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플럭스 관측 기반의 생태계 생산성과 효율성 평가: 해남 농경지 연구 사례

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Assessment of Ecosystem Productivity and Efficiency using Flux Measurement over Haenam Farmland Site in Korea (HFK)

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ABSTRACT

Time series analysis of tower flux measurement can be used to build quantitative evidence for the achievement of climate-smart agriculture (CSA). In this study, we have assessed the first objective of CSA (regarding ecosystem productivity and efficiency) for rice paddy-dominated heterogeneous farmland. A set of quantitative indicators were evaluated by analysing the time series data of carbon, water and energy fluxes over the Haenam farmland site in Korea (HFK) during the rice growing seasons from 2003 to 2015. Four different varieties of rice were cultivated during the study period in chronological order of Dongjin No. 1 (2003-2008), Nampyung (2009), Onnuri (2010-2011), and Saenuri (2012-2015). Overall at HFK, gross primary productivity (*GPP*) ranged from 800 to 944 g C m^{-2}, water use efficiency (*WUE*) ranged from 1.91 to 2.80 g C kg H_2O^{-1}, carbon uptake efficiency (*CUE*) ranged from 1.06 to 1.34, and light use efficiency (*LUE*) ranged from 0.99 to 1.55 g C MJ^{-1}. Among the four rice varieties, Dongjin No. 1-dominated HFK showed the highest productivity with higher *WUE* and *LUE*, but comparable *CUE*. Considering the heterogeneous vegetation cover at HFK, a rule of thumb comparison suggested that the productivity of Dongjin No1-dominated HFK was comparable to those of monoculture rice paddies in Asia, whereas HFK was more efficient in water use and less efficient in carbon uptake. Saenuri-dominated HFK also produced high productivity but with the growing season length longer than Dongjin No.1. Although the latter showed better traits for CSA, farmers cultivate Saenuri because of higher pest resistance (associated with adaptability and resilience). This emphasizes the need for the evaluation of other two objectives of CSA (i.e. system resilience and greenhouse gas mitigation) for complete assessment at HFK, which is currently in progress.

***Key words*: Climate-smart agriculture, Productivity, Efficiency, Eddy covariance, Rice paddy, Farmland**

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I. INTRODUCTION

The increasing concerns on the role of agriculture in ensuring food security, mitigating climate change, and preserving natural resources have resulted in the vision of climate-smart agriculture(CSA) in 2010 by the United Nations Food and Agriculture Organization(FAO) (Lipper *et al.*, 2014). The threefold objectives of CSA are: 1) sustainably increasing agricultural productivity and incomes; 2) adapting and building resilience to climate change; and 3) reducing and/or removing greenhouse gases(GHG) emissions (Palombi and Sessa, 2013). The CSA initiative helps practitioners, policy-makers, scientists, and engineers to identify synergies and trade-offs among the above triad goals which do not necessarily have the same priority depending on the individual circumstances (Lipper *et al.*, 2014).

Recent reviews of the progresses in CSA have stressed that several urgent actions are needed for more effective implementation of CSA. Such actions include building scientific evidence and more appropriate assessment tools, emphasizing the need for robust studies to further the understanding of how CSA works in different ecological-societal systems(e.g. Lipper *et al.*, 2014; Rosenstock *et al.*, 2016). Clear assessments are needed on the synergies and/or trade-offs among the threefold objectives of CSA, necessitating the establishment of scientifically credible and relevantly integrated indicators(Neufeldt *et al.*, 2013).

South Korea, a major food-importing country(e.g., rice, wheat), has been trying to strengthen its agricultural production and to minimize imports. However, the amount of import has been increasing. For example, from 2005 to 2013, import has increased from 9,528 to 25,612 million-dollar(KOSIS, 2015). Rice production in Korea is affected by climate change which can contribute to ~60% of rice yield(Lee *et al.*, 2012). Regarding the readiness of Korean agriculture to adapt to climate change, there are some concerns including the lack of relevant tools to assess the biophysical and socio-economic impacts associated with climate change(Yoo and Kim, 2007). Here, the CSA assessment on rice productivity can be an alternative tool to test if the overall management is indeed climate-smart or not.

Micrometeorological eddy covariance(EC) measurement provides a quantitative assessment of energy, matter, and information flows in and out of ecosystems(e.g. Kang *et al.*, 2017; Yun *et al.*, 2014). The EC time series data are now available for considerably long periods along with diverse variables with a wide range of environmental conditions. These data are available through the global network(e.g. AsiaFlux, FLUXNET) with open access(e.g. Baldocchi *et al.*, 2001; Mizoguchi *et al.*, 2009). The EC time series data are valuable sources not only to support model development and satellite remote sensing but also to develop useful indicators for decision making processes. They can be used directly and effectively to provide quantitative and integrative indicators in ecosystem scale necessary for the assessment of threefold objectives of CSA.

In this study, we used the long-term EC measurement over the Haenam farmland site in Korea(HFK), which is a typical rice paddy-dominated farmland) to build quantitative indicators for the assessment of CSA. Our focus is to assess the first objective of CSA by quantifying ecosystem productivity and efficiency as a prerequisite to assess the other two objectives. We used gross primary productivity(*GPP*) as an indicator for productivity, while the consumption in the production process was measured by water use efficiency(*WUE*), carbon uptake efficiency(*CUE*), and light use efficiency (*LUE*). We evaluated how the ecosystem productivity and efficiency at HFK have been changing and their implication on CSA.

