Time Series Analysis of Noise Component of Single Cell Infra-Red Gas Analyzer (IRGA) CO₂ Assimilation Data

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Time series analysis on the noise component of CO₂ concentration data, measured by a single cell infra-red gas analyzer was conducted. The analysis was performed to examine whether there is any periodic noise in automatically recorded CO₂ assimilation data. Two methods were performed for testing the randomness, turning point analysis and phase length analysis. Autocorrelation functions (ACF) and partial autocorrelation functions (PACF) were also computed and inspected. All results were consistent and there was no evidence that indicates the presence of time series noise.

Keywords: instrumentation, IRGA, time series analysis

INTRODUCTION

The infra-red gas analyzer (IRGA) is a common instrument to determine photosynthetic CO₂ assimilation and photorespiratory CO₂ release in plants and other applications. Typical IRGAs measure absorption of 4.25 μ m inside infra-red (IR) band, which is a peak absorption waveband of CO₂. By measuring input and output concentration of CO₂, one can determine amount of CO₂ assimilated by plants (Long and Hällgren, 1993; Hall and Rao, 1995).

There are two types of IRGA instruments commercially available in terms of number of IR cell. One is double cell and the other is single cell IRGA (Fig. 1).

Many IRGAs used for photosynthesis measurement are of the double cell design referred to as an analysis cell and a reference cell (Long and Hällgren, 1993). With this configuration, sample air inside a leaf chamber is measured continuously but care must be taken to zero the cells. Some IRGA manufacturers, such as LI-COR, Inc., employ this double cell design for their products. In addition, LI-COR, Inc. introduced LI-6400 (LI-COR, Inc., U.S.A.), which is the first IRGA to put the gas analyzers right in the sensor head. This engineering design eliminates time delay in measurements and mechanical uncertainty related to the air flow control, which in turn, minimize noise component in operations. Such newly developed high precision IRGA devices have been commercially available.

On the other hand, some of commercially available IRGAs such as a portable IRGA LCA-4 (Analytical Development Company (ADC) Limited, England) utilize only one IR cell to measure both input and output concentration of CO₂. An IR sensor measures input concentration of gas for a period of time then the sensor measures output concentration. This design reduces the cost of the instrument. This is a good engineering design idea since the measurement errors introduced by the IR sensor are identical. However, another kind of error

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might be introduced by employing this engineering design since, unlike double cell IRGAs, measurement is being done in time rather than in space. Because measurement is being performed intermittently, some suggest that the system is sensitive to time related causes. In addition, in case of LCA-4, as well as some double cell instruments, the IR cell is located apart from a leaf chamber and it has been suggested that the design might be introducing time lag noise into the measurements (Pickering et al., 1993).

The single cell IRGA design is still being available as commercial products and being used for research. Therefore, it is still useful to analyze characteristics of such IRGA designs.

The purpose of this analysis is to examine whether there is a periodic noise in CO₂ assimilation data measured by an IRGA device with a single IR cell.

METHODS

Experimental methods. A commercial IRGA, LCA-4 (ADC Limited, England) was tested. Among the single cell IRGAs, LCA-4 is one of the most popular IRGA, which is currently commercially available. LCA-4 has been used successfully for physiological measurements (Fetene et al., 1997; for example). The resolution of CO₂ concentration measurement for the device is 0.2 vpm (Analytical Development Company Limited, 1993).

Experiments were performed under ambient condition without any leaves or empty cuvette. Therefore, expected average CO₂ assimilation rate is zero. To use empty cuvette for evaluation of IRGA is a known technique (Whitfield, 1980). A broad chamber PLC4(B) (ADC Limited, England) or a cuvette which usually used for measurements of normal flat leaf was used. Flow rate of 285 $\mu\text{mol s}^{-1}$, which lies in mid range of acceptable flow rate for LCA-4, was used. The CO₂ assimilation data, with unit of $\mu\text{mol m}^2 \text{s}^{-1}$, were recorded every 30 s automatically. A 30-s interval is the best resolution in time for automatic recording, although typical one measurement cycle of LCA-4 is 12 to 16 s (Analytical Development Company Limited, 1993).

Prior to the each experiment, the IRGA was allowed to warm up, as was suggested on the operating manual. The entire experiment was repeated ten times. Each experiment was conducted at least 1 h.

Analytical methods. The presence of periodic noise was tested. Two methods for testing randomness, turning point analysis and phase length analysis were performed. Turning point analysis examines the number of peaks or troughs in the series. Phase length

Fig. 1 Simplified diagram of single cell infra-red CO₂ analyzer circuit.

analysis examines the length of time between successive turning points. Both tests are useful to examine presence of trends and cycles. These procedures described by Kendall et al. (1983) and Kendall and Ord (1990) were used. Analysis was performed on S-plus (MathSoft Inc., Cambridge, MA) using script functions (Venables and Ripley, 1998). Autocorrelation function (ACF) and partial autocorrelation function (PACF) were also computed and plotted using general function of S-plus. ACF is the serial correlation coefficients for consecutive lags. PACF is the correlation between two variables after removing their mutual linear dependence on the intervening variables. Pattern of ACF and PACF were visually inspected to exam presence of periodicity. This is a typical procedure to inspect the structure of time series data. The technique has been applied for engineering applications (Montgomery et al., 1990; for example).

