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A simplified system to quantify storage of carbon dioxide, water vapor and heat within a maize canopy

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Highlights

1. A new multiport profile system simplifies examining the CO_2 and H_2O storage terms.
2. Neglecting canopy storage terms leads to inaccuracies in crop energy balance closure.
3. Energy closure is improved if canopy storage is considered.
4. The multiport system is necessary for eddy covariance-derived fluxes over maize canopy.

Abstract

The significance of canopy storage of CO_2, latent energy and sensible heat within agricultural crops has not been fully examined. Reported canopy storage terms are consistently smaller than found for a forest ecosystem, such that they are often neglected. A novel multiport profile system has been developed to examine these storage terms. The system sequentially samples air from four heights to a single non-dispersive Infrared Gas Analyzer (IRGA). Following extensive laboratory testing, the system was used to measure CO_2 and H_2O within an eastern Tennessee maize canopy in 2023. The storage of latent and sensible heat was large enough to merit incorporation with conventional field measurements. The new system will enable profile measurements of CO_2 sufficient to quantify canopy storage terms as are needed in agricultural field campaigns.

Keywords: Multi-port system, vertical canopy profile, storage terms, energy balance closure, maize, carbon sequestration

1 Introduction

In the last few decades, significant work has been conducted to improve understanding of gaseous exchanges between soils, plants, and the atmosphere. These improvements have been rapidly incorporated into land-surface models and numerical-based weather prediction as well as assessment of atmospheric fluxes of carbon dioxide (Lamas Galdo et al., 2021), water vapor (Wang et al., 2023), and heat over vegetated landscapes (e.g., Tilden and Steven, 2004). Eddy covariance (EC) is a widely accepted method to measure the fluxes of CO_2, H_2O, and heat in the ecosystem (Nicolini et al., 2018). Routine EC measurements are now made at more than 650 locations, distributed globally (Fluxnet; Baldocchi, 2003).

At most forest experimental sites, the measured energy budget is not always close to the balance calculated by the conventional method expressed by Eq. (1) (Wilson et al., 2002). An important

https://doi.org/10.5194/egusphere-2024-2041
Preprint. Discussion started: 13 August 2024

factor emerging from forest ecosystem studies is that storage terms contribute substantially to the energy closure of forests and to the quantification of evapotranspiration (McCaughy and Saxton, 1988). In most forest studies, storage terms are ignored in consideration of the energy balance equation:

$$R_n - G = H + LE \quad (1)$$

Here, R_n is net radiation, G is soil heat flux, H is sensible heat flux and LE is latent heat flux.

Storage measurement is challenging due to temporal changes in CO_2, H_2O, and heat (Yang et al., 1999). Globally, only a few sites (less than 30 %) apply a profile measurement system to calculate the temporal variations and storage terms (Papale, 2006). Many studies have reported that energy balance closure is an unsolved problem for a variety of vegetation types: the sum of sensible and latent heat flux is found to be 10-30% lower than the available energy (Wilson et al.,2002; Twine et al.,2000; Leuning et al. 2012; Russell et al. 2015; Liu et al. 2017; Raza et al., 2023a). There are several possible reasons for energy closure errors resulting from EC experimentation, such as neglecting the canopy and soil storage terms, loss of low- or high-frequency flux components, and the use of inappropriate averaging times, etc. (Massman, 2000; Meyers and Hollinger, 2004). Measurement procedures to test energy balance closure vary by researchers and there is no standardized way to address the issues that arise.

In the case of agricultural cropping systems, storage terms are considered small and are often ignored (Raza et al., 2024; Nicolini et al., 2018). Studies on the assessment of storage terms within agricultural ecosystems are few, but the matter is well documented by researchers in the case of forest ecosystems studies (Mayocchi and Bristow, 1995; Wilson et al., 2002).

Storage terms quantification is challenging because of its requirement for measurements both within and above the canopy (Yang et al., 1999). Finnigan (2006) reported that the storage term is underestimated when the average sampling time is large. Neglecting canopy storage terms in studies of Net Ecosystem Exchange (NEE) can also cause substantial errors (Raza et al., 2023b). To understand the role of the storage terms in energy balance closure and NEE, new measurement and analysis approaches are required (Irmak et al, 2014).

In the most recent series of field experiments conducted by the present research team, as now reported, the emphasis has also been on fluxes of carbon dioxide (CO_2). The field site is

https://doi.org/10.5194/egusphere-2024-2041
Preprint. Discussion started: 13 August 2024

large enough to warrant the use of EC measurement systems without fears of fetch and/or footprint limitations (q.v., Foken et al., 2017). Measurement procedures followed the recommendations of FLUXNET (Wilson et al., 2002) and ICOS (Montagnani et al., 2018). A key aspect of the research program was the requirement for CO_2 concentration measurements at several heights within the plant canopy, to permit examination of (1) flux interactions with pooled CO_2 at night; (2) the CO_2 storage term derived from EC observations; and (3) sub-canopy mixing.

The purpose of the present paper is to describe a measurement system specifically designed to provide observations for assessing the quantities contributing to the diurnal heat cycle, including the various storage terms and net ecosystem exchange. The instrumentation now described will be used to extend the analysis into the inter-canopy airspace, using eddy covariance observations as a basis for assessing storage terms. The protocols recommended by the ICOS community (e.g., Montagnani et al., 2018) have been used as guidance.