Source: google earth image

Fig. 1. Haenam Farmland in Korea (HFK) site location.

II. MATERIALS AND METHODS

2.1. Site conditions

HFK is located in the southwestern end of Korean Peninsula(34.55°N, 126.57°E, 13.74 m above mean sea level) with relatively flat terrain except for the southeast section with a slope of about 4°. The land cover around the study site is the mixture of rice paddies and various agricultural crops(Fig. 1). The maximum canopy height of dominant agricultural crops such as rice was approximately 1 m. The climate at HFK is typical of moist subtropical mid-latitude(i.e. hot, humid summer and cool, dry winter) and the soil type varies from silt loam to loam(Lee *et al*., 2008).

The representativeness of land cover at HFK was analyzed using two satellite images: the IKONOS image on 18 March 2004 and the Google images on 9 July 2011. Within 200 meters around the tower, the dominant land cover representation was rice paddy field for both years(i.e. 48% in 2004 and 55% in 2011) (Table 1). We conducted footprint analysis(with 30-minute flux data) from 2003 to 2012 for the 2 km × 2 km-sized grid(the flux tower is located at the center of the grid) using the 2-dimensional analytical footprint model proposed by Hsieh *et al*.(2000) and the land cover map provided by Environmental Geographic Information Service(EGIS, 2007). The observed daytime fluxes came from rice paddy(41±2%), other crops(29±2%), other vegetation(e.g. forest, 2%), non-vegetated area(e.g. settlement, 6%), and outside of the grid (23±2%) during the rice growing season (i.e. DOY 160-290) (NCAM, 2013).

2.2. Flux measurement

Flux measurement using the EC technique has been conducted since July 2002 until now. The main system consisted of a three-dimensional sonic

Table 1. Land cover representation of HFK in 2004 and 2011

Distance (m)	**Land cover representation (%)**											
	rice-paddy		**seasonal crops**		**tall canopy**		**settlement**		**livestock**		**others**	
	2004	**2011**	**2004**	**2011**	**2004**	**2011**	**2004**	**2011**	**2004**	**2011**	**2004**	**2011**
0-200	48.1	54.5	43.9	38.7	3	1.9	48.1	54.5	43.9	38.7	3	1.9
200-500	81.5	66.0	10.5	18.5	0.1	0	81.5	66.0	10.5	18.5	0.1	0
500-1000	73.4	61.6	7.1	20.5	11.6	8.9	73.4	61.6	7.1	20.5	11.6	8.9

anemometer(CSAT3, Campbell Scientific Inc, Logan, UT) and an open-path H_2O/CO_2 gas analyzer(LI7500, LICOR, Lincoln, NE), which were installed at 20.8 m above the ground(for more detail, see http://asiaflux.net/index.php?page_id=60). Half-hourly *EC* and the associated statistics were calculated online from 10 Hz raw data. Other micrometeorological variables such as incoming solar radiation(R_s), net radiation(R_n), photosynthetically active radiation(*PAR*), air temperature(T_a), soil temperatureT_s), soil water content(*SWC*), and precipitation(*P*) were measured and averaged every 30 minutes(Kwon *et al*., 2009).

To improve the data quality by eliminating undesirable data, the collected data were examined by the quality control(QC) procedure based on the KoFlux data processing protocol(Hong *et al*., 2009; Kang *et al*., 2017). This procedure includes the coordinate rotation(double rotation; McMillen, 1988), density correction(Webb *et al*., 1980), storage calculation(Aubinet *et al*., 2001; Papale *et al*., 2006), spike detection(Papale *et al*., 2006), gap-filling with marginal distribution sampling method(Reichstein *et al*., 2005), and nighttime CO_2 flux correction. Three different method of nighttime corrections(i.e., filtering and replacing) are provided in KoFlux protocol: 1) the friction velocity($u*$) filtering method, 2) light response curve(LRC) method, and 3) modified van Gorsel(VGF) method(Kang *et al*., 2014; Van Gorsel *et al*., 2009). The daily net ecosystem exchange(*NEE*), gross primary productivity(*GPP*) and ecosystem respiration(*RE*) used in this study are the averaged values from the above three methods. Daily flux and meteorological data from 2003 to 2015 were used for the analysis. We excluded 2007 and 2014 when the data availability after QC for flux variables was less than 30%(Table 2).

2.3. Growing season length(*GSL*)

Rice growing season length(*GSL*) is generally defined as number of days from transplanting to harvest, which is typically between 100 and 160 days (IRRI, 2013). In this study, we used different method to calculate *GSL* because information regarding transplanting and harvest dates was not available for individual years. It is further complicated by the

Table 2. Data availability (%) after quality control (QC) of eddy covariance flux data (CO_2 flux (Fco_2), latent heat flux (*LE*), sensible heat flux (*H*) and friction velocity ($u*$) and some meteorological variables (solar radiation (R_s), wind speed (W_s), air temperature (T_a), relative humidity (*RH*), air pressure (*Press*)) in growing season

