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한국 김제의 벼 경작 시스템의 기후스마트농업 (Climate-Smart Agriculture) 기반의 평가

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Climate-Smart Agriculture (CSA)-Based Assessment of a Rice Cultivation System in Gimje, Korea

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ABSTRACT

The overarching question of this study is how a typical rice cultivation system in Gimje, Korea was keeping up with the triple-win challenge of climate-smart agriculture (CSA). To answer this question, we have employed (1) quantitative data from direct measurement of energy, water, carbon and information flows in and out of a rice cultivation system and (2) appropriate metrics to assess production, efficiency, GHG fluxes, and resilience. The study site was one of the Korean Network of Flux measurement (KoFlux) sites (i.e., GRK) located at Gimje, Korea, managed by National Academy of Agricultural Science, Rural Development Administration. Fluxes of energy, water, carbon dioxide (CO_2) and methane (CH_4) were directly measured using eddy-covariance technique during the growing seasons of 2011, 2012 and 2014. The production indicators include gross primary productivity (*GPP*), grain yield, light use efficiency (*LUE*), water use efficiency (*WUE*), and carbon uptake efficiency (*CUE*). The GHG mitigation was assessed with indicators such as fluxes of carbon dioxide (F_{CO2}), methane (F_{CH4}), and nitrous oxide (F_{N2O}). Resilience was assessed in terms of self-organization (*S*), using information-theoretic approach. Overall, the results demonstrated that the rice cultivation system at GRK was climate-smart in 2011 in a relative sense but failed to maintain in the following years. Resilience was high and changed little for three year. However, the apparent competing goals or trade-offs between productivity and GHG

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mitigation were found within individual years as well as between the years, causing difficulties in achieving the triple-win scenario. The pursuit of CSA requires for stakeholders to prioritize their goals (i.e., governance) and to practice opportune interventions (i.e., management) based on the feedback from real-time assessment of the CSA indicators (i.e., monitoring) - i.e., a purpose-driven visioneering.

***Key words*: Climate-smart agriculture, Rice, GHG mitigation, Resilience, Eddy covariance flux**

I. Introduction

The increasing concerns on the role of agriculture in ensuring food security, coping with climate change, and preserving natural resources have given a birth to the 'climate-smart agriculture (CSA)' vision in 2010 by the United Nations Food and Agriculture Organization (FAO) (http://www.fao.org). CSA is a triple-win challenge to transforming and reorienting agricultural systems to support food security under the new realities of climate change through (1) sustainably increasing agricultural productivity and small-holders' income, (2) reducing and/or removing greenhouse gas (GHG) emission, where possible, and (3) adapting and building resilience to climate change. The CSA initiative helps scientists, engineers, practitioners, and policy-makers to identify synergies and trade-offs among the above triad goals (e.g., Lipper *et al*., 2014). To further the understanding of how the implementation of CSA works in different ecological-societal systems, recent progress reviews have stressed the necessities of urgent actions such as building scientific evidence and more appropriate assessment tools (e.g., Rosenstock *et al*., 2016). In order to ascertain the synergies and/or trade-offs among the three-fold objectives of CSA, the development of holistic indicators that are scientifically credible and relevantly integrated are essential. However, the paucity of holistic indicators and quantitative measurement data hinders farmers, researchers, and policy makers from making measurable assessment of the progress and the impact of CSA (e.g., Neufeldt *et al.,* 2013; Kim *et al*., 2018).

Rice is a leading food crop in the world (Ricepedia, n.d.). Usually, rice paddies act as carbon sink by sequestering CO_2 (Diaz *et al*., 2019). On the contrary, they are also one of the major sources of CH_4 whose 100-year global warming potential (GWP) is 28 x CO_2 (e.g., Miyata *et al*., 2000; Forster *et al.,* 2007; Shindell *et al*., 2009). CH_4 emission from rice paddies is expected to increase in the future due to growing demand for food, warming effect with increasing temperature, and fertilization effect with increasing CO_2 concentration (e.g., Smith *et al*., 2007; Pereira *et al*., 2013; Van Groenigen *et al*., 2013). In addition, rice paddies are also minor sources of nitrous oxide (N_2O) which has 298 times greater GWP than that of CO_2 (Forster *et al.,* 2007; Sun *et al*., 2016).