2 Methodology/Configuration

2.1 Apparatus design, operation, and measurement

Field experiments have repeatedly shown that the need for an uninterrupted series of observations of difficult–to–measure variables impose technical requirements that are often difficult to satisfy. In practice, the more complicated a measurement system, the more likely the desired continuous records will be interrupted by instrumentation malfunctions or by a variety of other unanticipated issues. Such interruptions have been a challenge in the many studies of maize crops conducted by the University of Tennessee (O'Dell et al, 2014; Hicks et al., 2020) in their series of field experiments These field experiments (in Lesotho and Zimbabwe as well as in Tennessee and Ohio in the USA) have demonstrated the need for a reliable yet technically simple measurement system to measure profiles of the quantities of interest, within and above a growing crop. To satisfy the basic requirements for time continuity and reliability of the data record, a multi-port sampling system has been developed. The intent is to facilitate the routine acquisition of temperature, humidity, and carbon dioxide data within and above a maize canopy.

Analysis of the recorded observations requires attention to gradients of the variables measured and well as to the variables themselves. To minimize consequences of individual sensor offsets when gradients are computed, the new system is designed to use a single detection system (an

https://doi.org/10.5194/egusphere-2024-2041
Preprint. Discussion started: 13 August 2024

IRGA —LI-COR-850, CO_2/H_2O gas analyzer). In the application considered here, the system was used to measure four heights, two within a maize canopy and two above.

Figure 1 presents a schematic description of the apparatus. The system is designed to maintain continuous airflow through all intake tubes, to cycle through all heights of measurement every minute and to minimize the switching time between samplings. The system consists of two small pumps [Model TD-3LSA, Brailsford & CO., INC. Antrium. NH, USA], one pump (purge pump) draws in the sampling air to maintain constant flow to minimize hygroscopic interactions along the tube wall while the other pump pushes the drawn air to the IRGA. The sampling pump is mounted close to the IRGA so that air smoothly enters the IRGA at ambient pressure. The airflow rate through the sampling tubes is regulated by a flow meter [LZQ-7 flowmeter, 101.3 KPa, Hilitland] at 700 ml/min; the flow rate through the IRGA is maintained 1000 ml/min. The switching between heights is controlled by four three-way solenoid valves [231Y-6, Ronkonkoma, NY, USA]. The body material of the solenoid is brass, and the internal component material is stainless steel as is required when water vapor is present.

Each sampling tube is 10.5 m long to ensure each sampling height has the same transit time. The purge pump manifold and all sampling tubes are of the same kind of urethane [BEV-A-LINE, Polyethylene material, Cole Parmer]. Before passing through the analyzer, the air is passed through a 1-µm pore filter [LI-6262, LI-COR NE, USA] to avoid the drifting of the analyzer and pumps during the time of measurement due to the accumulation of debris, dirt, particulates, etc., that can cause blockage in the analyzer optical cells. The air outlet of the purge pump and IRGA are open directly to the atmosphere.

https://doi.org/10.5194/egusphere-2024-2041
Preprint. Discussion started: 13 August 2024