	Data availability after QC (%)								
	Fco_2	***LE***	***H***	***u****	**R_s**	**W_S**	**T_a**	***RH***	***Press***
2003	48	52	60	66	83	66	100	100	71
2004	64	70	86	92	96	92	96	96	96
2005	67	71	82	88	95	88	100	100	92
2006	56	61	72	77	82	77	100	100	80
2007	26	29	37	40	42	41	100	100	42
2008	64	70	86	92	96	92	96	96	96
2009	70	73	89	95	100	95	100	100	100
2010	68	72	90	95	100	95	100	100	100
2011	69	72	89	95	100	95	100	100	100
2012	64	70	86	92	96	92	96	96	96
2013	59	65	80	84	88	84	88	88	88
2014	26	29	34	37	40	37	40	40	40
2015	65	65	85	90	99	90	94	93	100

Table 3. Growing Season Length from 2003 to 2015

Rice variety	**Dongjin No. 1**					**Nampyung**	**Onnuri**		**Saenuri**		
year	2003	2004	2005	2006	2008	2009	2010	2011	2012	2013	2015
starting date (DOY)	141	145	143	145	148	127	142	147	134	128	144
end date (DOY)	280	279	286	287	285	292	269	291	290	270	289
***GSL* (day)**	139	134	143	142	137	165	127	144	156	142	145

mosaic patchiness of the farmlands which are owned by different farmers over the 13 years of the study period. In previous study, *GSL* was fixed as the period from late May(planting time) to early October(without considering the changes in variety or other factors that would affect the changes in *GSL*(Kwon *et al*., 2010; Xin *et al*., 2017).

Following Churkina *et al*.(2005) and Saito *et al*.(2005), we determined *GSL* on the basis of changing patterns of 10-day integrated *NEE* as the number of days from the day when *NEE* changes from negative to positive(around DOY 140 ±7) to the day when *NEE* changes the sign from negative to positive(around DOY 283 ±8). The resultant mean *GSL* during the study period was 143 ±10 days. Table 3 demonstrates that the *GSL* at HFK varied among the four varieties and also from year to year.

2.4. Productivity indicators

2.4.1. Gross primary productivity

GPP is one of the best indicators for productivity(e.g. Ciais *et al*., 2005; Falge *et al*., 2002). *GPP* represents the total amount of organic matter produced through photosynthesis in a defined area per unit time(e.g. Gitelson *et al*., 2006). Actual yield is related to net primary productivity(*NPP*) which is roughly 50% of *GPP*(e.g. Zhang *et al*., 2009). Four rice varieties were transplanted at HFK which are Dongjin No 1(2003-2008), Nampyung (2009), Onnuri(2010-2011), and Saenuri(2012-2015) during study period(for more details about the traits, see NCIS, 2017). Changing in rice variety were taken into account in the analysis along with other driving factors.

2.4.2. Water use efficiency

Method to calculate water use efficiency was developed to capture vegetation response to the environmental change by using Bowen ratio (Baldocchi *et al*., 1985), isotope(Farquhar and Richards, 1984), modeling(Wang *et al*., 2005) as well as eddy covariance(e.g. Beer *et al*., 2009; Beer *et al*., 2007; Keenan *et al*., 2013; Kuglitsch *et al*., 2008; Law *et al*., 2002). In this study, *WUE* at the ecosystem level defined as

$$WUE = \frac{GPP}{ET}$$

where *GPP* and *ET* are the daily sums of half-hourly fluxes from the eddy covariance measurement(e.g. Kuglitsch *et al*., 2008; Ponton *et al*., 2006; Reichstein *et al*., 2007; Yu *et al*., 2008). *ET* was calculated by dividing the *LE* by the latent heat of vaporization. The unit of daily *GPP* is in g C m^{-2}, *ET* is in mm, and *WUE* is in g C kg H_2O^{-1}. Reichstein *et al*.(2007) finding indicated that the drop in productivity is not primarily caused by high T_a but rather by limitation of water which implied the importance of *WUE* to monitor water stress.

2.4.3. Carbon uptake efficiency

Carbon uptake efficiency(*CUE*) is defined as the ratio of *GPP* and ecosystem respiration(*RE*):

$$CUE = \frac{GPP}{RE}$$

where in this study *RE*(in g C m^{-2}) is estimated from EC measurement of CO_2 flux. *CUE* describes how efficiently an ecosystem manages the carbon uptake for growth and development relative to the maintenance(Odum, 1969). *CUE* also represents the strength of net ecosystem carbon uptake(when *CUE* > 1) or release(when *CUE* <1).

Table 4. Summary of monthly (from May to October) and growing season of R_s, R_n, P, and T_a at HFK from 2003 to 2015

