Effects of CO₂ Concentration and Air Temperature on Entropy Production of a Micro-biosphere

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Abstract

Analyses of biospheres, ecosystems, and/or plants from the First Law of Thermodynamics have brought about fruitful results, while comparatively few studies on application of the Second Law of Thermodynamics to biospheres (ecosystems) have been conducted. We studied the effects of elevated CO₂ concentration ([CO₂]), effects of elevated air temperature, and effects of both elevated [CO₂] and elevated air temperature on entropy production of a small biosphere (plants) using a chamber system called ENTRON. We found that elevated [CO₂] had little effect on the entropy production, while elevated air temperature reduced significantly the entropy production. Change in evapotranspiration rate from the plants due to the environmental change was the main reason of the change in entropy production.

Key words: biosphere, ecosystem, entropy, evapotranspiration, global change, second law of thermodynamics

1. Introduction

In the light of thermodynamics, study from an entropy viewpoint is as important as energy study (heat-budget study) (Aoki, 1990). Heat budget analyses have been applied to biosphere (ecosystem) studies and have brought about fruitful results. On the other hand, the concept of entropy and related concepts have been ignored in biosphere studies, and only recently did some pioneering studies appear and attract attention (e.g., Aoki, 1990). Although it is not yet clear what will be brought about by entropy studies on the biosphere, there is the possibility of the entropy viewpoint demonstrating what cannot be seen from the heat budget viewpoint only.

An enormously large amount of energy has been put into environmental studies (e.g., IPCC, 2001). The effects of increase in atmospheric [CO₂] and/or related global warming on the biosphere are one of the issues of these studies. However, there has been no study on this from the entropy viewpoint. The objective of the present study was to clarify the effects of the increase in atmospheric [CO₂] and related global warming on entropy production by the biosphere. We used a small chamber system, called ENTRON, to measure the entropy production from a small biosphere (micro-biosphere).

2. Materials and Methods

2.1 ENTRON and Calculations

To measure the entropy production rate of the micro-biosphere, we constructed a chamber system, called ENTRON (Kurata et al., 2004). ENTRON consists of mainly three parts: a chamber, a controlled air production unit, and a data acquisition unit. Figure

1 presents a schematic illustration of the controlled air production unit and the chamber. The chamber is enclosed with insulating walls, except for the opening from which a micro-biosphere (in this case, plants, as described below) is illuminated. The size of the chamber is 49 × 51 × 50 cm (height). Plants are cultivated hydroponically within the chamber. The controlled air production unit produces temperature-, humidity- and [CO₂]-controlled air and sends it to the chamber at a regulated flow rate.

The micro-biosphere is defined as the entire space within the chamber. By this definition of the micro-biosphere, the entropy balance of the micro-biosphere can be expressed as:

$$Inc = Air_{in} - Air_{out} + Light_{in} + Heat_{in} - Heat_{out} + S_{product} \quad (1)$$

where *Inc* is the increase rate of entropy content of the micro-biosphere, *Air_{in}* is the entropy inflow rate associated with the air inflow, *Air_{out}* is the entropy outflow rate associated with air outflow, *Light_{in}* is the entropy inflow rate associated with light (shortwave radiation), *Heat_{in}* is the entropy inflow rate associated with heat conduction through the glass plate at the boundary with the light source space, *Heat_{out}* is the entropy outflow rate associated with heat leakage through the wall, and *S_{product}* is the entropy production rate of the micro-biosphere. Transposing the terms in equation (1) gives:

$$S_{product} = Inc - Air_{in} + Air_{out} - Light_{in} - Heat_{in} + Heat_{out} \quad (2)$$

Equation (2) is used to evaluate *S_{product}* by measuring each term on the right side. For details about the

Fig.1. Schematic illustration of a controlled air production unit and a chamber of ENTRON (Kurata et al., 2004)

Table 1. Experiment conditions

	Expt.1	Expt.2	Expt.3
Measurement Period (h)	24→ 24→ 24	24→ 24→ 24	24→ 24→ 24
CO ₂ concentration ($\mu\text{mol mol}^{-1}$)	370→570→370	370→370→370	370→570→370
Air temperature ($^{\circ}\text{C}$)	25→ 25→ 25	25→ 30→ 25	25→ 30→ 25
Dew point temperature ($^{\circ}\text{C}$)	15→ 15→ 15	15→ 22→ 15	15→ 22→ 15

expression of each term and relevant measurement, refer to Kurata et al., (2004).

