WORKSHOP 06

10년 타워 플럭스 관측에 기초한 농업생태계의 생태학적 지표 평가

Yohana Maria Indrawati[1], 이가람[2], 강민석[1], 김준[1,2,3*]
[1]국가농림기상센터, [2]서울대학교 협동과정 농림기상학전공, [3]서울대학교
생태조경지역시스템공학부/그린바이오과학기술원

Assessment of Ecological Indicators of Agricultural Ecosystem Based on a Decade-Long Tower Flux Measurement

Yohana Maria Indrawati[1], Lee Galam[2], Kang Minseok[1], Kim Joon[1,2,3*]
[1]National Center for AgroMeteorology
[2]Interdisciplinary Program in Agricultural & Forest Meteorology, Seoul National University
[3]Department of Landscape Architecture and Rural Systems Engineering/ Institute of Green Bio Science and Technology, Seoul National University

I. Introduction

Ecological indicators (EI) are developed based on the framework on ecosystem structure and function, which are constrained by the flows of energy, matter and information. Nielsen and Jørgensen (2013) have identified three major directions in the development of EI: 1) biotic (i.e. related to already well-known and well-established classical indices in ecology), 2) network (i.e. based on various directions of network theory) and 3) thermodynamic (i.e. mainly derived from physics either first or second law of thermodynamics).

Field observation of micrometeorology including eddy covariance (EC) flux measurement provides the quantitative assessment of energy, matter and information flows in ecosystems. EC measurement has advantages for developing EI by offering continuous and long-term time series data for various variables with wide ranges of environmental conditions, along with the availability of global network with open access data (Baldocchi *et al.*, 2001). By employing the information theory to such time series, EC measurement can also be used for the assessment of biotic, network and thermodynamic indicators, which are available for the same system both spatially and temporally.

In this study, we focused on assessing the biotic and thermodynamic EI derived from EC measurement in agricultural ecosystem. In this study, the biotic indicators which are derived from many traditional measures include net ecosystem exchange (NEE), gross primary productivity (GPP), crop coefficient (K_c), and water use efficiency (WUE)). Thermodynamic indicators used in this study are based on entropy balance (dS/dt) (Brunsell *et al.*, 2011) as well as energy capture (R_n/R_{snet}) and

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* Correspondence to : joon@snu.ac.kr

dissipation ability (in terms of thermal response number, TRN) (Kutsch *et al.*, 2001; Lin *et al.*, 2009; Lin *et al.*, 2011). We expected that the integration of biotic and thermodynamic indicators will provide better holistic representation of the system state of the agricultural ecosystem.

II. Materials and Methods

The EC measurements of CO_2, water and energy at Haenam Farmland in Korea (HFK) site over rice growing season from 2003 to 2012 were used in this study. Flux data processing was conducted using the KoFlux data processing protocol (Kwon *et al.*, 2009). The biotic and the thermodynamic EIs used in this study are presented in Table 1.

Table 1. Ecological indicators tested for agricultural ecosystem in this study

No	Category	variables	Symbol	Unit
1	**Biotic indicator**	Net ecosystem exchange	*NEE*	g C m^{-2}
		Gross primary productivity	*GPP*	g C m^{-2}
		Ecosystem respiration	*RE*	g C m^{-2}
		Evapotranspiration per precipitation	*ET/P*	unitless
		Bowen ratio	*b*	unitless
		Crop coefficient	K_c	unitless
		Water use efficiency	*WUE*	g C kg H_2O^{-1} hPa
2	**Thermodynamic indicator**	entropy balance	dS/dt	MJ m^{-2} K^{-1}
		energy capture	R_n/R_{snet}	Unitless
		energy dissipation	TRN	MJ m^{-2} K^{-1}

III. Results

3.1. Biotic indicators

In terms of carbon exchange during the rice growing season (Table 2), the averaged *NEE* during the study period was -113 ± 56 g C m^{-2} with the peak carbon uptake in 2008 (-176 g C m^{-2}) and the lowest uptake in 2012 (-4 g C m^{-2}). From 2004 to 2009, the agricultural system remained a strong carbon sink. Then, from 2010, the sink strength became weaker. The averaged *GPP* during the rice growing season was 838 ± 41 g C m^{-2}, amounting up to approximately 70% of the annual *GPP*. The *GPP* varied with a minimum in 2003 (782 g C m^{-2}) and a maximum in 2006 (901 g C m^{-2}). The *RE* averaged to be 726 ± 48 g C m^{-2} (about 64% of the annual *RE*) and fluctuatued with a tendency to increase toward the end of period.

ET during the rice growing season was 375 ± 24 mm, accounting for ~60% of the annual total. The ratio of *ET* to *P* was on average 0.41 ± 0.08. The *ET* in 2008 (driest year) accounted for 57% of *P* while only 33% in 2003 (wettest year). The averages of *H* and *LE* were 240 ± 19 and 914 ± 57 MJ m^{-2}, respectively. Hence, the *b* (= *H*/*LE*) was on average 0.26 ± 0.03 with the highest in 2008 and the lowest not in 2003 but in 2012.

In terms of water use, the growing season average of K_c was 0.94 ± 0.07. The K_c values fluctuated with a maximum of 1.04 in 2012. On the other hand, the *WUE* was on average 22.25 ± 3.37 g C kg H_2O^{-1} hPa. From 2004 to 2009, *WUE* was higher than the average and then lower thereafter.