	2003	**2004**	**2005**	**2006**	**2007**	**2008**	**AVG**	**2009**	**2010**	**2011**	**AVG**	**2012**	**2013**	**2014**	**2015**	**AVG**
Variety	**Dongjin No. 1**							**Nampyung**	**Onnuri**			**Saenuri**				
R_s (MJ m^{-2})																
May	507	503	665	478	590	596	557	655	572	548	560	628	627	842	682	695
Jun	513	504	538	518	421	404	483	569	503	485	494	518	505	504	490	504
Jul	363	510	472	398	515	527	464	430	451	522	486	491	465	476	484	479
Aug	465	550	510	585	579	579	545	489	491	382	437	518	614	434	528	523
Sept	464	383	445	427	427	415	427	467	465	506	486	450	476	496	496	480
Oct	445	485	416	438	416	409	435	449	426	443	435	447	445	456	456	451
Growing season	**2088**	**2155**	**2358**	**2271**	**1534**	**2157**	**2094**	**2774**	**1984**	**2264**	**2124**	**2608**	**2479**	**1747**	**2447**	**2320**
R_n (MJ m^{-2})																
May	269	278	349	261	334	338	305	370	347	335	341	367	366	430	412	394
Jun	288	285	310	301	263	254	284	353	323	315	319	321	338	262	314	309
Jul	242	333	294	271	344	353	306	291	310	356	333	341	315	305	327	322
Aug	287	358	313	381	367	365	345	309	332	254	293	347	394	262	333	334
Sept	246	204	247	248	249	241	239	276	289	294	291	280	278	274	299	283
Oct	155	188	159	219	190	185	183	218	209	209	209	218	242	251	245	239
Growing season	**1198**	**1281**	**1354**	**1387**	**983**	**1336**	**1257**	**1674**	**1309**	**1407**	**1358**	**1640**	**1572**	**1031**	**1534**	**1444**
P (mm)																
May	221	112	85	235	81	195	155	136	122	82	102	27	124	0	87	60
Jun	149	191	139	257	28	344	185	81	84	200	142	45	67	0	98	52
Jul	370	313	226	362	229	127	271	543	111	237	174	136	185	85	201	152
Aug	283	429	364	136	232	123	261	95	285	179	232	233	177	146	139	174
Sept	216	275	26	79	492	33	187	57	103	53	78	261	103	73	66	126
Oct	34	1	15	39	69	34	32	83	46	32	39	35	3	81	62	45
Growing season	**1206**	**1236**	**768**	**870**	**960**	**736**	**963**	**966**	**625**	**690**	**657**	**683**	**641**	**309**	**554**	**547**
T_a (°C)																
May	17.7	17.1	17.1	16.5	17.0	17.0	17.1	17.7	16.9	17.3	17.1	18.3	17.2	16.1	17.7	17.3
Jun	20.9	21.4	22.4	20.7	21.1	20.6	21.5	21.5	21.7	21.7	21.7	21.9	22.0	20.1	21.0	21.3
Jul	22.7	25.3	25.0	23.7	24.0	26.0	24.5	24.2	25.3	25.9	25.6	25.4	26.4	24.0	24.3	25.0
Aug	24.3	25.6	25.4	26.4	26.4	25.1	25.5	25.1	27.5	25.2	26.4	27.2	27.4	23.1	25.4	25.8
Sept	21.8	21.8	23.2	19.5	21.9	22.2	21.7	21.7	23.2	21.9	22.6	20.4	22.2	20.7	21.0	21.1
Oct	14.7	15.1	15.5	16.5	15.6	16.5	15.7	16.5	15.5	14.8	15.2	15.6	15.7	16.2	15.9	15.9
Growing season	**22.0**	**23.0**	**23.1**	**21.9**	**24.2**	**22.9**	**22.9**	**21.6**	**24.0**	**22.5**	**23.3**	**22.5**	**23.6**	**22.1**	**22.1**	**22.6**

2.4.4. Light use efficiency

Based on Monteith and Moss(1977), dry matter yield can be expressed as a function of the amount of intercepted solar radiation and the efficiency with which that radiation is converted to biomass. The carbon exchange between the crop canopy and the atmosphere is controlled by the amount of absorbed *PAR*(*APAR*) as well as light use efficiency(*LUE*). In this study, *LUE* is calculated as(e.g. Gitelson and Gamon, 2015):

$$LUE = \frac{GPP}{APAR}$$

where *APAR* is calculated from the fraction of *PAR*(*fPAR*) collected from MODIS collection 6 product from a single pixel(1x1 km) around the EC tower at HFK and direct measurement of *PAR*.

III. RESULTS AND DISCUSSION

3.1. Climate conditions

Table 4 shows the monthly- and the growing season-integrated(or averaged) R_s, R_n, P, and T_a at HFK from 2003 to 2015. For the sake of completeness, the data of 2007 and 2014 are also presented but were not used in our analysis(see Sec. 2.2). During this study periods with the mean *GSL* of 137 days, the growing season-integrated R_s was on average 2220 ± 339 MJ m^{-2} and the ratio of R_n to R_s was about 0.614. The inter-annual variation of this ratio reflects the system's ability to dissipate incoming energy, and thus, can be used as a thermodynamic indicator (Schneider and Kay, 1994). The seasonality of R_s and R_n varied from year to year, depending on the distribution and the amount of P associated with the migrating band of the Asian summer monsoon between mid-June to late July. The maxima of R_s and R_n were observed in 2009 whereas the minima of R_s and R_n were observed in 2010 and in 2003, respectively.

The mean growing season P was amounted to 788 ± 258 mm with its peak mostly in July except in 2008(peaked in June) and in 2012(peaked in September). Despite its significant inter-annual variations(~33%), P showed gradually decreasing pattern from 2003 to 2015. On the other hand, T_a showed no trend with low inter-annual variation(~4%) and the growing season T_a was on average 22.7 ± 0.8 ℃.