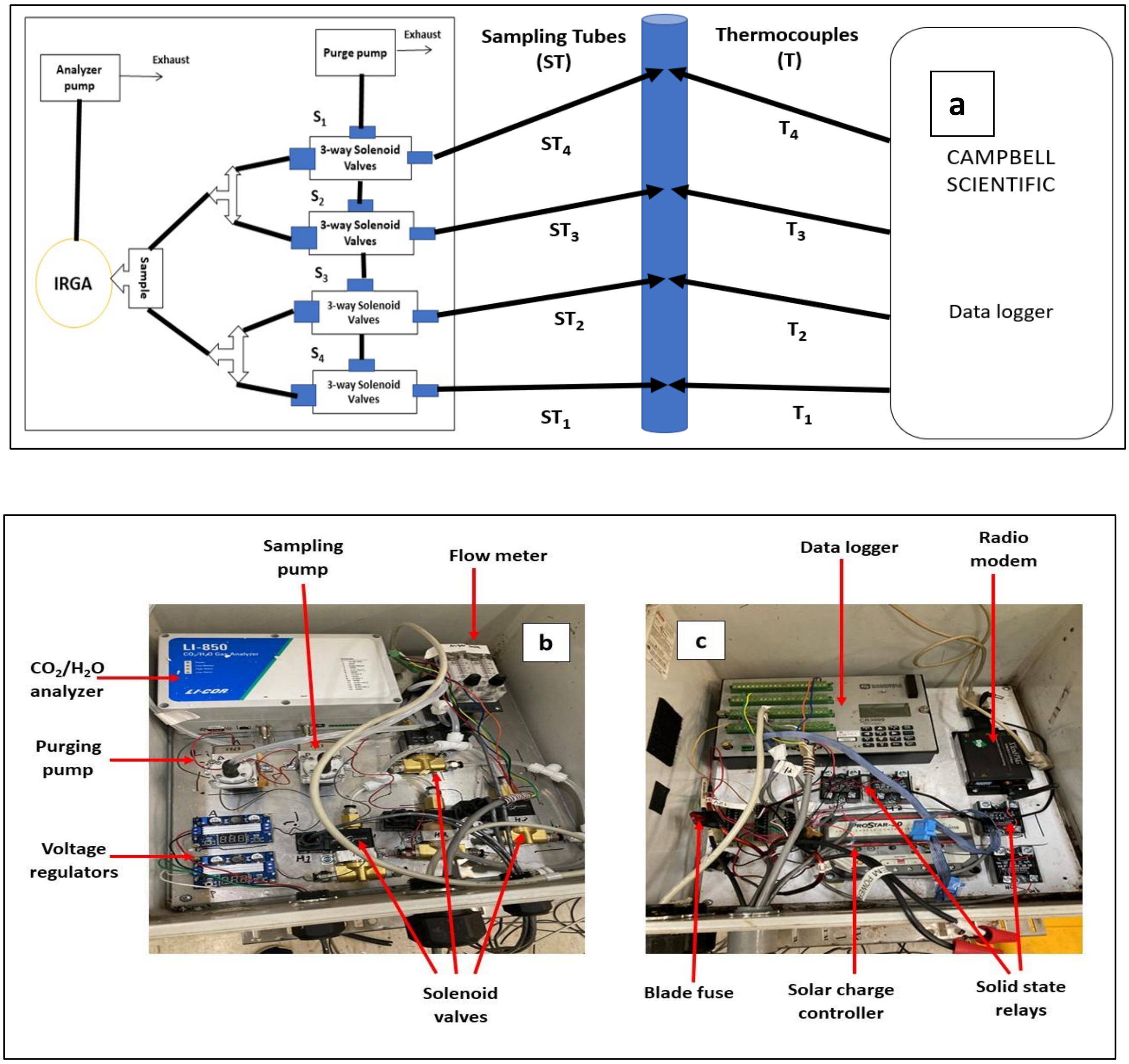

Figure 1abc (a) Schematic diagram of the manifold for profile sampling of CO_2, water vapor (H_2O), (b) analyzer, pump, and manifold system, (c) data logger for data collection

2.2 Sampling time

To determine the sampling time of the multiport system for accurate measurement of CO_2 and H_2O, the system was first evaluated in the laboratory. The apparatus was first flushed with nitrogen (N_2) gas to create a zero-carbon dioxide (0 ppm) environment. Subsequently, a known

https://doi.org/10.5194/egusphere-2024-2041
Preprint. Discussion started: 13 August 2024

concentration of CO_2 (430 ppm) at ambient pressure was fed through the intake tubes and system outputs were measured, with results as shown in Table 1 and Fig. 2. This process allowed determination of the minimum amount of time reach a stable measurement reading.

To derive a continuous record of concentrations at each of the heights of interest (in the present experiment, four of them) switching between heights was set at every 7.5 seconds allowing each of the heights to be sampled twice a minute. Figure 2 shows the delays associated with the switching; these are confirmed by consideration of the known travel length and flow rate in the tubes. The delay (3.2 seconds) in reading by the IRGA was due to the presence of residual air in the previous sampling tube and other components of the apparatus, including the solenoid and manifold (refer to Fig. 1). This delay indicates how much time the system takes to purge the shared air in the manifold system. The sampling pump has a flow rate of 1 L/min, optimized to maximize cycling time and minimize any water vapor surface interaction in the urethane tubes. 3.2 seconds were ignored, and the remaining 4.3 seconds were recorded by the datalogger.

The laboratory tests showed that as the IRGA received known [CO_2], it took approximately 1.8 seconds to achieve a steady output. During the laboratory evaluation period, the recorded error was less than 0.5% in [CO_2] between sampling heights as shown in Table 1. An accuracy error of less than 1% is well within the acceptable range for the IRGA now used, according to the specifications provided by the manufacturer. Montagnani et al. (2012) found 11% error for a set of measurements when estimating CO_2 storage flux using the ICOS method.

Table 1 IRGA output for multiport air sampling system for CO_2 conc. (430 ppm) fed through the sampling manifold at ambient pressure.

Sampling tube	**Mean CO_2 concentration (ppm)**	**SD**	**No. of samples**	**Error %**
Intake 1	430	0.474	23	0.00
Intake 2	431	0.196	15	0.20
Intake 3	431	0.167	16	0.20
Intake 4	432	0.119	13	0.46

https://doi.org/10.5194/egusphere-2024-2041
Preprint. Discussion started: 13 August 2024

