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Elevated atmospheric CO_2 levels in enhancing primary productivity: Potential and limitations

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Abstract

Feeding a growing population in the face of a changing climate poses a major challenge since it involves maintaining the gains needed to sustain the productivity of major crops. There has been an unprecedented urgency and greater momentum in recent decades to find global solutions to this challenge. However, Carbon dioxide is essential to the process of photosynthesis. Most plants grown indoors require a minimum CO_2 concentration of 330 mg/l to enable them to photosynthesis efficiently and produce energy in the form of carbohydrates. These concentrations of CO_2 are enough for plants to grow and develop normally. Lower concentrations can seriously impede plant growth and general health. In fact, a drop of 25% in natural CO_2 concentrations can easily inhibit growth by over 50%. The ability to use leaf N for photosynthesis is considered to be the main limiting factor in photosynthesis adaptation for most plants in elevated CO_2 environments. Rising CO_2 over the next century is likely to affect both agricultural production and food quality. Multidisciplinary research and implementation are needed to ensure that a growing global population, particularly those in low- and middle-income countries, will have sufficient access to plentiful, safe, and nutritious food. Understanding the magnitude and pattern of the problem, and effectiveness of potential solutions, is critical for ensuring the health and well-being of future populations.

Keywords: Elevated CO_2, photosynthesis, water use efficiency, climate change, Multidisciplinary research.

Introduction

Feeding a growing population in the face of a changing climate poses a major challenge since it involves maintaining the gains needed to sustain the productivity of major crops. There has been an unprecedented urgency and greater momentum in recent decades to find global solutions to this

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challenge. Greenhouse gases have increased since 1750, with CO_2, methane and nitrous oxide rising by about 40%, 150% and 20%, respectively. Global warming triggered by increased greenhouse gases, especially CO_2 (carbon dioxide), poses a serious threat to crop productivity across the globe. The Intergovernmental Panel on Climate Change (IPCC) 2018 special report on the "Impact of global warming of 1.5 °C (SR 15) above pre-industrial levels" pledges to limit global warming to 1.5 °C, which requires that "CO_2 emissions need to fall 45% from 2010 levels by 2030, and reaching 'net zero' around 2050". A recent report curating 174 papers, including 1540 experiments on the effects of ambient temperature, tropospheric CO_2 and O_3 concentration, water availability and salinization estimated the mean effect of standardized environmental changes. It revealed that mean yield (95% confidence interval) and reported yield changed in all vegetables and legumes, ranging from a 22% variation for a 250 ppm increase in CO_2, 8.9% for a 25% increase in O_3 and 31.5% reduced mean yields with a 4°C increase in temperature.

The synergistic interplay of existing abiotic and biotic stresses with rising CO_2 levels, especially in legumes has been revealed with a combination of heat and drought stresses in legumes like common bean (*Phaseolus vulgaris*) and soybean (Glycine max) and cereals like sorghum (Sorghum bicolor) and barley (*Hordeum vulgare*). This multifaceted and alarming scenario is being addressed by scientists in various ways – by focusing on individual stressors, or combined stressors like elevated CO_2 and existing biotic and abiotic stresses through physiological, biochemical and molecular studies.

Global atmospheric CO_2 levels

Data are reported as a dry air mole fraction defined as the number of molecules of carbon dioxide divided by the number of all molecules in air, including CO_2 itself, after water vapor has been removed. The mole fraction is expressed as parts per million (ppm). Example: 0.000400 is expressed as 400 ppm. Data from the past 10 years suggests that the average yearly rate of increase is 2.24 ppm. This rate of increase is more than double that observed during the 1960s. The CO_2 concentration will reach 700-1000 ppm by the end of 21st century.

Potential of elevated atmospheric CO_2 levels

Mostly, the potential of elevated atmospheric CO_2 levels for enhancing plant primary productivity can be explained by following:

- Increased photosynthesis/biomass
- Better Water use efficiency

- Better Nutrient use efficiency
- Increased yield

1. Increased photosynthesis/biomass

Carbon dioxide is essential to the process of photosynthesis. Most plants grown indoors require a minimum CO_2 concentration of 330 mg/l to enable them to photosynthesis efficiently and produce energy in the form of carbohydrates. These concentrations of CO_2 are enough for plants to grow and develop normally. Lower concentrations can seriously impede plant growth and general health. In fact, a drop of 25% in natural CO_2 concentrations can easily inhibit growth by over 50% (Fig. 3). Consequently, the grow room should be set up to replenish CO_2 levels to at least 330 mg/l throughout the plant's day time. Natural ventilation (using convection and chimney effects) or forced ventilation (using intake/exhaust fans) can usually ensure that this objective is met adequately.

2. Better Water use efficiency

Elevated carbon dioxide increases the productivity and water use efficiency of nearly all plants. The mechanism of improving water use efficiency is shown in fig. 7.

3. Better Nutrient use efficiency

The response of plants to rising CO_2 can cause an increase in nutrient use efficiency of utilizing plant essential macro and micronutrients.

4. Increased yield

The overall effect of elevated CO_2on rice is quite different to other C3 species. A large amount of dry mass was partitioned to the roots at elevated CO_2 at the expense of the leaf blades and sheaths. The concentrations of N, P and K were lower in the plants grown at elevated CO_2 on a percentage dry mass basis; Mg was unaffected and Ca was increased.