Results of simple correlation analyses between climate variables(i.e., R_s, R_n, P, T_a) and fluxes(i.e., *GPP* and *ET*) are summarized in Table 5. On a monthly basis, as expected, R_s and R_n show significant positive correlation with *GPP* particularly in July and August; T_a shows weaker correlation; and P in July-September shows moderate negative correlation. On a growing season basis, all the correlations are weaker than the monthly correlations except T_a which shows highest positive correlation with *GPP*. Similar relationships were found between the climate variables and *ET* except stronger correlation with radiation components and the negative correlation with P all the times.

Table 5. Correlation coefficient of R_s, R_n, T_a, P toward gross primary productivity (*GPP*) and evapotranspiration (*ET*) for monthly period and growing season

	GPP							***ET***						
	May	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**growing season**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**growing season**
R_s	0.56	0.36	0.77	0.80	0.62	0.40	**0.41**	0.81	0.76	0.85	0.79	0.78	0.62	**0.77**
R_n	0.50	-0.33	0.76	0.82	0.67	0.62	**0.51**	0.80	0.77	0.85	0.80	0.77	0.60	**0.81**
P	-0.38	0.38	-0.49	-0.33	-0.38	0.42	**-0.23**	-0.43	-0.40	-0.40	-0.30	-0.38	-0.19	**-0.32**
T_a	-0.21	0.43	0.54	0.43	0.47	-0.16	**0.70**	0.01	0.23	0.57	0.49	0.28	0.21	**0.43**

Table 6. Growing season productivity and efficiency indicators in HFK from 2003 to 2015

Year	2003	2004	2005	2006	2008	AVG	2009	2010	2011	AVG	2012	2013	2015	AVG
Variety	Dongjin No. 1						Nampyung	Onnuri			Saenuri			
GSL (day)	139	134	143	142	137	139	165	127	144	136	156	142	145	148
GPP (g C m^{-2})	800	839	944	881	881	869	845	809	816	813	847	853	904	868
WUE (g C kg H_2O^{-1})	2.35	2.25	2.80	2.55	2.41	2.47	2.17	2.26	2.22	2.24	1.91	2.16	2.58	2.22
CUE (-)	1.15	1.30	1.19	1.17	1.34	1.23	1.23	1.27	1.18	1.23	1.06	1.15	1.22	1.14
LUE (g C MJ^{-1})	1.46	1.55	1.46	1.45	1.52	1.49	0.99	1.41	1.37	1.39	1.06	1.20	1.08	1.11

3.2. Productivity and efficiency indicators

3.2.1. Gross primary productivity(*GPP*)

On average(regardless of variety and excluding 2007 and 2014), the total *GPP* for the individual growing seasons amounted to 856 ± 41 g C m^{-2}. The inter-annual variation was <5%, which is similar to that of T_a but lower than those of R_s and *GSL*(～15%) (see Table 6). Examination by individual variety indicates that the inter-annual variability within a variety was greater than the differences among the varieties. For example, the inter-annual variation of *GPP* of Dongjin No. 1(here after Dongjin) (from 2003 to 2008) was of the order of 50 g C m^{-2} which is a factor of two greater than the standard deviation of the mean *GPP* among the four varieties. The maximum *GPP* of 944 g C m^{-2} was observed in 2005 which was a normal year whereas the minimum of 800 g C m^{-2} in 2003 with abnormally high amount of *P*(1206 mm).

In Fig. 2, the accumulated *GPP* throughout the growing season for the individual varieties shows different rates of increase. For example, Dongjin(with a mean *GSL* of 139 ± 4 days) showed the fastest accumulation of *GPP* in the least time. On the other hand, the single year cultivation of Nampyung in 2009(with the longest *GSL* of 165 days) showed the slowest accumulation of *GPP* that eventually reached about 97% of that of Dongjin. It is worth noting that

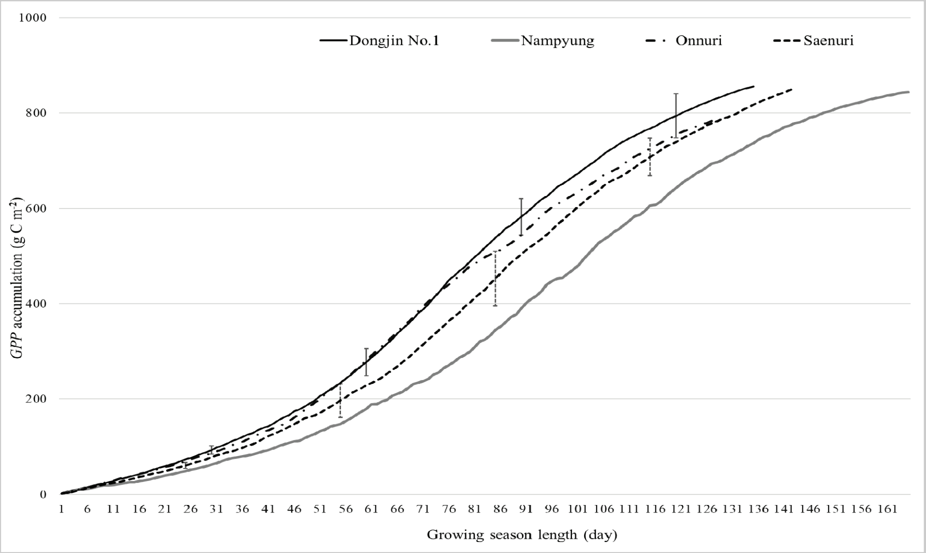


Fig. 2. Accumulated *GPP* during growing season categorized by the variety planted (*GSL* represent the average *GSL* of each variety and inter-annual variation within the variety indicated by error bar).