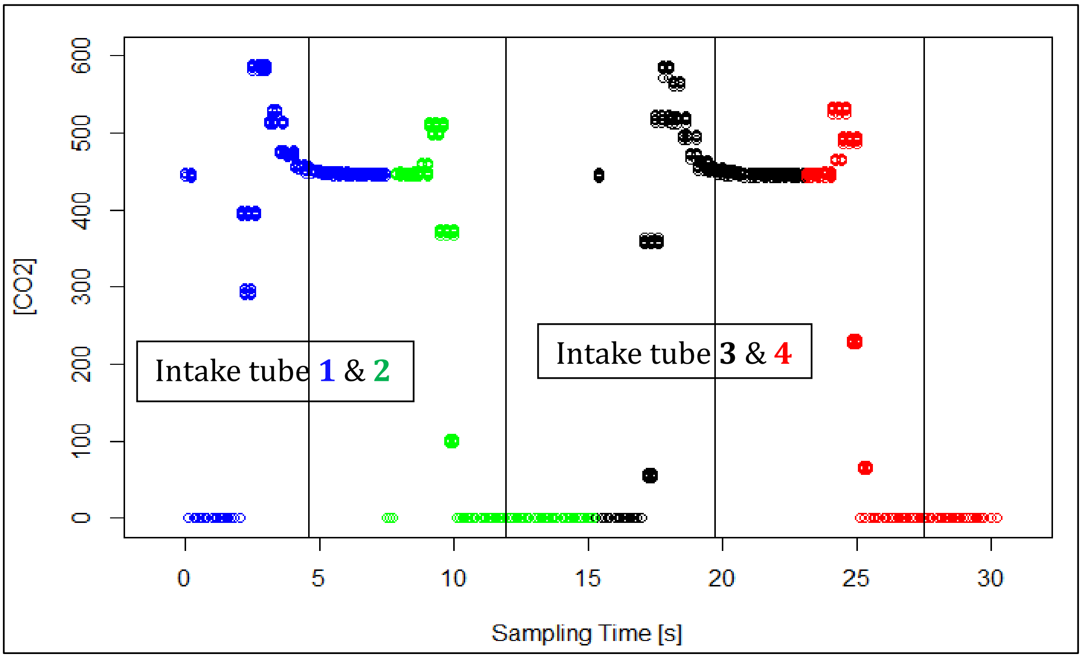

Figure 2 The time-dependent relationship between the infrared gas analyzer (IRGA) in the multiport air sampling apparatus for a gas concentration of 430 ppm CO_2 flowing at <1 L/min. The switching between the intakes occurs every 7.5 seconds. Blue corresponds to sampling intake height 1, green to height 2, black to height 3, and red to height 4. The vertical lines demarcate the stable, equilibrium regions where the measurements were suitable to be recorded. Here the lines were at 4.9 seconds but were further improved to 3.2 seconds.

3 Field measurement setup

Following laboratory testing, the system was deployed in a field study conducted at Loudon, Tennessee, in 2023. In this study, four intake sampling tubes were positioned at heights (m) of 0.11, 0.5h, 1+h, and 2+h, where h is maize canopy height above the soil surface. Note that one height was permanently set at 0.11 m and three of these heights were adjusted as the crop grew. Sampling intakes were positioned on a 10 m steel mast at the respective positions. Thermocouples at the same height were used to measure temperature within and above the

https://doi.org/10.5194/egusphere-2024-2041
Preprint. Discussion started: 13 August 2024

canopy; these thermocouples were aspirated within a white PVC pipe of 1.9 cm diameter (Figure 3) that also served as a radiation shield.

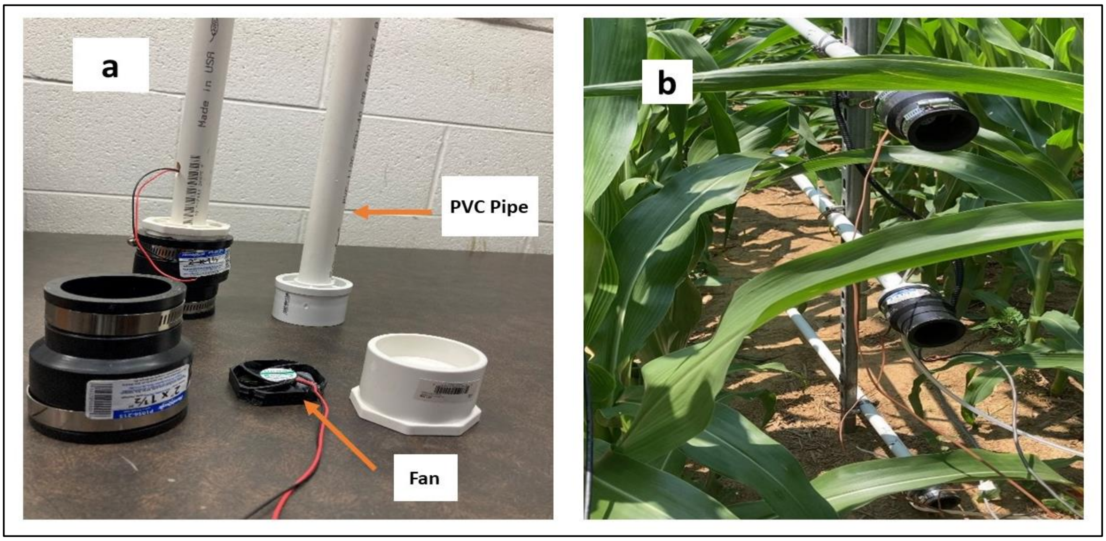

Figure 3ab Aspiration of CO_2 intake tubes and thermocouples and their application in the maize canopy.

To provide the measurements necessary to interpret the gradient observations, a tripod tower was used to support an eddy covariance system and supporting micrometeorological variables — an IRGASON [CO_2/H_2O] open path gas analyzer system, [Campbell Scientific, Logan, Utah], a net radiometer [Kipp & Zonen SR# 103660, OTT HydroMet B.V. Delft, Netherland], infrared radiometers [IRs-S1-111-SS, Apogee Instruments Inc, USA], and type T thermocouples [Omega, USA]. A schematic diagram of the system is shown in Fig. 1. The system was visually inspected every week for any leakage, condensation, and contamination.