Limitations of elevated atmospheric CO_2 levels

The major limitations under elevated atmosphericCO_2 levels are as follows:

- Greenhouse effect/global warming
- Drought stress
- Heat stress
- C/N imbalance
- Decreased yield quality

a. Greenhouse effect/global warming

Carbon dioxide (CO_2) is the primary greenhouse gas emitted through human activities. In 2019, CO_2 accounted for about 80 percent of all U.S. greenhouse gas emissions from human activities. Carbon dioxide is called a greenhouse gas because it is one of the gases in the atmosphere that warms the Earth through a phenomenon called the greenhouse effect. Carbon dioxide molecules in the atmosphere absorb long-wavelength infrared energy (heat) from the Earth and then re-radiate it, some of it back downward. CO_2 has caused most of the warming and its influence is expected to continue. Carbon dioxide (CO_2) has contributed the most to climate change between 1750 and 2011. Radiative forcing units are expressed as the power (watts) per square meter surface area of Earth.

b. Drought stress

Elevated CO_2 levels in long-term cause drought stress by decreasing soil water status. Drought stress in plants is characterized by reduced leaf water potential and turgor pressure, stomatal closure, and decreased cell growth and enlargement. Under the moderate or severe drought conditions, the accumulation of salts and ions in soil upper layers leads to osmotic stress and ion toxicity in plants. With an increase in the degree of drought stress, turgor pressure of the plant cells decreases, causing plant cell wall wrinkled and loose.

c. Heat stress

Elevated atmospheric CO_2 levels increase global temperature due to its greenhouse effect and global warming. The increased temperature resulted in heat stress for the crop plants. Heat stress is defined as the rise in soil and air temperature beyond a threshold level for a minimum amount of time such that permanent harm to plant growth and development occur. A detailed multi-location study highlights the impact of temperature effects on the yields. Heat stress induces changes in respiration and photosynthesis and thus leads to a shortened life cycle and diminished plant productivity. The early effects of thermal stress comprise of structural alterations in chloroplast protein complexes and reduced activity of enzymes

d. C/N imbalance

As elevated atmospheric CO_2 levels increase carbon fixation in plants and soil by increasing biomass production and photosynthetic activity. But nitrogen content decreases in the plant and soil due to dilution effect and hence there is an imbalance between C:N ratio which directly affects organic matter decomposition, nutrient recycling and nutrient availability to the crop plants.

e. Decreased yield quality

Food quality is declining under the rising levels of atmospheric carbon dioxide that we are experiencing. If carbon dioxide levels continue to rise, the amount of food proteins in the whole world could drop as much as three percent in just a few decades. There are already people all around the world without enough food or proper nutrition, especially protein.

Mitigation strategies

The effects of CO_2 on nutrient concentrations in edible tissues of C3 plants are reflected. The mechanisms proposed as responsible for changing the plant mineral concentration are: "carbohydrate dilution" in which there is an increase in carbon (C) assimilation relative to the mineral concentration, decrease in transpiration rates that reduces mass flow of nutrients, and shifting nutrient allocation by altered biochemical processes between tissues can affect nutrient uptake. In addition, down-regulation of photosynthesis and increased photorespiration has been also expected to elucidate the variations in mineral concentrations. The CO_2 concentration has also a direct effect on the bioavailability of nutrients in soils and, consequently, affecting the quantity of existing microorganisms. Possibly, due to changes in soil pH, eCO_2 improves the exudation processes affecting nutrient availability. Furthermore, the role of eCO_2 increasing mycorrhizal colonization and organic matter (OM) decomposition in the soil, facilitating the availability of several nutrients

The mitigation strategies need to be adopted in future to cope-up the negative effects of elevated atmospheric CO_2 levels. Multidisciplinary research and implementation are needed to ensure that a growing global population, particularly those in low- and middle-income countries, will have sufficient access to plentiful, safe, and nutritious food.

Conclusion

Elevated CO_2 increases the size and dry weight of most C_3 plants and plant components. Selection of plants that could partition more photo-assimilates to reproductive growth should be a goal for future research. C_4 plants include most tropical and sub-tropical grasses and several important crops, including maize (corn), sugar cane, sorghum, and the millets. There has, therefore, been considerably more research on the responses to elevated CO_2 in C_4 than in CAM plants. Rising CO_2 over the next century is likely to affect both agricultural production and food quality. Elevated CO_2 and N_2 increased photosynthesis and water use efficiency (WUE) of plants. The ability to use leaf N for photosynthesis is considered to be the main limiting factor in photosynthesis adaptation for most plants in elevated CO_2 environments. Elevated CO_2also tends to reduce the density of stomata on leaves of some plant species. This effect, together with CO_2-induced reduction in stomatal apertures, can reduce a plant's capability to cool itself because of reduced evaporation of water from leaves. This may increase susceptibility to heat stress, which in turn can affect water use and yield. An advanced understanding of the mechanisms and genes that mediate CO_2 regulation of stomata could become valuable for better adjusting C3 plants in light of the steeply increasing atmospheric CO_2. For most C4 crops, photosynthesis is generally already working at maximum capacity, due to the increased atmospheric CO_2 concentration; such crops would thus instead be candidates for the manipulations described above that aim to increase water use efficiency by reducing stomatal apertures while enabling optimal CO_2 intake for C4 photosynthesis. Multidisciplinary research and implementation are needed to ensure that a growing global population, particularly those in low- and middle-income countries, will have sufficient access to plentiful, safe, and nutritious food. Understanding the magnitude and pattern of the problem, and effectiveness of potential solutions, is critical for ensuring the health and well-being of future population.