Table 2. Ecological indicators over rice growing seasons at HFK

N	**Category**	**EI**	**2003**	**2004**	**2006**	**2008**	**2009**	**2010**	**2011**	**2012**	**AVG**	**std**
1	**Biotic indicator**	***NEE***	-88	-165	-148	-176	-160	-91	-68	-4	**-113**	**56**
		GPP	782	851	901	890	806	866	803	808	**838**	**42**
		Re	694	685	753	714	646	775	735	803	**726**	**48**
		ET/P	0.33	0.32	0.41	0.57	0.40	0.48	0.39	0.36	**0.41**	**0.08**
		b	0.26	0.25	0.32	0.26	0.30	0.24	0.27	0.21	**0.26**	**0.03**
		K_c	0.78	0.89	0.97	0.95	0.94	0.97	0.97	1.04	**0.94**	**0.07**
		WUE	17.9	26.6	25.3	25.5	24.8	19.4	19.8	18.7	**22.3**	**3.4**
2	**Thermodynamic indicator**	**dS/*dt***	1.11	1.09	1.02	0.76	1.12	0.92	0.88	0.83	**0.97**	**0.13**
		R_n/R_{snet}	0.78	0.75	0.72	0.72	0.72	0.76	0.75	0.75	**0.74**	**0.02**
		TRN	0.96	0.90	0.82	0.74	0.76	0.88	0.78	0.84	**0.84**	**0.07**

Unit: *NEE, GPP, Re* = g C m^{-2}, ET/P, *b*, K_c, R_n/R_{snet} = unitless, *WUE*= g C kg H2O^{-1} hPa, ds/dt, TRN= MJ m^{-2} K^{-1}.

3.2. Thermodynamic indicators

The changes in entropy with time (*dS*/*dt*) were positive with an average of 0.97 ± 0.13 MJ m^{-2} K^{-1}, indicating the overproduction of entropy in this agricultural ecosystem. In general, however, decreased from 2003 to 2012 except a sudden drop in 2008 and the recovery in 2009, thereby gradually approaching the dynamic equilibrium.

In terms of energy capture, R_n/R_{snet} was on average 0.74 ± 0.02, which was higher than the annual R_n/R_{snet} (i.e., 0.59 ± 0.03). The measure of energy dissipation, *TRN* was on average 0.84 ±

0.07 MJ m^{-2} K^{-1}, higher than the annual *TRN* (0.54 ± 0.05). During the rice growing season, the enhanced energy capture resulted in more energy dissipation, which also lowered the gradient of surface temperature.

3.3 Integration of biotic and thermodynamic indicators

It is important to integrate and summarize the multiple EIs in a way that not only experts but also stakeholders can understand their meanings. By providing such an integration, the users of these EIs can easily understand the behaviors of the indicators against some conditions (e.g. disturbances). In Fig. 1, we used the amoeba diagram method to synthesize the EIs by comparing and contrasting the two different cases: when EI was higher than the average and when EI was lower than the average of the representative biotic and thermodynamic indicators (i.e., *NEE* and *dS*/*dt*).

Based on NEE (Fig. 1a), for the period when the agricultural system absorbed more carbon (i.e., higher *NEE*) than the average, we note higher *WUE*, higher *β*, and higher *ET*/*P*, while other EIs showed no significant differences.

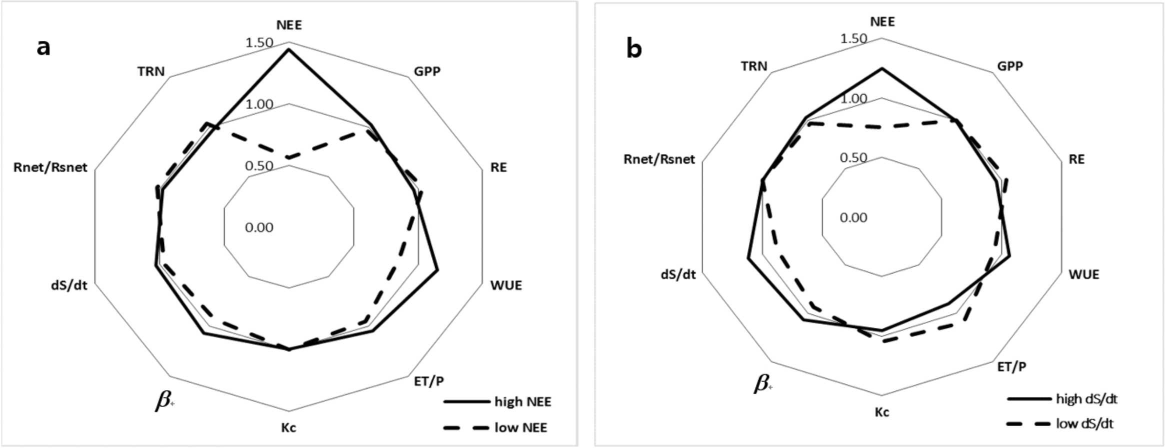

Fig. 1. Amoeba graphs of the EIs based on the contrasting conditions of (a) *NEE* and (b) *dS/dt.*

K_c and *RE*. Relatively insignificant changes in *GPP*, R_n/R_{snet} and *TRN* suggest that these indicators were not the causes of the enhanced *NEE* and *WUE*. The lack of sensitivity of R_n/R_{snet} and *TRN* to changes in *dS*/*dt* suggests that these two thermodynamic indicators may be good indicators for self-organization but may be inadequate for holistic EIs. Our results provide further implication that the triple wins (i.e., more production, less carbon emission, and better resilience) pursued by climate smart agriculture (CSA) would be a difficult challenge facing the CSA communities.

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