon climate with hot and humid summers and cold and dry winters. The average annual temperature is 15.8 °C and the average annual precipitation is 1149 mm (Cui and Shi 2012). According to the International Common Soil

Classification (ICSC), the soil type of the region is loam. The specific particle composition is 53.4 ±0.9% sand, 22.01 ±0.9% chalk and 24.58 ±1.6% clay.

To investigate the effect of plant-derived ethylene under drought conditions, a spray solution of ethylene biosynthesis inhibitor aminoethoxyvinylglycine (AVG) (50 μM) (Sigma, Shanghai, China) was used (Gu et al. 2022; Ozturk et al. 2012). We determined the appropriate concentration of AVG for this study by referencing related studies and verified the effectiveness of AVG in reducing ethylene by indoor experiments (Fig. S1). In the field experiment we selected beef heart kale, Chunfeng VI, and planted it at a density of 6 plants/m^2. The full factorial combination of drought and AVG addition was achieved using a randomized block design, yielding four treatments, namely (1) environmental control, (2) AVG, (3) drought and (4) drought and AVG, with four replicates per treatment. Finally, we established 16 sample plots, each measuring 2 m ×1 m and spaced 2 m apart. The environmental control treatment was watered a total of four times during the period to maintain the water content at 60 ±5% of the field holding capacity, while the simulated drought treatment was irrigated twice during the crop growth period to maintain the field holding capacity of the plot at 40 ±5% (Li and Zhou 2014; Gu et al. 2022). For the AVG treatment, AVG solution was mainly sprayed on the crop leaves applied four times at one-week intervals during the crop growth period, while the plots without AVG treatment were sprayed with the same volume of distilled water. Fertilizer and management practices were kept consistent in each sample plot during the experiment, and the specific fertilizer application regimen included the application of 59 kg/m^2 of compound fertilizer annually, with a composition of 15% nitrogen, phosphorus and potassium. Additionally, 450 kg/m^2 of organic fertilizer was also applied.

Measurement of crop growth indicators

We used chlorophyll content, net photosynthetic rate, and yield at maturity as indicators of cabbage growth (Yang et al. 2014). Chlorophyll content was determined at maturity by randomly selecting three leaves from each sample area and using a portable chlorophyll meter (Model: SPAD- 502 PLUS) to determine the relative chlorophyll content, repeating the readings 10 times for each leaf and taking the average value as the SPAD value of the leaves of the plant. The net photosynthetic rate (Pn) was measured using a fully automated photosynthesis measurement system (model: LI- 6800) on three randomly selected leaves in each sampling plot on a sunny and cloudless morning (9:00–11:00 a.m.), and the mean value was taken as the net photosynthetic rate of the sampling plots (Saathoff and Welles 2021). Yield was determined by weighing the above-ground portion of the crop at maturity and dividing it by the sample area. The frequency of the above measurements was once in a growing season.

Measurement of soil in-situ ethylene concentrations

The static box method was used to measure in situ ethylene concentrations during the crop growing season (Zhou et al. 2021). The static box body has a plastic hose connected to a three-way valve at the top of the box to extract gas from the box. After the static box was randomly installed in the sample plots, an open slot in the base of the box was filled with water to guarantee the airtightness of the gas inside. Gas samples were taken in the middle of the experiment. Before sampling, the gas was mixed by pulling and pushing the plunger of a 30 ml sterile syringe, and the extracted gas samples were transferred into pre-vacuumed 10 ml glass tubes and brought back to the laboratory for analysis. The gas samples were placed in a gas chromatograph equipped with a flame ionization detector for measurement using a GDX- 502 column and injection mode (Varian GC 9800, Shanghai, China) (Bu et al. 2019). The specific parameters were: the column temperature was 80 ℃, the injection cell temperature was 100 ℃, and the detector temperature was 120 ℃; the flow rate of carrier gas (N_2) was 40 mL min^{-1}.

Measurement of soil function indicators

In this study, soil respiration, microbial activity, and soil extractable carbon (EOC) and nitrogen content (EON) were assessed as indicators of soil function in agricultural ecosystems.