2.2 Plant Materials

Seeds of Japanese Green (*Brassica campestris* L. cv. Komatsuna) were germinated and cultivated by hydroponics in an environmentally-controlled room for 20 days. Five seedlings with four fully expanded leaves were then selected for the measurement in ENTRON.

2.3 Environmental conditions

Three experiments were conducted. In all the experiments, the photoperiod was 12 hours, PPFD in the photoperiod was $100 \mu\text{mol m}^{-2} \text{s}^{-1}$, and ventilation rate through the chamber was $1.7 \times 10^{-4} \text{ m}^3 \text{s}^{-1}$. Table 1 shows [CO₂], air temperature and dew point in each experiment. The duration of the measurement period in each experiment was three days. In Experiment 1, the conditions on the first and the third day were the same and only on the second day was elevated [CO₂] compared to that of the first and the third day. The entropy production rate measured on the second day was compared to the average of that on the first and the third day, so that the effects of plant growth during the experiment could be cancelled out and only the effects of elevated [CO₂] could be extracted. Due to technical reasons, the environmental change from the first day to the second day and also from the second day to the third day took about one hour. For this

reason, a one-hour 'adjusting' time was inserted between these days. In Experiment 2, the effects of air temperature elevation were investigated in a similar way. In this case, the dew point temperature was also raised on the second day to maintain constant VPD. The 'adjusting' time in this case was 12 hours. In Experiment 3, the effects of simultaneous increase in [CO₂] and air temperature were investigated in a similar way. The 'adjusting' time was 12 hours.

3. Results and Discussion

The average entropy production rate on the first day and the third day (hereafter Control) was compared with that of the second day. In Experiment 1, entropy production did not change much at elevated [CO₂] from the Control (Fig. 2a). In Experiment 2, entropy production at 30 $^{\circ}\text{C}$ was smaller than at 25 $^{\circ}\text{C}$ both during the photoperiod and the dark period (Fig. 2b). Similar results were obtained when both [CO₂] and the air temperature were raised in Experiment 3 (Fig. 2c). The above mentioned trends can also be confirmed in Table 2. In Table 2, to exclude the effects of transition time at the beginning of the photoperiod and the dark period, the average entropy production rates between 6h and 11h in the photoperiod and that between 16h and 21h in the dark period are presented.

Investigations into each term in equation (2) showed

Fig. 2. Comparisons of entropy production rate variation of a micro-biosphere during one day under (a) elevated $[CO_2]$ (■), (b) elevated air temperature (▲), and (c) both elevated $[CO_2]$ and elevated air temperature (◆) with the Control (□) (average of the first and the third day).

that the largest difference between the elevated treatment and the Control was found in $(Air_{out} - Air_{in})$ in all the experiments. This term represents the difference between the entropy inflow with the air inflow into the chamber and entropy outflow with the air outflow from the chamber. All the other terms showed negligible change between the elevated treatment and the Control compared to this term. Table 3 shows values of this term. In Experiment 1, there was no significant change in $(Air_{out} - Air_{in})$ when

$[CO_2]$ was elevated. Both in Experiment 2 and 3, $(Air_{out} - Air_{in})$ was remarkably reduced at elevated conditions.