Table 7. Growing season ecosystem respiration (*RE*), evapotranspiration (*ET*), photosynthetically active radiation (*PAR*), fraction of *PAR* (*fPAR*), and absorbed *PAR* (*APAR*) in HFK from 2003 to 2015

Year	2003	2004	2005	2006	2008	AVG	2009	2010	2011	AVG	2012	2013	2015	AVG
Variety	**Dongjin No. 1**						**Nampyung**	**Onnuri**			**Saenuri**			
***ET* (mm)**	340	373	337	346	365	352	390	358	368	363	443	395	350	396
***RE* (g C m^{-2})**	697	646	792	755	658	710	687	635	693	664	803	740	743	762
***PAR* (MJ m^{-2})**	908	938	1026	988	938	960	1207	863	985	924	1135	1079	1065	1093
fPAR	0.61	0.58	0.63	0.62	0.62	0.61	0.71	0.66	0.60	0.63	0.70	0.66	0.79	0.72
***APAR* (MJ m^{-2})**	550	542	649	609	579	586	851	572	595	584	798	711	837	782

Onnuri(in 2010 and 2011) showed the rate of increase in *GPP* similar to that of Dongjin until the middle of the growing season when the system appeared to be disturbed, resulting in 6% less *GPP*(with shorter *GSL* of 136 days) than that of Dongjin. The accumulated *GPP* of the latest variety, Saenuri(planted from 2012 to 2015) reached that of Dongjin but with longer time with a mean *GSL* of 148 ± 7 days.

3.2.2. Water use efficiency(*WUE*)

For the entire study period, the growing season *ET* was on average 370 ± 29 mm which accounted for about 45% of the corresponding *P* of 788 mm(Table 7). However, the ratio of *ET* to *P* for the individual years varied, depending on the amount of *P*(and the amount of irrigation, not measured). Among the four varieties, Dongjin had the lowest *ET* with small inter-annual variation(~4%). Even with a decreasing pattern, Saenuri showed the highest *ET* with moderate inter-annual variation(~10%). As pointed out by Kang(2013) the total amount of *ET* was positively related with *GSL*, explaining the higher *ET* of Nampyung and Saenuri with longer *GSL*. Accordingly, with highest *GPP* and lowest *ET*, Dongjin showed highest *WUE* with inter-annual variation of ~8%. The *WUE* of other varieties was lower than that of Dongjin.

3.2.3. Carbon uptake efficiency(*CUE*)

The growing season *RE* amounted to 714 ± 55 g C m^{-2} which was about 83% of the mean *GPP* (Table 7). Despite similar environmental conditions (i.e. high T_a and below normal *P*), Saenuri showed the highest *RE* (762 ± 29 g C m^{-2}) and Onnuri showed the lowest *RE* (664 g C m^{-2}). The growing season *CUE* of the first three cultivars (i.e. Dongjin, Nampyung, and Onnuri) was similar with an average of 1.23 whereas the lowest *CUE* of 1.14 was observed with Saenuri.

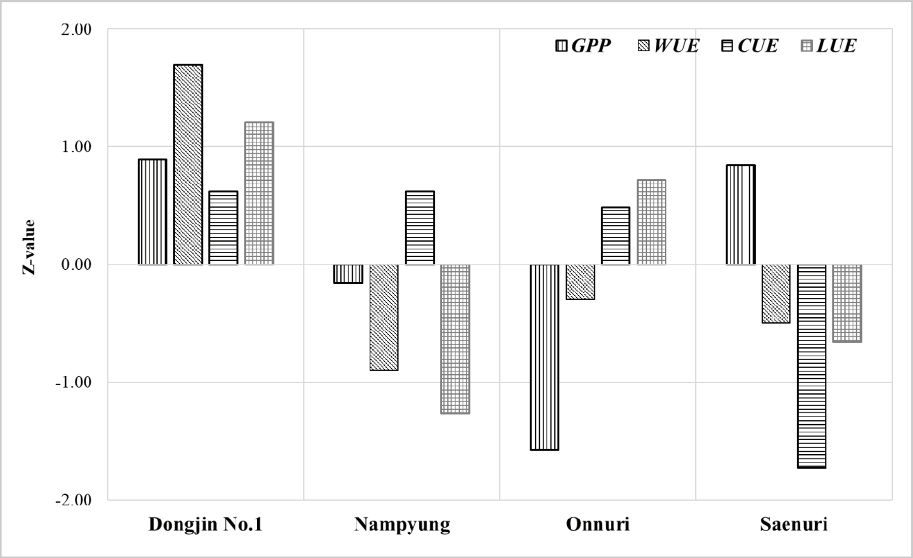
3.2.4. Light use efficiency(*LUE*)

With the mean *GSL* of 137 days, the growing season-integrated *PAR* was on average 1012 ± 98 M J m^{-2}(Table 8). Absorbed *PAR*(*APAR*) is determined as the product of *PAR* and *fPAR*. The latter varied from 0.58 to 0.79, depending on variety as well as individual years. Although the result is based on a single year observation, Nampyung in 2009 showed the highest *APAR* because of higher *PAR* and higher *fPAR*. Onnuri and Dongjin were the lowest because of the opposite conditions(i.e., low *PAR* and *fPAR*).