Soil respiration was measured using a procedure similar to that for in situ ethylene concentrations, with gas samples collected biweekly for a total of five measurements, ultimately characterizing the changes in soil CO_2 levels. Microbial activity was evaluated using an incubation method. A fresh 10 g soil sample was placed in a 1 L glass bottle equipped with a three-way valve for gas collection and a moist absorbent paper at the bottom, ensuring a good airtight seal. Pre-incubation occurred for one week at a constant temperature of 22 °C in a light-protected environment to activate microorganisms in the samples. Gas samples were collected at the end of the incubation period, and a second gas sample was taken during the next incubation cycle, following the same procedure, with the timing recorded. Microbial activity was expressed by analyzing the change in gas concentration between the two time points. The calculation formula is provided below:

$$f_{incubation} = \frac{\Delta m}{M\Delta t} = \frac{\rho v \Delta c}{M\Delta t} \quad (1)$$

The soil microbial respiration during incubation is measured in mg kg^{-2} dry soil h^{-1}. In this equation, $\Delta m/\Delta t$ denotes the rate of change in the mass of CO_2 in the jar over time, $\Delta c/\Delta t$ characterizes the rate of change of CO_2 concentration over time, v refers to the volume of the incubation jar, and M is the mass of the soil sample (Gu et al. 2020). ρ represents the density of CO_2 at the temperature of the glass jar, with the calculation formula as follows:

$$\rho = \frac{273}{273 + T} \times \frac{44}{22.4} \quad (2)$$

In this formula, T is the experimental temperature (in degrees Celsius).

EOC and EON were determined using the hot water extraction method (Zhou et al. 2012; Bu et al. 2018). A mixture of 3.6 g of soil sample and 30 ml of sterile water was placed in a centrifuge tube and incubated at 70 °C for 16 h. The supernatant was obtained by mixing at 200 rpm, followed by centrifugation at 4500 rpm for 30 min. The contents of EOC and EON were accurately measured using a total organic carbon/total nitrogen analyzer (Analytik Jena, Germany). Soil total carbon and nitrogen contents were measured using an elemental analyzer (Vario MICRO cube, Germany). Soil moisture content was determined by drying samples at 105 °C overnight, while soil pH was assessed at a dry soil/water ratio of 1:2.5.

Metagenomic sequencing and bioinformatics analysis of soil microbes

DNA from soil microorganisms was extracted using a DNA kit (Magen, Guangzhou, China) and subjected to metagenomic sequencing. The raw data obtained from the Illumina platform were filtered via FASTP (v0.20.0) to eliminate low-quality and host-contaminated fragments, resulting in high-quality reads. Contigs were generated by assembly using MEGAHIT with default parameters. Gene prediction was conducted for contigs exceeding 500 bp using MetaGeneMark. Non-redundant gene sets were constructed by clustering predicted genes across all samples with 95% identity and 90% read coverage using CD-HIT (version 4.6.1). The resulting high-quality reads were aligned to these non-redundant gene sets using Soapaligner version 2.21 to calculate the raw abundance information for each sample. Species classification and gene function annotations were obtained by comparing the non-redundant gene set sequences against the NR and KEGG databases. Ultimately, the specific microbial community composition within each sample was quantified at seven taxonomic levels: kingdom, phylum, order, family, genus, and species.

The top nine bacterial phyla in terms of relative abundance and the top fifteen bacterial genera were designated as dominant microbial taxa, according to a standardized abundance table. The richness index and the ACE index were used to measure changes in microbial richness among the various samples. Meanwhile, the Shannon–Wiener index and Simpson index were employed to calculate the α-diversity of microorganisms within the soil samples.

Data analysis

The effects of drought and AVG addition, as well as their interactions, on crop growth, soil function, and microbial community diversity were investigated using two-way ANOVA with R software. Differences among the four treatment groups were analyzed using the LSD test at a significance level of $P < 0.05$. Correlation analyses of soil microbial community structure and diversity were performed using the "vegan" package in R. The relationship between soil microbial communities and environmental factors was examined using redundancy analysis (RDA), based on the maximum gradient length of detrended correspondence analysis (DCA), with model testing conducted via Monte Carlo permutation (999 iterations) (Xue et al. 2020). The Mantel Test was used to assess correlations between plant factors, soil properties, and dominant microbial taxa. All graphical representations were created using Origin 2021.

Results

Effects of drought and AVG addition on crop growth

Our findings indicate that the ethylene concentration in situ significantly increased to 46.1% under drought conditions compared to the control plot. Conversely, the application of AVG resulted in significant reductions in soil ethylene concentration, decreasing it to 68.9% and 68% under drought and non-drought conditions, respectively, indicating the effectiveness of AVG treatment (Fig. S2).