Table 2. Average of entropy production rate between 6h and 11h in photoperiod and between 16h and 21h in dark period

Experiments	Treatments	Entropy production rate (kJ h ⁻¹ K ⁻¹)	
		Photo-period (6h-11h)	Dark period (16h-21h)
Expt.1	Contl.	3.86 ± 0.01	2.87 ± 0.09
	Elevated	3.78 ± 0.05	2.91 ± 0.10
Expt.2	Contl.	4.13 ± 0.02*	2.75 ± 0.13*
	Elevated	2.21 ± 0.05	1.48 ± 0.02
Expt.3	Contl.	3.84 ± 0.02*	2.54 ± 0.09*
	Elevated	2.12 ± 0.06	1.41 ± 0.02

Means ± standard errors (n=6). Means with an asterisk (*) are significantly different at the 5% level by t test in each column.

Table 3. Average of $(Air_{out} - Air_{in})$ between 6h and 11h in photoperiod and between 16h and 21h in dark period

Experiments	Treatments	$(Air_{out} - Air_{in})$ (kJ h ⁻¹ K ⁻¹)	
		Photo-period (6h-11h)	Dark period (16h-21h)
Expt.1	Contl.	3.86 ± 0.02	2.92 ± 0.09
	Elevated	3.78 ± 0.05	2.97 ± 0.11
Expt.2	Contl.	4.14 ± 0.03*	2.80 ± 0.43*
	Elevated	2.20 ± 0.05	1.52 ± 0.03
Expt.3	Contl.	3.85 ± 0.03*	2.59 ± 0.10*
	Elevated	2.10 ± 0.07	1.45 ± 0.02

Means ± standard errors (n=6). See Table 2 for the asterisk (*).

In this experiment, air was regarded as a mixture of H_2O , O_2 , CO_2 and N_2 (for details, refer to Kurata et al., 2004), and the entropy inflow and outflow were measured for each gas component. In other words, $(Air_{out} - Air_{in})$ could be decomposed to contributions of each gas component:

$$(Air_{out} - Air_{in}) = (H_2O_{out} - H_2O_{in}) + (CO_{2out} - CO_{2in}) + (N_{2out} - N_{2in}) + (O_{2out} - O_{2in}) \quad (3)$$

Table 4 shows the values of $(H_2O_{out} - H_2O_{in})$. Note that values in Table 4 are almost the same as those in Table 3. This means that differences in water vapor contents at the inlet and outlet of the chamber were the main factors in $(Air_{out} - Air_{in})$, and hence in entropy production of the micro-biosphere.

Table 4. Average of ($H_2O_{out} - H_2O_{in}$) between 6h and 11h in photoperiod and between 16h and 21h in dark period

Experiments	Treatments	$(H_2O_{out} - H_2O_{in})$	$(kJ\ h^{-1}\ K^{-1})$
		Photo-period (6h-11h)	Dark period (16h-21h)
Expt.1	Contl.	3.80 ± 0.01	3.54 ± 0.01
	Elevated	3.73 ± 0.02	3.53 ± 0.02
Expt.2	Contl.	$3.65 \pm 0.02^*$	$3.42 \pm 0.02^*$
	Elevated	2.70 ± 0.01	2.53 ± 0.01
Expt.3	Contl.	$3.42 \pm 0.03^*$	$3.03 \pm 0.02^*$
	Elevated	2.47 ± 0.03	2.33 ± 0.02

Means $\pm$ standard errors (n=6). See Table 2 for the asterisk (*).

Figure 3 shows the entropy production rate plotted against the evapotranspiration rate. There are linear relationships between these two factors.

4. Conclusions and further study

From the present study we can conclude that entropy production of the biosphere will almost stay the same when $[CO_2]$ increases, but will remarkably decrease when the air temperature rises. The main factor for the decrease in entropy production of the biosphere is the change in the evapotranspiration rate from the biosphere.

In the present study, 'adjusting' time was inserted between the days due to technical reasons. This might have affected the circadian rhythms of the plants. We plan to conduct experiments without disturbing the plants' circadian rhythms.

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Fig. 3. Relationships between evapotranspiration rate and entropy production rate at (a) elevated $[CO_2]$ (Δ), (b) at elevated air temperature (Δ), (c) at both elevated $[CO_2]$ and elevated air temperature (Δ) together with the Control ($\circ$).