Strategic and quantitative monitoring of rice paddy ecosystem is the prerequisite to finding out whether the current setting of rice cultivation is a proper configuration toward sustainable management in terms of productivity, GHG mitigation, and system resilience to climate change. Micrometeorological eddy covariance (EC)-based time series data are valuable resources to develop CSA metrics (e.g., Indrawati *et al*., 2018). They can be used directly and effectively to provide quantitative and integrative indicators at ecosystem scale needed for the assessment of triple objectives of CSA. It is particularly challenging to assess resilience which is associated with functionality, directionality and consequence of interaction (Nielsen and Jørgensen, 2013). Based on complex systems theory, self-organizing capacity of a system has been proposed as an indicator for system's resilience (e.g., Prokopenko *et al.,* 2009). Information-theoretic approaches gain more recognition for evaluating self-organizing capacity (Zaccarelli *et al*., 2013; Zurlini *et al*., 2013). Alternatively, thermodynamics indicators also have been proposed such as energy capture, energy dissipation (Lin *et al*., 2009, 2011), and thermodynamic entropy budget (Svirezhev, 2010; Brunsell *et al*., 2011; Cochran *et al*., 2016; Yang *et al*., 2020).

In this study, we question, “how is a rice cultivation system in Gimje, Korea keeping up with the triple-challenge of CSA?” We hypothesized that Gimje rice cultivation system is ‘climate-smart’, i.e., the triad goals are not only achieved in tandem in each individual years but also maintained in the following years at Gimje site. To make a relative sense of evaluation, we also compared these results with those reported in the literature from other rice cultivation sites. For the assessment of CSA metrics, fluxes of energy, water, CO_2 and CH_4 were monitored using eddy-covariance technique during the growing seasons of 2011, 2012 and 2014. The production efficiency was evaluated by examining the indicators such as gross primary productivity (*GPP*), ecosystem respiration (*RE*), grain yield, light use efficiency (*LUE*), water use efficiency (*WUE*), and carbon uptake efficiency (*CUE*). The GHG mitigation was assessed with directly measured fluxes of CO_2 (F_{CO2}) and CH_4 (F_{CH4}), along with indirectly estimated flux of nitrous oxide (F_{N2O}) following the IPCC guideline. For the resilience indicator, self-organizing capacity was quantified for three most comprehensive processes that represent overall state of the rice cultivation system (i.e., *GPP,* CH_4 exchange, and evapotranspiration for biochemical, biogeochemical and biophysical processes, respectively).

II. Materials and Methods

2.1. Study Site

The study site with the flux tower was located in Gimje, South Korea (35°44′42.4″N, 126°51′8.8″E, and 4.2 m above m.s.l) (Fig. 1). The dominant land use was cropland characterized by relatively wide plains with a moderate oceanic climate. Seasonal monsoon was characterized by persistent and intensive rainy periods during the summer (i.e., ‘Changma’) and frequent passes of typhoons. Soil texture was silt loam and the porosity was ~0.52. At the study site, rice (*Oryza sativa*) - winter barley (*Hordeum vulgare*) double crop rotation was practiced. The growing season of rice was typically from mid-June to early-October. Maximum leaf area index (LAI) was 4.4, 3.9, and 4.7 $m^2\ m^{-2}$ in 2011, 2012, and 2014, respectively with the maximum canopy height of ~1.05 m (Min *et al*., 2013).