Drought stress significantly impacted the physiological and growth parameters of cabbage, leading to reductions in yield, chlorophyll content, and net photosynthesis rate by 16.8%, 12.9%, and 23.8%, respectively (Fig. 1a-b; Fig. S3). In contrast, AVG treatment significantly enhanced cabbage growth, increasing yield by 7.4% and 8.9% under drought-free and drought conditions, respectively (Fig. 1a). The

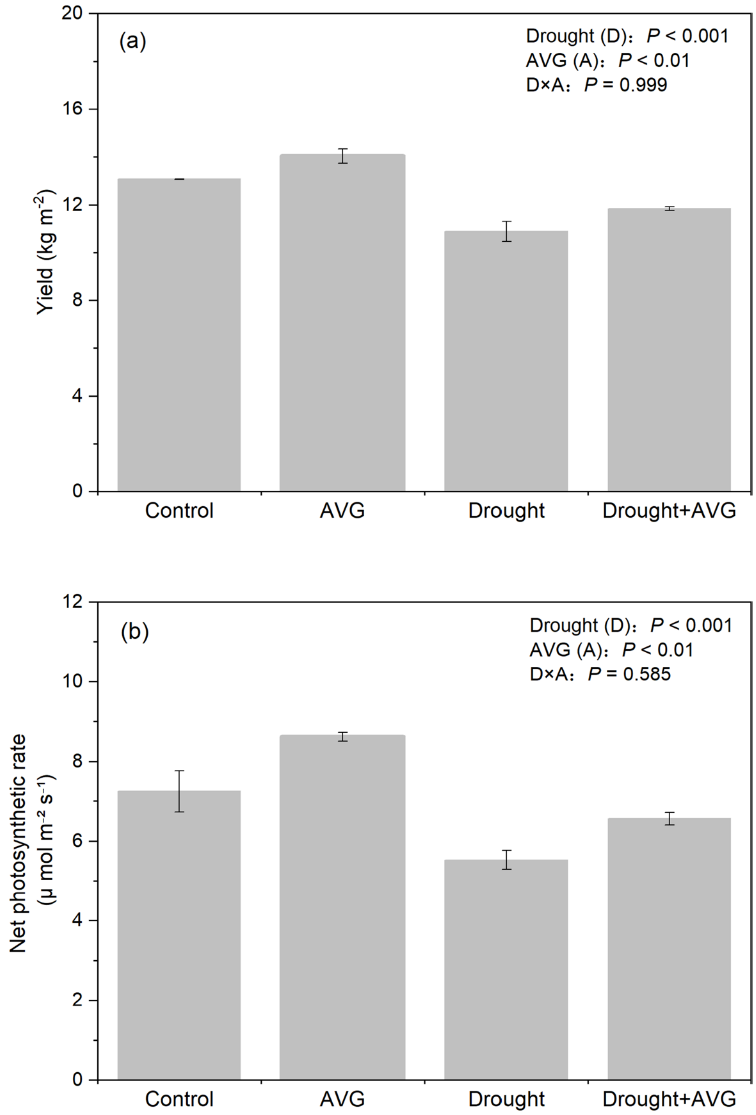

Fig. 1 Effects of drought and AVG addition treatments on crop yield (**a**), net photosynthesis rate (**b**) in a subtropical agroecosystem. Data represent the mean values with standard errors

net photosynthetic rate also increased by 19% and 18.8% in drought-free and drought conditions, respectively (Fig. 1b), while chlorophyll content increased by 11.1% and 10.7% (Fig. S3). Notably, the effects of drought and AVG addition on the physiological and growth parameters of cabbage appeared to be independent of each other, with no significant interaction observed.

Effects of drought and AVG addition on soil functions

The average soil respiration rate under drought conditions was significantly reduced by 24.7% compared to the control (Fig. 2a). However, the addition of AVG significantly increased soil respiration rates by 20% and 37.7% under drought-free and drought conditions, respectively. Additionally, the soil respiration rate exhibited significant dynamic changes over the experimental period, gradually decreasing over time ($P < 0.001$).

Regarding soil microbial activity, drought conditions resulted in a significant decrease of 65.4%. However, AVG addition significantly increased microbial activity by 58.92% under drought-free conditions and 165.9% under drought conditions (Fig. 2b). Soil extractable carbon content (EOC) was also significantly reduced by 15.6% under drought conditions compared to the control, while AVG addition significantly increased EOC by 8.1% and 13% under both drought-free and drought conditions (Fig. 2c). In terms of soil extractable nitrogen content, drought significantly decreased its concentrations by 44.6%, whereas AVG addition significantly increased nitrogen contents by 32.2% and 67.2% under drought-free and drought conditions, respectively (Fig. 2d).