3.1 Experimental site

The field study was conducted near Philadelphia, in Loudon County Tennessee (35.6729° N, 84.4651° W). The study area is twenty-three hectares of agricultural farmland cultivated with a maize cropping system. The red point on the map represents the location of the site where the system was installed. The mean annual temperature and precipitation of the site are 12-15 ^oC and 132-142 cm respectively. The elevation and slope of the site are 280 m (Figure 4A) and 2-5%

https://doi.org/10.5194/egusphere-2024-2041
Preprint. Discussion started: 13 August 2024

(Figure 4B) respectively. The soil was classified as Alcoa Loam (Rhodic Paleudult) according to the USDA classification scheme (Soil Taxonomy, 1976).

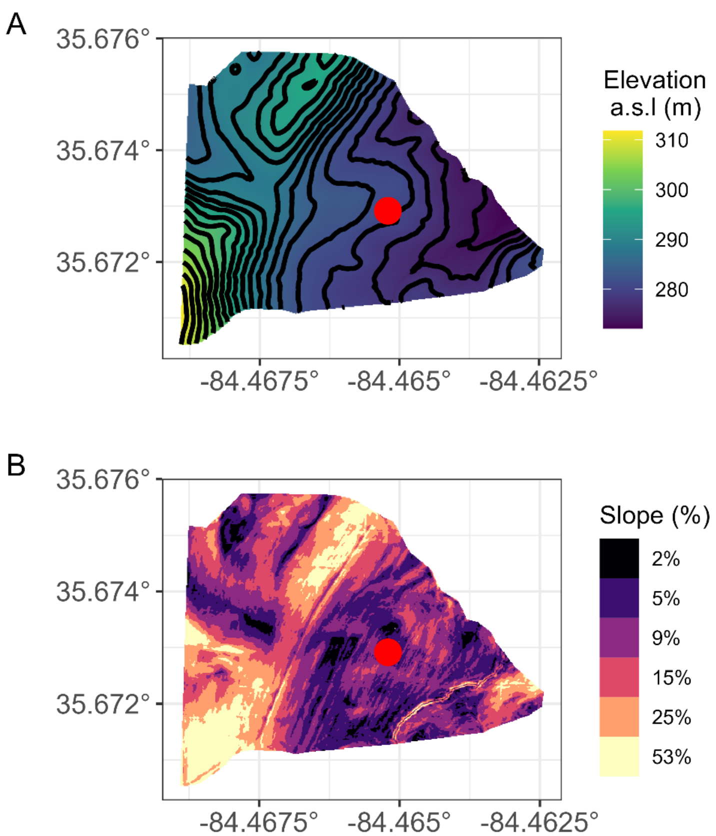

Figure 4 Soil elevation and slop overview of the test site in rural Philadelphia Tennessee, USA. A) The red point on the map shows the instrumentation location.

3.2 Calculation of storage terms

In accordance with other studies of the surface energy budget using EC systems, storage terms refer to depletion or accumulation of scalar quantities (CO_2, H_2O, etc.) in a hypothetical control volume beneath the height of EC flux measurement. A storage flux is defined as the rate of change of dry molar concentrations of the same variables within the same control volume. Both concepts relate most directly to the conditions of “perfect” micrometeorology. In practice, natural complexities of surroundings and

https://doi.org/10.5194/egusphere-2024-2041
Preprint. Discussion started: 13 August 2024

exposures interfere to the extent that will necessarily be site-specific. Moreover, the covariances that are central in related deliberations are statistical quantities, with well-recognized error margins associated with every quantification of them. During this study, the storage fluxes of scalar quantities (CO_2, water vapor, etc.) were calculated using the ICOS methodology (Montagnani et al., 2018). For the case of CO2,

$$J_c = \overline{\rho_d} \sum_{i=1}^{N} \left(\frac{\Delta c}{\Delta t} \right)_i \Delta z_i. \qquad (2)$$

Here, J_c is the storage term of CO_2 within the i_{th} layer over which Δc is measured, Δz_i is the thickness of this layer and Δt is the measurement time step; $\bar{\rho}_d$ is dry air density, and N is the number of layers.

4 Results and discussion

4.1 Vertical profile of CO_2 within a maize canopy

Previous experiments revealed the ubiquity of nocturnal pooling of CO_2 because the presence of the maize canopy and the development of a strongly stable atmospheric surface layer that permits CO_2 emitted by the soil biota to accumulate overnight. Fig. 5 presents average diurnal cycles of CO_2 concentrations measured at four heights, two within the canopy and two above. The concentrations of CO_2 observed low in the canopy exceed those elsewhere. Moreover, note that the increasing concentrations within the pool closely parallel each other, providing support for the assumptions made elsewhere about CO_2 profile linearity within the pools. The fact that concentrations drop below ambient (~425 ppm) suggests that photosynthesis is ongoing which rapidly reduces the canopy concentrations.