The dates of transplanting, mid-season drainage (MSD), and harvesting along with the growing season length (GSL) are summarized in Table 1. Thirty-day old seedlings were transplanted (5-6 seedling per hill) mechanically at a density of 0.30 x 0.15 m with

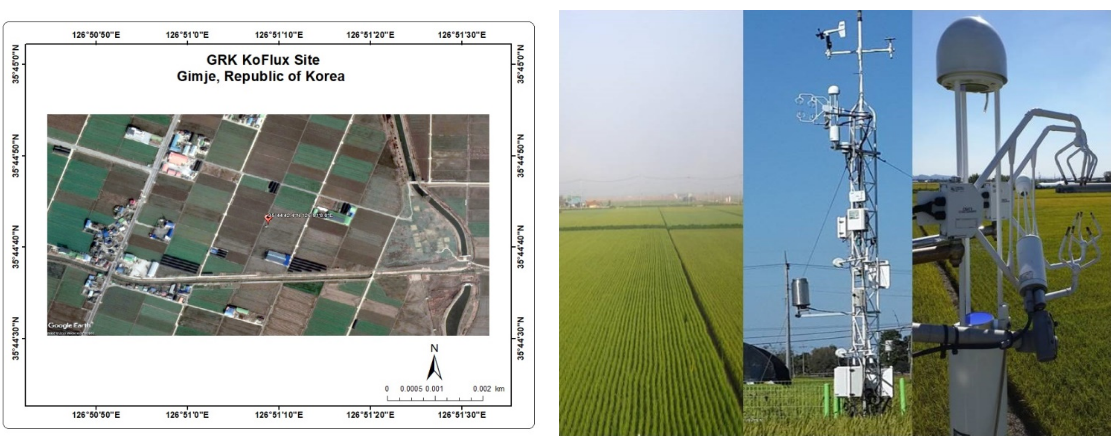

Fig. 1. The map of the study site and the eddy covariance flux measurement tower in the rice paddy in Gimje, South Korea.

Table 1. Transplanting, mid-season drainage, and harvesting dates (in day of year, DOY) and growing season length for Gimje rice paddy in 2011, 2012 and 2014

Activity	2011	2012	2014
Transplanting	19 June (170)	21 June (173)	9 June (160)
Mid-season drainage	25 July (206)	21 July (203)	16 July (197)
Harvesting	16 October (289)	20 October (294)	12 October (285)
Growing season length	119 days	121 days	125 days

east-west planting direction. 'Sindongjin' hybrid variety, a medium-late *japonica* rice cultivar, was selected mainly for their high yield potential based on performance in local yield trials (Kang *et al*., 2015). The nitrogen fertilizer management was barely changed. Fertilizers were applied at a rate of 110 kg N ha^{-1}, 45 kg P_2O_5 ha^{-1} and 57 kg K_2O ha^{-1} in total. As a basal application, 50% of N, all of P_2O_5 and 70% of K_2O were broadcasted just prior to transplanting. The 40% of the remaining N was applied at the tillering stage and 60% shortly after the panicle initiation stage as top dressing along with the remaining 30% of K_2O. Flooded irrigation was carried out from early-June to mid-July, and then the field was fully drained from mid-July to mid-August (i.e., mid-season drainage, MSD). Intermittent irrigation practice was applied from mid-August to mid-September (Kim *et al*., 2016).

2.2. Biometeorological Measurements

2.2.1. Field measurement

The EC flux measurement tower was located at the center of the paddy field to monitor energy, water vapor, CO_2 and CH_4 fluxes. The LI-7700 open-path CH_4 analyzer (LI-COR Biosciences, USA), the LI-7500 open-path H_2O/CO_2 analyzer (LI-COR Biosciences, USA), and the CSAT3 three-dimensional sonic anemometers (Campbell Scientific Inc., USA) were installed at 5.2 m above the ground (see Fig. 1). There was no vertical separation between these instruments. The horizontal separation between the LI-7700 and the CSAT3 was 0.52 m, and that between the LI-7500 and the CSAT3 was 0.43 m. The wind vectors and gas concentrations were recorded at a sampling rate of 10 Hz. A rain gauge (52203 Tipping Bucket Rain Gauge, RM Young Company, USA) was located 1 m above the ground, and a four-compnent net radiometer (CNR1, Kipp & Zonen B.V., Netherlands) was installed 2.7 m above the ground. Soil temperature and soil moisture contents at 0.05 m depth were measured with thermometers (TCAV, Campbell Scientific Inc. USA) and tensiometers (CS616, Campbell Scientific Inc. USA) at 2 locations, respectively. Soil heat flux was measured with soil heat flux plates (HFP01, Hukseflux Thermal Sensors, Netherlands) which were buried at 0.05 m depth at 2 locations. The burial locations of these soil sensors were near the flux tower, which are far from a drainage channel and at a relatively lower level. Such a placement led to slower drainage around the measurement area than the overall conditions of the entire paddy field. A data logger (CR5000, Campbell Scientific Inc. USA) was used to store and compile both turbulence and biometeorological data.