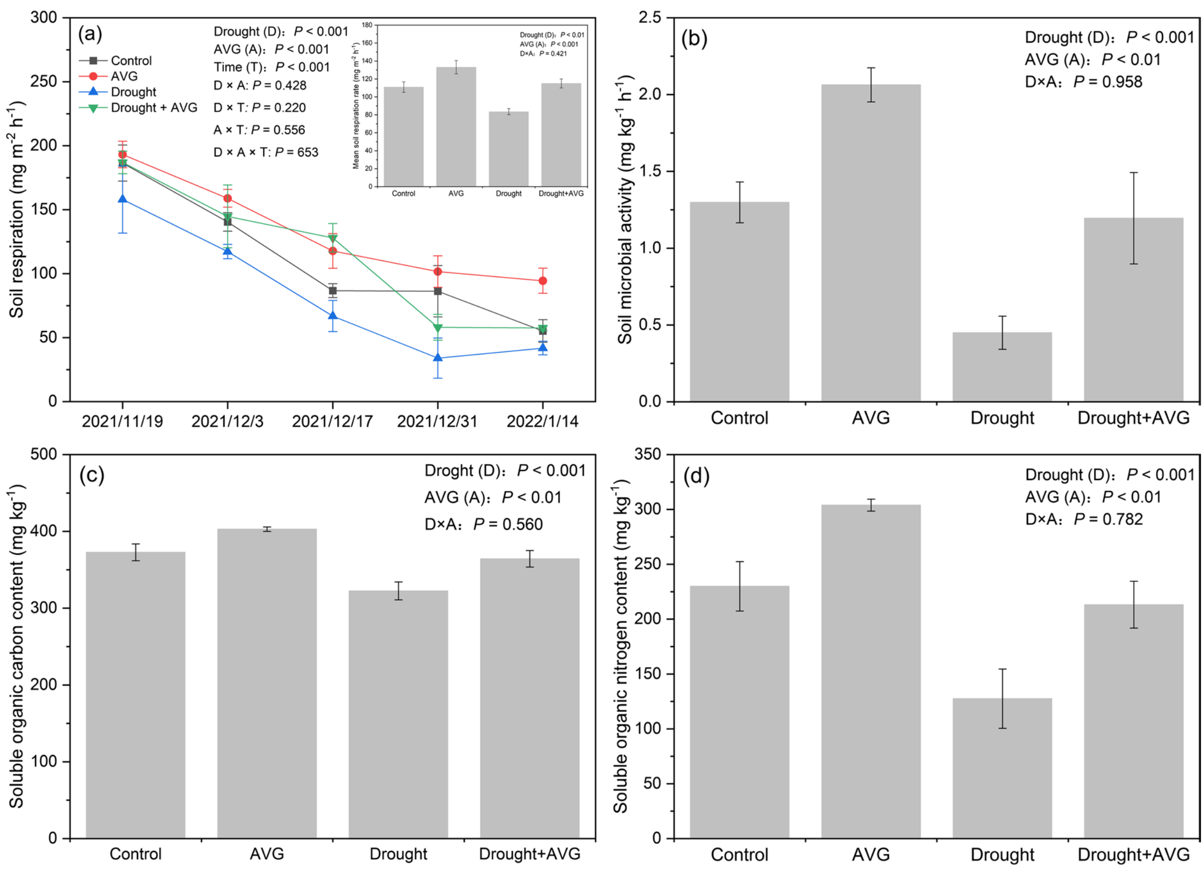

Fig. 2 Soil functional changes in subtropical agroecosystems under drought and AVG addition treatments, including soil respiration (**a**), microbial activity (**b**), soil extractable carbon (**c**), and soil extractable nitrogen content (**d**). Data are presented as mean values with standard errors

Importantly, neither drought nor AVG addition showed significant interactive effects on the aforementioned soil function indicators. Additionally, neither treatment significantly impacted soil pH, temperature, total carbon, total nitrogen, ammonium nitrogen, or nitrate nitrogen (Table S1).

Relationships between soil-dominant taxa and agroecosystem functions

Metagenomic sequencing revealed that the soil microbial community composition was largely similar but significantly different across the four treatment plots. By ranking the relative abundance, we identified nine dominant bacterial phyla and fifteen dominant bacterial genera, followed by ANOVA for these taxa. The results indicated that the relative abundances of Proteobacteria, Acidobacteria, Planctomycetes, and Nitrospirae were significantly lower under drought treatment than under non-drought treatment. Meanwhile, AVG addition increased the relative abundance of Proteobacteria and Actinobacteria compared to samples without AVG, though these changes did not reach statistical significance (Fig. S4a; Table S2).