In terms of *LUE*, Nampyung was the lowest(0.99) with low *GPP* and high *APAR*. Despite the high *GPP*, Saenuri's *LUE* was low due to high *APAR*. Followed by Onnuri, Dongjin showed the highest *LUE*(1.49 ± 0.04 g C M J $^{-1}$) with small inter-annual variation(~3%) due to high *GPP* and low *APAR*. Saenuri which produced high *GPP* showed low *LUE* because of low *PAR* and *fPAR*.

3.3. Discussion

Among the four rice varieties, Dongjin showed the highest productivity with higher *WUE* and *LUE*, but comparable *CUE*. Saenuri also showed similarly high productivity but lower efficiencies(Fig. 3). This is also reflected in *GSL* which provides the connection between time and energy dissipation. For example,



standardized z-value of *GPP*, *WUE*, *CUE* and *LUE*

Fig. 3. Comparison of productivity and efficiency between different rice varieties.

to produce the same amount of *GPP*, Saenuri took 148 days whereas Dongjin took only 139 days, indicating that the latter was more productive in the least time.

Table 8 summarizes the comparison of productivity and efficiencies at HFK(for which Dongjin-dominated HFK was used for inter-comparison) against monoculture rice paddy sites in Asia. Those sites were selected based on the availability of EC measurement and the geographic representativeness. Overall, the *GPP* at HFK lies in the middle of the range shown in Table 8. Compared to other sites, HFK was less efficient in terms of *CUE* mainly due to larger magnitude of *RE*. It is interesting to note that IRRI data shows highly efficient management of carbon uptake but rather poorer management of water use. Due to data availability, the *LUE* at HFK was compared to MSE only, which was comparable. Although *CUE* at HFK was less efficient, *WUE* was highest among all sites because of low *ET*. The demand of water has been dramatically increasing in Korea(e.g. Jang *et al*., 2010), and better *WUE* would become an important trait with respect to the projected water storage.

Based on the assessment result, Dongjin would be the best choice to get higher productivity and efficiency. However, Saenuri, which has similar productivity but lower efficiency with longer growing season length, has been the dominant rice variety planted in 2016 and 2017. Part of the reason is because Saenuri is more resistant to rice blast, striped leaf blight, and brown planthopper than Dongjin. Rice resistance to pest and physiological damage is an important factor associated with resilience which should be considered together in the assessment of CSA. It is also important to conduct similar assessment on productivity and efficiencies of monoculture rice paddy(with intensive management) to come with direct implication of climate-smart agriculture, which is considered in further study.

It is important for agricultural ecosystem not only to increase productivity and efficiency but also to be resilient to maintain them. However, it is still challenging to measure resilience in a quantitative way. The indicators for the CSA assessment used in this study are the commonly used biotic indicators which inform little about functionality, directionality and consequence of interaction which needed to

Table 8. Site comparison in Asia

Site name	**Country**	**Latitude/ longitude**	**Variety**	***GSL*** **(day)**	**Year**	***GPP*** **(g C m^{-2})**	***RE*** **(g C m^{-2})**	***ET*** **(mm)**	***WUE*** **(g C kg H_2O^{-1})**	***CUE*** **(-)**	***LUE*** **(g C MJ^{-1})**	**Site Reference**
HFK	Korea	34.55°N, 126.57°E	Dongjin No. 1	Early June-Early Oct (139)	2003	800	697	340	2.35	1.15	1.46	**This study**
					2004	839	646	373	2.25	1.30	1.55	
					2005	944	792	337	2.80	1.19	1.46	
					2006	881	755	346	2.55	1.17	1.45	
					2008	881	658	365	2.41	1.34	1.52	
					AVG	**869**	**710**	**352**	**2.47**	**1.23**	**1.49**	
GRK	Korea	35.73°N, 126.85°E	Sindong jin	Mid Jun–Mid Oct (122)	2011	997	670	528	2.10	1.49	-	Kim *et al.* (2016)
					2012	957	802	435	2.40	1.19	-	
					2014	1028	760	552	2.05	1.35	-	
					AVG	**994**	**744**	**502**	**2.18**	**1.34**	-	
CRK	Korea	38.2°N, 127.25°E	Ode 1	Late May–Early Sep (130)	2016	921	570	426	2.16	1.62	-	Choi *et al.* (2018)
MSE	Japan	36.05°N, 140.03°E	Koshihi kari	Early May-Mid Sept (120)	2003	809	470	366	2.23	1.72	1.53*	Ikawa *et al.* (2017)
					2004	996	526	518	1.95	1.89	1.44*	
					2005	901	554	442	1.99	1.63	1.35*	
					2006	872	483	373	2.35	1.81	1.75*	
					AVG	**895**	**508**	**425**	**2.13**	**1.76**	**1.52***	
Liaohe Delta	China	40.94°N, 121.97°E		Mid May-Early Oct	2013	808	-	816	0.99	-	-	Wang *et al.* (2017)
					2014	838	-	829	1.01	-	-	
					AVG	**823**	-	**823**	**1.00**	-	-	
IRRI	Philippi nes	14.14°N, 121.26°E	NSIC Rc148	Jul-Oct (121)	2008	932	393	401	2.32	2.37	-	Alberto *et al.* (2011)
			NSIC Rc122	Jun-Nov (121)	2009	879	412	531	1.65	2.13	-	
					AVG	**905**	**403**	**466**	**1.99**	**2.25**	-	