RESULTS

Ten data sets were obtained. Each data set contains a few outliers but they were not removed from the analysis since these data are part of the interest. Inclusion of 'valid' outlier for time series analysis is a common procedure, if necessary (Chatfield, 1984). Table 1 shows summary of data sets and turning point analysis. Nine out of ten data sets were not significant based on z statistic. Table 2 shows the summary of results for phase length test. Nine out of ten data sets were not significant based on chi-square statistic. Figures 2 and 3 show typical result of ACF and PACF, respectively. On Figs. 2 and 3, y axis shows ACF and PACF, correspondingly. The x axis shows the different lags. In this analysis, the minimum unit of lag is one measurement data. Approximate 95% confidence limits are shown as dotted straight lines. Figures 2 and 3 showed that all ACF and PACF lie inside the confidence limits, except lag zero. This means that there is no strong statistical evidence, which shows the presence of periodicity. Overall, although some ACF and PACF results

Table 1 Summary of data sets and turning point analysis.

	Data set number									
	1	2	3	4	5	6	7	8	9	10
Number of observation	125	134	139	140	140	140	140	140	140	140
Number of turning points	75	87	91	90	95	87	79	86	96	94
Expected turning points	82	88	91.3	92	92	92	92	92	92	92
z statistic	-1.4958	-0.2062	-0.2062	-0.4035	0.6052	-1.0087	-2.6228	-1.2105	0.807	0.4035
Significance	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	Significant at $\alpha=0.05$	N.S.	N.S.	N.S.

N.S., not significant.

Table 2 Summary of the phase length test.

	Data set number									
	1	2	3	4	5	6	7	8	9	10
Chi-square statistic	0.2587	2.9784	5.5100	4.6138	1.8334	4.7404	4.1146	0.1812	0.8730	2.5312
Significance	N.S.	N.S.	Significant at $\alpha=0.1$	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

N.S., not significant.

Fig. 2 Typical result of autocorrelation function, ACF (data set 2).
Dotted lines show 95% confidence limits.

Fig. 3 Typical result of partial autocorrelation function, PACF (data set 2).
dotted lines show 95% confidence limits.

showed weak patterns, no strong pattern showing the presence of cyclical noise was observed.

DISCUSSION

It has been suggested that the different approach for CO₂ exchange measurements have different advantages and disadvantages for certain applications (Midgley et al., 1997). Majority of researches on engineering aspects of IRGA were focused on differences on CO₂/air supply, namely open and closed IRGA systems (Field et al., 1989 ; Winner et al., 1989 ; Long and Hällgren, 1993 ; Midgley et al., 1997). On the other hand, less attention has been paid for nature of single versus double IR cell configurations.

Behavior of IRGA measurements, in terms of both accuracy and precision, has been

documented. Whitfield (1980) utilized both empty cuvette and artificial leaf, which was made of ascarite CO₂ absorber and aluminum foil to test IRGA. For artificial leaf experiment, the result was fraction of 2 to 3% differences between IRGA and gravimetric measurements. However, CO₂ concentration changes were observed even for the empty cuvette experiment. McPherson et al. (1983) evaluated repeatability of measurements utilizing artificial leaf made of filter paper soaked in different concentration of KOH solution. They determined coefficient of variation from 1.9 to 4.7% for different level of CO₂ absorption rates. Greater coefficient of variation has been observed from the field performance test under ambient condition with real leaf samples. Based on the actual field experiment, the coefficients of variation from 27% to 37% were observed (Midgley et al., 1997).

Even though variability has been observed, time domain aspect of the noise has not been analyzed. The reason is simple, such noise can be easily removed, if there is any. When one wants to use IRGA instruments under constant controlled condition, practically, cyclical noise does not matter since one can eliminate such a noise simply by taking a mean. As long as numbers of samples are being used, the CO₂ assimilation rate data from adequately calibrated IRGA should be valid. However, once premise is forgotten, or fewer number of data are used to calculate small CO₂ assimilation rate under varying environment conditions, some attention might be needed.

Digital or discrete signal data as a function of time index form a time series. Typically, commercially available IRGAs can measure data with certain time intervals, therefore such data form a discrete time series data. In this case, time series analysis can be applicable. If there is systematic noise with some periodicity, the analysis employed in this paper should detect it. The fact that results from time domain analysis both tests of randomness, ACF, and PACF were not statistically significant, concludes that there is no statistical evidence which suggests the noise have periodic nature.

CONCLUSION

Based on the tests performed using a commercially available single cell IRGA, LCA-4 with a broad chamber PLC4(B) (ADC Limited, England), under ambient conditions, there is no statistical evidence that indicates presence of periodic noise. Results from turning point analysis, phase length test, ACF and PACF plots were consistent.

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〈和文抄録〉

シングル・セル型赤外線ガス分析計における二酸化炭素同化データの ノイズ成分の時系列分析

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光合成速度測定装置として用いられている赤外線ガス分析計 (IRGA) には、二つのセルを用いて、同化箱の二酸化炭素濃度を連続的に計測する方式と、単一のセルで出入り口の濃度を交互に計測するシングル・セルの二つの方式がある。シングル・セル方式の IRGA については、幾つかの技術的課題も指摘されているものの、センサー間誤差をなくするという利点や、セル数を減らすことでコストを削減できる等の利点もあり、現在でも市販の IRGA に採用されている。本研究では、このシングル・セル方式の IRGA の二酸化炭素同化データに見られたノイズについて時系列分析を行い、ノイズの周期性の有無について検討を行った。時系列分析手法としては、ターニング・ポイント分析、フェーズ長分析、および ACF, PACF を用いた。その結果、本研究で用いた IRGA データには、有意な周期的ノイズは見られなかった。