Changes at the genus level mirrored those observed at the phylum level, with relative abundances of *Nitrospira* and *Hyphomicrobium* significantly lower under drought treatment compared to non-drought conditions. The addition of AVG slightly increased the abundance of dominant genera, such as *Nocardioides*, when compared to samples without AVG (Fig. S4b; Table S3). Alpha diversity analysis, employing Chao1, ACE richness, Shannon, and Simpson indices, showed no significant effects of drought or AVG on soil microbial diversity (Table S4).

Results from redundancy analysis (RDA) indicated that crop growth and soil function indicators significantly impacted the soil microbial community, explaining 86.3% and 78.5% of the variability in microbial community composition, respectively. The net photosynthetic rate and crop yield emerged as primary crop growth parameters affecting bacterial community structure (Fig. 3a; Table S5), while soil moisture, microbial activity, and soil extractable carbon content were the main soil functional parameters contributing to bacterial community changes (Fig. 3b; Table S6).

To further explore relationships between dominant taxa and agroecosystem functions, we found significant positive correlations between *Hyphomicrobium* and both yield and net photosynthetic rate, as well as with soil moisture, soil respiration, microbial activity, and soil extractable carbon content. Additionally, the relative abundance of *Nitrospira* exhibited significant

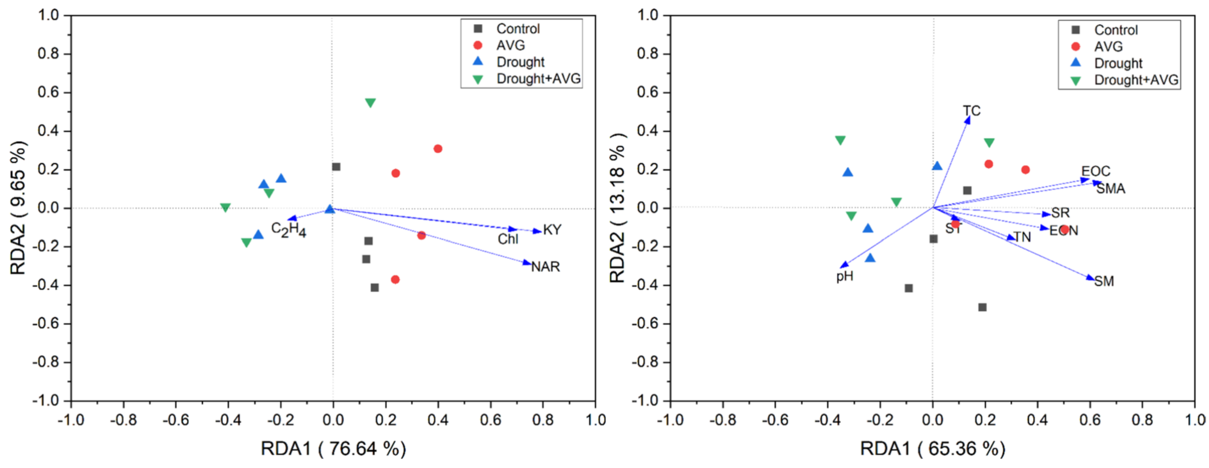

Fig. 3 Redundancy analysis illustrating the effects of crop growth (**a**) and soil function indicators (**b**) on soil microbial communities. Different colored points represent soil microbial communities from various samples. Blue arrows indicate crop growth indicators or soil physicochemical indicators, with arrow length reflecting the influence of environmental factors on changes in microbial communities. The axes illustrate the proportion of variance explained by these factors in relation to community changes. Abbreviations: KY – cabbage production; Chl – chlorophyll content; NAR – net photosynthesis rate; SM – soil water content; SR – soil respiration; ST – soil temperature; SMA – soil microbial activity; TC – total carbon; TN – total nitrogen; EOC – soil extractable carbon content; EON – soil extractable nitrogen content

positive correlations with all crop growth parameters, as well as with soil moisture and soil extractable carbon content (Fig. 4).