Following dawn (or sunrise as indicated in Fig. 5) the accumulated concentrations of CO_2 drop rapidly as convection starts to mix surface air with that aloft and as photosynthesis commences. Concentrations decrease to about 350 ppm, due to the maize photosynthetic requirement for CO_2 from the air. After sunset, concentrations of CO_2 rise uniformly with little evidence of a separation between sub-canopy and upper-canopy concentration regimes. Note, however, that there is evidence of early effects of soil emissions, such that the 11–cm trend departs from the others soon after solar noon.

https://doi.org/10.5194/egusphere-2024-2041
Preprint. Discussion started: 13 August 2024

Furthermore, at all four heights, CO_2 concentrations were greatest during late night and early morning until 0600 local time (LT), after which concentrations declined rapidly and reached a relatively constant level of approximately 350 ppm in the afternoon (1200 to 1800 LT). The 350 ppm observation is 70 ppm less than current ambient CO_2 due to photosynthetic demand. Subsequently, CO_2 concentrations increased again, with a more pronounced increase during late night. Soil respiration, photosynthesis, and temperature contribute to this trend. During the late night, the surface atmosphere stabilizes and wind speeds decrease allowing emitted CO_2 to accumulate. Moreover, in many climatic regions like our experimental site, nighttime soil temperatures remain high enough to sustain microbial and soil respiration activities, resulting in CO_2 accumulation in the stratified air above the ground. As the sun rises, increased light availability increases stomatal activities, leading to higher photosynthesis rates.

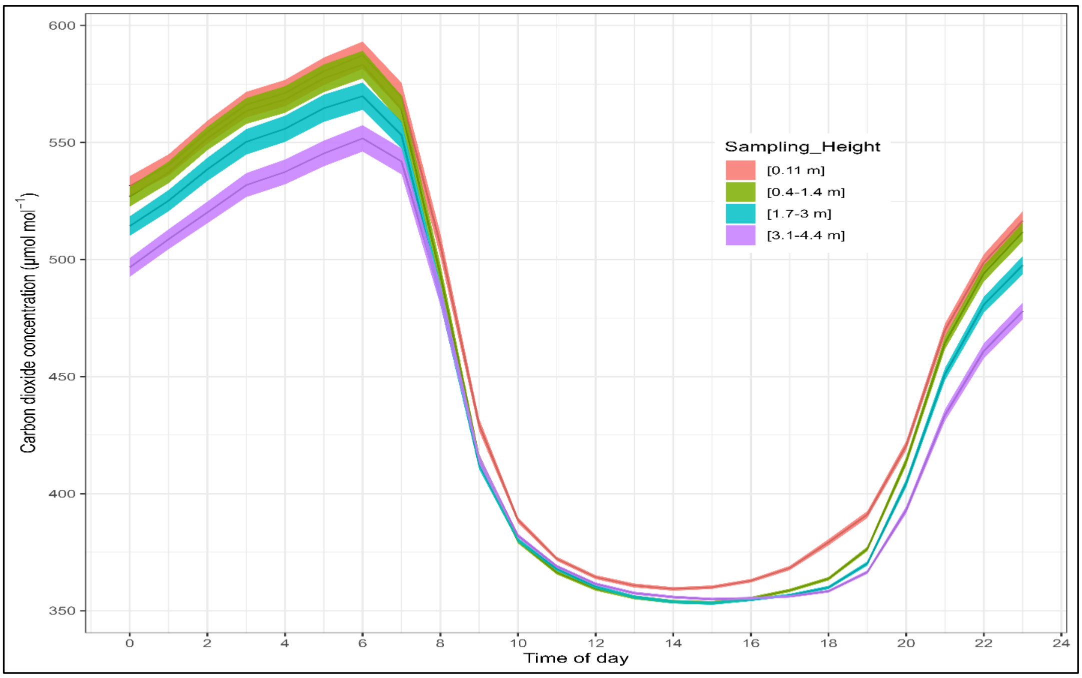

Figure 5 Average diurnal vertical cycle of CO_2 for over two months of maize canopy growth/monitoring. Times of sunrise and sunset are shown.

4.2 Vertical profile of H_2O in a maize canopy

As in Fig. 5, Fig. 6 shows 15-minute H_2O concentration observations have been used to construct an average diurnal cycle for the two-month period exemplified shown here. During daytime, H_2O

https://doi.org/10.5194/egusphere-2024-2041
Preprint. Discussion started: 13 August 2024

concentrations were significantly higher when compared to nighttime, peaking between 1200 LT and 1400 LT and then gradually decreasing. Notably, after 2000 LT, we recorded a rapid decline in H_2O concentration. At 0600 LT, the H_2O reached its minimum concentration throughout the cycle, followed by a sharp increase in the first hour. The H_2O concentration decreased as the height increased for both day and nighttime because at both times a source of water vapor is the soil surface, with crop evapotranspiration adding in the daytime.

A comparison of the diurnal cycles shown in Figs. 5 and 6 indicates considerably different cycles of CO_2 and H_2O cases. At night, Fig. 5 shows that the CO_2 profile appears to be stronger than in the daytime. The opposite is seen, for H_2O, in Fig. 6. The reason is presumed to be that CO_2 continues to be emitted from the soil at night, whereas there is no parallel process influencing the H_2O concentrations. This is a feature made apparent by the profile sampling system.

The processes of evaporation from the soil surface and evapotranspiration from leaves are linked with solar radiation. Overall, the study highlights the vertical distribution of water vapor concentration and its temporal variability, indicating that factors such as height and diurnal variations significantly influence the profile/gradient and temporal patterns of water vapor in the canopy profile.