**LUE* from calculation by using same method used for HFK.

measure resilience(Nielsen and Jørgensen, 2013). For example, from the complex systems perspective, self-organization capacity of a system has been proposed as an indicator for systems resilience(e.g. Prokopenko *et al.*, 2009). Recently, information-theoretic approaches gain more attentions for measuring self-organization capacity in terms of normalized spectral entropy(Kim and Kim, in prep; Zaccarelli *et al.*, 2013; Zurlini *et al.*, 2013). Alternatively, thermodynamics indicators have been proposed such as energy capture(R_n/R_s), and energy dissipation(thermal response number/*TRN*) (Lin *et al.*, 2009; Lin *et al.*, 2011) and thermodynamic entropy budget(e.g. Brunsell *et al.*, 2011; Cochran *et al.*, 2016; Svirezhev, 2010). Using the above-mentioned indicators for the assessment of the other two CSA objectives are the prerequisite to the development of a holistic CSA evaluation, which is currently in progress.

IV. SUMMARY

In this study, we have assessed the first objective of CSA(regarding productivity and efficiency) for a typical farmland dominated by rice paddies over the Haenam farmland site in Korea (HFK) during the rice growing seasons from 2003 to 2015. Four different varieties of rice(i.e., Dongjin, Nampyung, Onnuri, and Saenuri) were cultivated at HFK during the study period. Our analyses of their energy, water and carbon flux time series demonstrated dynamically varying productivity and efficiencies along with changes in varieties and surrounding conditions. Regardless of rice varieties, the *GPP* at HFK ranged from 800 to 944 g C m^{-2} in which Dongjin and Saenuri showed the best performance. In terms of *WUE*, the efficiency ranged from 1.91 to 2.80 g C kg H_2O^{-1}, with the highest efficiency observed in Dongjin and the lowest in Nampyung. In terms of carbon uptake, Dongjin, Nampyung and Onnuri were comparable with *CUE* of~1.23 and more efficient than Saenuri(*CUE* of~1.14). In terms of light use, Dongjin showed the highest efficiency with *LUE* of~ 1.49 g C MJ^{-1}.

In the context of climate-smart agriculture, Dongjin was most productive and efficient in terms of water, carbon, and light use. Dongjin No1-dominated HFK was comparable to those of monoculture rice paddies in Asia, whereas HFK was more efficient in water use and less efficient in carbon uptake. The current result suggested that Dongjin would be the best choice to get higher productivity and efficiency. However, farmers cultivate Saenuri that less efficient than Dongjin because of higher pest resistance(associated with adaptability and resilience). This emphasizes the need for the evaluation of the other objectives of CSA(i.e. system resilience and greenhouse gas mitigation) for complete assessment at HFK.

적 요

기후스마트농업(Climate-Smart Agriculture, CSA)이 성취되고 있는지에 대한 정량적인 평가방법을 구축하기 위해 타워 기반의 플럭스 관측 시계열 자료를 활용할 수 있다. 이 연구에서는 벼농사가 지배적인 전형적인 비균질 농경지를 대상으로 CSA의 첫 번째 목표와 관련된 생산성과 효율성 평가를 시도하였다. 이를 위해 해남 농경지에 위치한 KoFlux 사이트(HFK)에서 2003년부터 2015년까지 벼의 생장기간 동안에 관측된 탄소, 물 및 에너지 플럭스의 시계열 자료를 분석하여 일련의 정량적인 지표들을 평가하였다. 이 연구기간 동안에 HFK에서는 네 가지의 다른 품종(동진 1호; 2003-2008, 남평; 2009, 온누리; 2010-2011, 새누리; 2012-2015)의 벼가 경작되었다. 전반적으로 품종을 구분하지 않을 경우, 연구기간 동안의 HFK의 총일차생산(*GPP*)은 800 – 944 g C m-2, 물사용효율(*WUE*)은 1.91 – 2.80 g C kg H2O-1, 탄소사용효율(*CUE*)은 1.06 – 1.34, 그리고 광사용효율(*LUE*)은 0.99 – 1.55 g C MJ-1이었다. 벼 이외의 다른 식생이 포함된 HFK의 비균질성을 고려하여 어림 잡아 비교해 보면, 네 품종 중에서 동진1호를 재배했을 때에 HFK의 생산성이 아시아의 단일 벼논의 생산성과 비슷했고 *WUE*도 높았던 반면에 *CUE*는 상대적으로 낮았다. 또한, 새누리를 재배했을 때에도 HFK가 비슷하게 높은 생산성을 보였으나 동진1호보다 생장기간이 상대적으로 길었다. 따라서 동진1호가 지배적인 HFK가 CSA의 관점에서 더 좋은 특성을 보여 준다. 그러나 현실적으로는 농부들이 해충 저항성이 동진1호보다 높은 새 누리를 재배하고 있다. 이는 CSA의 나머지 두 목표의 하나인 탄력(resilience) 향상을 통한 적응력 강화와 관련된 것으로 온실가스 방출 저감을 포함한 총체적인 평가가 이루어져야 함을 시사하며, 이에 대한 평가와 분석이 현재 진행 중에 있다.

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