Discussion

Effects of plant-derived ethylene on agroecosystem functions under drought

Drought is increasingly threatening agroecosystems in the context of climate change (Christian et al. 2021). However, previous studies have often overlooked the significant impact of ethylene produced by plant roots on agricultural ecosystem function under drought conditions, potentially leading to an underestimation of drought stress effects on ecosystems. In this study, the use of AVG demonstrated contrasting effects on crop growth and soil function within a subtropical agroecosystem, highlighting the critical role of drought-induced plant ethylene at the field scale. Research indicates that the biosynthesis of plant-derived ethylene is closely associated with its precursor, 1-aminocyclopropane- 1-carboxylic acid (ACC) (Van De Poel and Van Der Straeten 2014; Sun et al. 2017). Our findings reveal that AVG increases the activity of ACC deaminase, promoting the breakdown of ACC, which reduces plant-derived ethylene synthesis (Gu et al. 2022). This reduction alleviates the negative effects of high ethylene concentrations on agroecosystem functionality.

Chlorophyll content and the net photosynthetic rate are indicators of leaf efficiency in assimilating substances, directly influencing dry matter accumulation and yield formation (Orsák et al. 2023). In this study, drought and AVG treatment significantly altered the chlorophyll content and net photosynthetic rate, correlating with the regulatory role of ethylene in plants' responses to stress (Habben et al. 2014). Excessive ethylene accumulation has been shown to accelerate

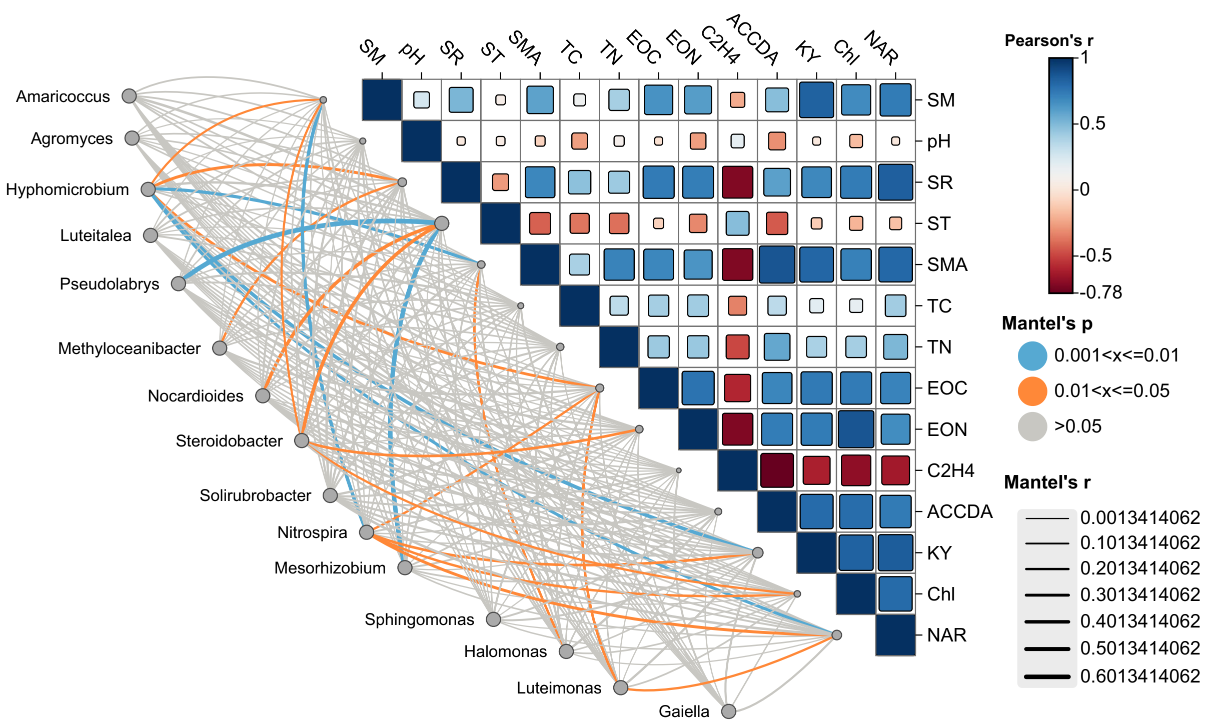

Fig. 4 Correlation analysis of dominant soil bacterial genera and indicators of crop growth and soil function under drought and AVG addition treatments. Gray lines represent Mantel-test correlations with $p > 0.05$, while colored lines indicate Mantel-test correlations with $p < 0.05$. Abbreviations: KY – cabbage production; Chl – chlorophyll content; NAR – net photosynthesis rate; SM – soil water content; SR – soil respiration; ST – soil temperature; SMA – soil microbial activity; TC – total carbon; TN – total nitrogen; EOC – soil extractable carbon content; EON – soil extractable nitrogen content

chlorophyll degradation and decrease photochemical efficiency, leading to leaf senescence and abscission. Our results support this notion (Danish and Zafar-ul-Hye 2019). However, AVG application reduced ethylene concentration, mitigating the plant's sensitivity to drought and positively enhancing drought resistance (Dong et al. 2011).