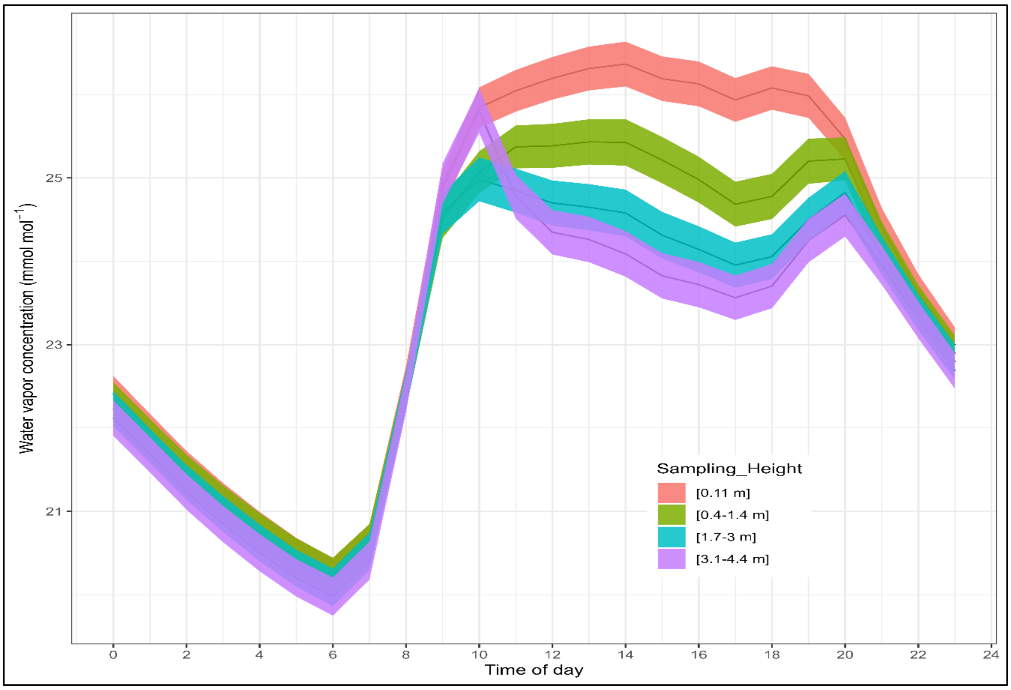

Figure 6 Diurnal vertical profile pattern of water vapor averaged over two months as in Fig. 5.

4.3 Latent heat, sensible heat and CO_2 storage fluxes of maize profile

The vertical profile data were also used to investigate how various storage fluxes influence the energy balance closure of the maize crop. The diurnal average behavior of these storage fluxes is shown in Fig. 7. CO_2 storage (Fig. 7a) exhibited higher values at nighttime as compared to daytime, due to the CO_2 pooling effect. During both early morning and late night, CO_2 storage increased at a rate of approximately 1 µmol m^{-2} s^{-1}, after which it gradually decreased until 0730-0800 LT when it became negative. CO_2 storage started to increase again, remaining close to zero until the following day. This trend indicates that CO_2 storage was significantly higher during early morning and late night as compared to daytime when photosynthesis processes actively utilized CO_2 within the canopy. During nighttime and morning, these processes were reversed, leading to CO_2 storage.

Sensible heat energy storage (Fig. 7b) was found lower than latent energy storage (Fig. 7c).

https://doi.org/10.5194/egusphere-2024-2041
Preprint. Discussion started: 13 August 2024

The diurnal patterns of sensible (Fig. 7b) and latent energy storage (Fig. 7c) show similar characteristics. Sensible heat storage remained zero until after sunrise, eventually rising to a maximum value (around 2.5 W m^{-2}) recorded between 1200 LT and 1230 LT. After that, this sensible energy storage rate declined, reaching negative values until 2400 LT and returning to zero until 0700 LT the following day.

Latent energy storage (Fig. 7c) exhibited a pattern like sensible energy storage but with comparatively higher values. The maximum latent energy storage (> 4 W m^{-2}) occurred between 0700 LT and 0730 LT, followed by a rapid decrease and negative storage until 2000 UTC. After a brief increase (presently unexplained, about 4 W m^{-2}) for thirty minutes, rapid decline ensued, leading to negligible values during the late nighttime until the next morning. The diurnal variations in sensible and latent energy storage are influenced by several factors, including solar radiation, temperature fluctuations, and plant physiological processes. The variation in canopy density, structure, and microclimate within the canopy significantly changes the canopy storage which directly influences the daily integrated fluxes. Forest studies reported that the exchange of CO2 and H2O between plant and atmosphere is regulated by canopy density (e.g. LAI), surface conductance, etc. and these canopy characteristics change seasonally which influences the estimation of flux (Renchon et al., 2024; Chen et al., 2019). Therefore, consideration of canopy storage into our analysis can improve the accurate estimation of flux.