Soil function plays a vital role in maintaining soil fertility and supplying nutrients for crop growth (Piao et al. 2019). We further explored the effects of plant-derived ethylene on soil function under drought conditions, and our results confirmed our hypothesis that ethylene not only regulates in individual plant growth in response to drought, but also alters soil function by influencing plant organic matter input. Our study provides the first large-scale field evidence that reducing plant-derived ethylene enhances soil function under drought stress. Additionally, it demonstrates that ethylene is a significant factor in how drought impacts agroecosystem functioning. Ethylene is known to suppress root development, which can diminish soil autotrophic respiration (Fiorani et al. 2002; Wei et al. 2020). Furthermore, changes in root secretions under drought conditions may also affect the nutrient substrates available to microorganisms, thereby limiting microbial activity (Pierik et al. 2007). The increase in soil extractable carbon and nitrogen content associated with reduced ethylene concentrations via AVG may stem from enhanced crop productivity, resulting in greater organic matter input and more soluble organic content (Naikwade 2021).

However, this study focused on only one crop when investigating the role of plant-derived ethylene on crop growth and soil function. Future research could involve observing different crops over extended periods to confirm the generalizability of our findings. Given the widespread vulnerability of agroecosystems and the anticipated increase in the frequency and intensity of drought events (Haile et al. 2019), our findings emphasize that drought affects agroecosystem functionality by inducing ethylene production in plants. This insight is critical for improving resilience under drought stress.

Effects of plant-derived ethylene on soil microbial communities under drought

Soil microbial communities are pivotal for soil function and influence interactions between soil and plants (Carvalhais et al. 2014; Hartmann and Six 2023; Zhou et al. 2023). Changes in microbial community structure can modify soil nutrient cycling and, consequently, affect crop growth (Xun et al. 2019). In this study, drought and AVG application exerted markedly different effects on the microbial community structure. Under drought conditions, the relative abundance of Proteobacteria significantly declined, likely due to the higher sensitivity of Gram-negative bacteria to water stress (Yerbury et al. 2005). Previous studies have shown that the metabolic activity of these bacteria often diminishes or even leads to dormancy during such conditions (Hueso et al. 2012). Conversely, Acidobacteria and Nitrospirae are sensitive to soil available carbon and nitrogen; drought-induced reductions in aboveground biomass subsequently diminish soil organic carbon and nitrogen content (Breitkreuz et al. 2021).

Following AVG application, the relative abundances of Proteobacteria and Actinobacteria increased. This may be attributed to reduced plant-derived ethylene, which enhances crop productivity and root vigor, thereby improving soil nutrient availability and creating a rich energy source for these copiotroph bacteria (Chodak et al. 2015). Additionally, prior research has indicated that certain taxa, such as *Nocardioides*, can produce ACC deaminase to regulate soil ACC levels, indirectly influencing plant drought resistance (Singh et al. 2015).

Our findings reveal that the relative abundance of dominant microbial taxa is significantly influenced by crop growth and soil factors. This suggests that plant-derived ethylene indirectly affects microbial community structure by altering plant productivity and soil physicochemical properties (Carvalhais et al. 2014). This indirect mechanism offers new insights into the role of plant-derived ethylene in soil ecological processes. We found that the negative effects of drought on crop growth were mitigated by the application of ethylene inhibitors, which also significantly improved soil function and increased the abundance of eutrophic microbial taxa. This enhancement may be attributed to the ethylene inhibitor treatment, which boosted the aboveground biomass (Fig. 5), and subsequently promoted the root secretions and the associated microbial taxa.

Although drought and AVG addition significantly altered the relative abundance of dominant taxa, they did not significantly impact the microbial diversity

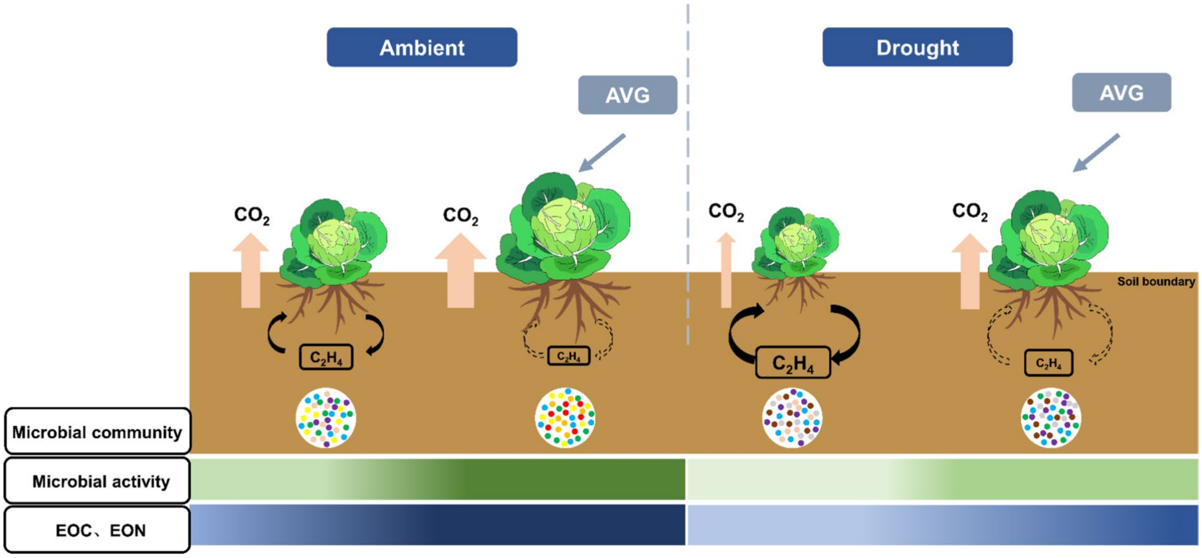

Fig. 5 Ethylene inhibitors (AVG) are utilized to regulate plant-derived ethylene (C_2H_4) concentrations under drought conditions, influencing crop growth and soil function in subtropical agricultural ecosystems. Drought stress leads to increased ethylene production, elevating its concentration in the soil, which can alter the soil microbial community, reduce microbial activity, decrease soil soluble organic carbon and nitrogen content, and lower soil respiration, ultimately inhibiting crop growth. The application of AVG under drought conditions mitigates the negative effects of elevated ethylene levels. Continuous and dashed black arrows represent ethylene concentrations following control and AVG application, respectively. Arrow width indicates hypothetical soil respiration rates. The color intensity of the solid lines reflects microbial activity, soil soluble organic carbon, and nitrogen content, respectively. Different colored spheres denote soil microbial communities under various treatments

index. This aligns with previous findings, which noted that drought stress primarily affects soil microbial components rather than diversity within farmland ecosystems (Kundel et al. 2020). While we observed changes in soil microbial diversity in response to drought stress and plant-derived ethylene, it is important that not all soil microorganisms detected were active. Therefore, future investigations into changes in soil microbial community structure could benefit from combining stable isotope nucleic acid probes with metagenomic sequencing techniques. Given the sensitivity of soil microbial communities to environmental changes, microbial community abundance and diversity often serve as key indicators of soil functional health (Qiu et al. 2021; Dong et al. 2024). Our study clarifies the microbial mechanisms through which agricultural ecosystem functions respond to drought, highlighting that the effects of drought on critical ecological functions, such as crop growth, are associated with shifts in the dominant taxa of soil microorganisms. This underscores the significance of ethylene in regulating changes in soil microbial communities. This also provides a scientific basis for considering the utilization of microbial resources in future drought management strategies aimed at enhancing crop growth and improving soil functions under drought stress.

Conclusion

Our results indicate that ethylene production by plant roots significantly influences agroecosystem functions under drought stress. Drought leads to increased ethylene content, which adversely affects crop growth and soil functions. Conversely, reducing ethylene concentration can mitigate some of the negative impacts of drought on agricultural ecosystem functionality, thereby enhancing overall ecosystem performance. The underlying mechanism for these changes involves AVG significantly increasing the relative abundance of Proteobacteria and Actinobacteria. This research marks the first field validation of the concept that reducing ethylene derived from plants improves agroecosystem functionality under drought stress. Furthermore, our findings provide a theoretical foundation for utilizing AVG to enhance drought tolerance in agroecosystem functions. Finally, given the differences in drought tolerance among crops and the adaptability of microbial communities, future research should further evaluate the specific effects of these factors.

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Data availability Data will be available on request. The sequencing data supporting the findings presented here are available in the NCBI repository with the identifiers PRJNA1195390.

Declarations

Competing interest The authors declare that there is no conflict of interest.

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