The results provide valuable insights into the energy dynamics within the maize canopy and contribute to a deeper understanding of its environmental response to plants during different periods of the day. Latent and sensible heat storage are the two most important components of the energy balance of maize crops and are primarily influenced by important environmental conditions such as temperature, humidity, solar radiation, and wind.

https://doi.org/10.5194/egusphere-2024-2041
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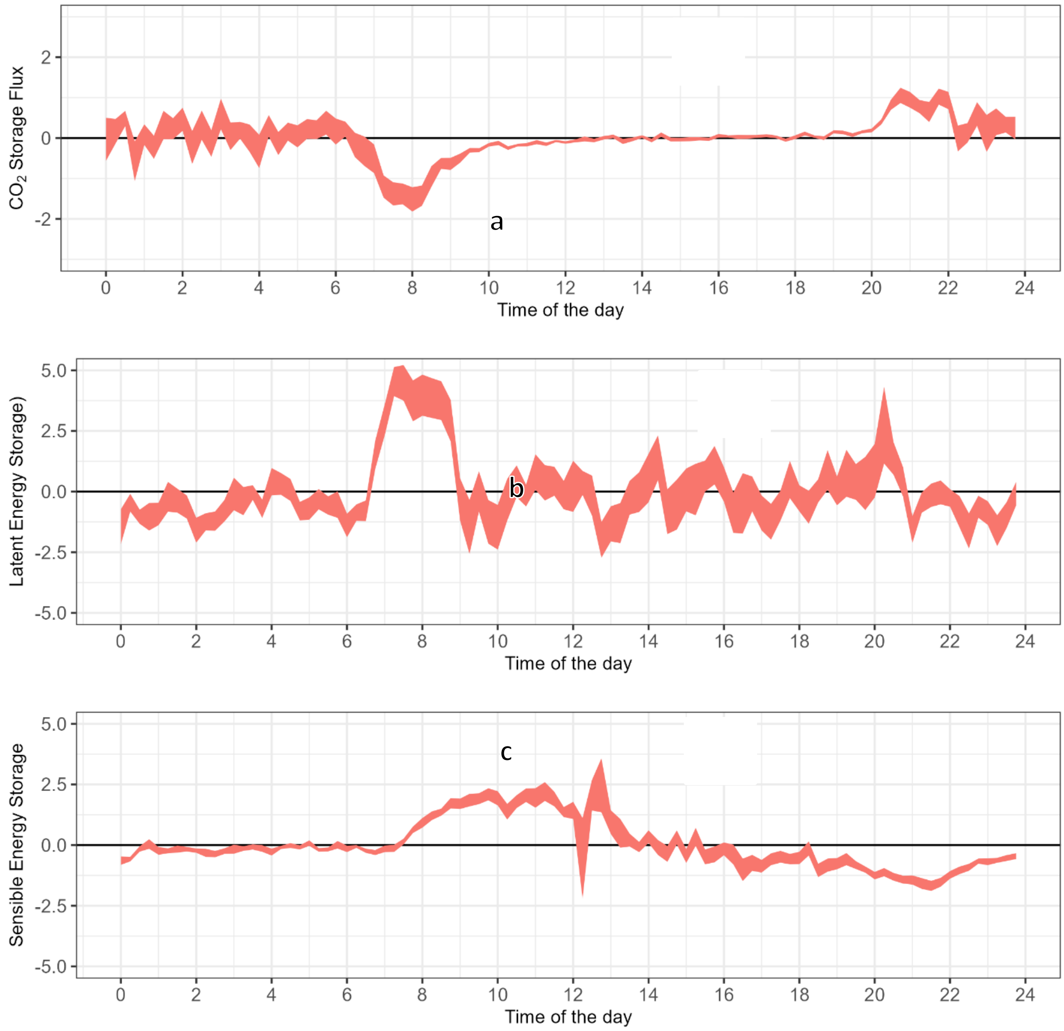

Figure 7abc Diurnal pattern of CO_2 storge (μmol m^{-2} s^{-1}), sensible energy storage (J m^{-2}s^{-1}) and latent energy storage (J m^{-2}s^{-1}) of a mature maize crop, averaged over a two month period.

Note that the definition of the heat storage used here (as in Eq. (2)) omits warming of the biomass. This omission accounts for the differences between the storage terms now computed and those published previously (e.g. Hicks et al., 2020), based on infrared measurements of

https://doi.org/10.5194/egusphere-2024-2041
Preprint. Discussion started: 13 August 2024

biomass temperature in addition to changes in air temperature and humidity below the level of atmospheric measurement.

5 Conclusions and summary

The new multi-port profile system demonstrated its effectiveness in the measurement of CO_2 and H_2O concentrations at different heights. Its development significantly aids in understanding CO_2 and H_2O concentration variations in the vertical profile of a rapidly growing maize crop, thereby facilitating precise assessments of their exchanges, storage, and overall balance within agricultural ecosystems. The new system is designed to provide the capability to change measurement heights simply, as crops grow in height, while relying on a single measurement device and thereby minimizing level-to-level biases.

The 2023 field experience with the new system indicates that canopy data obtained from the vertical profile observations hold potential for many applications in future studies such as evaluation of soil-plant-atmospheric models that rely on the precise estimation of CO_2, heat, and H_2O concentrations as well as future assessment of canopy nitrous oxide concentration.

Author contribution statement

TR: Data curation, Formal analysis, Methodology, Visualization, Writing – original draft. **NSE:** Supervising, Funding acquisition, Project administration, Writing – review & editing. **JNO:** Formal analysis, writing and reviewing. **BBH:** Supervision, Writing – review & editing.

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Declaration of computation intertest

Authors declare no competing interest associated with this submission.

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