2.2.2. Meteorological Data Processing

For the slow-response meteorological variables, the data logger outputs (i.e., the 30-minute averaged raw data without quality control) were categorized as the level 0 (L0) data. Then, following the KoFlux data processing protocol (Hong *et al*., 2009, Kang *et al.,* 2018), the L0 data were processed with quality control to produce L1 dataset. In order to provide seamless dataset (i.e., L2 data), the combination approach (including interpolation, mean diurnal variation, and linear regression) using data from the automated weather stations operated by the Korea

Meteorological Administration was applied for the gap filling of missing data. Then, L2 dataset was used for the gap-filling of flux data.

2.2.3. Flux Data Processing

The collected flux data were processed and quality controlled following the KoFlux data processing protocol (Hong *et al*., 2009, Kang *et al.,* 2017). Gap-filling was applied to the processed half-hourly fluxes using the standardized KoFlux protocol (Hong *et al*., 2009). CO_2 and CH_4 fluxes were gap-filled using the marginal distribution sampling (MDS) methods, following Kang *et al*. (2018). In case of CO_2 flux, three different nighttime CO_2 flux correction (i.e., filtering and replacing) methods were applied: 1) the friction velocity filtering method, 2) light response curve method, and 3) modified van Gorsel method (Kang *et al.,* 2014; Van Gorsel *et al.,* 2009). The daily net ecosystem exchange (*NEE*) of CO_2, gross primary productivity (*GPP*) and ecosystem respiration (*RE*) used in this study are the averaged values from these three methods. The flux and biometeorological data from 2011, 2012 and 2014 were used for further analysis (with the exclusion of 2013 when the data availability after quality control was < 50% during the growing season).

2.3. Assessment of the CSA Metrics

2.3.1. Indicators for productivity and efficiency

2.3.1.1. Gross primary productivity (*GPP*) and grain yield

Gross primary productivity is the total amount of organic matter produced through photosynthesis in a defined area per unit time, which represents vegetation productivity (e.g., Gitelson *et al*., 2006). *GPP* was calculated from *NEE* and *RE* (extrapolated from the nighttime temperature-response equation with daytime temperature) as:

$$GPP - RE = -NEE, \qquad \text{(Eq. 1)}$$

where -*NEE* is equal (but opposite in sign) to net ecosystem productivity (*NEP*).

The grain yield is related to net primary productivity (*NPP*) which is roughly 50% of *GPP* (e.g. Zhang *et al.,* 2009). In this study, the actual grain yields and *GPP* were used as productivity indicator. During the study period from 2011 to 2014, the rice varieties at GRK were the same, i.e., 'Sindongjin'.

2.3.1.2. Water use efficiency *(WUE)*

Water use efficiency (*WUE*) at ecosystem level is defined as:

$$WUE = \frac{GPP}{ET} \qquad \text{(Eq. 2)}$$

where *GPP* and *ET* are the daily sums of half-hourly fluxes from the EC measurement (e.g. Reichstein *et al*., 2007; Yu *et al*., 2008). *ET* was calculated by dividing the latent heat flux (λE) by the latent heat of vaporization. The unit of daily *GPP* is in g C m^{-2}, *ET* in mm, and *WUE* in g C kg H_2O^{-1}.

2.3.1.3. Light use efficiency *(LUE)*

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 (Monteith and Moss, 1977). The carbon exchange between the crop canopy and the atmosphere is controlled by the amount of absorbed photosynthetically active radiation (*APAR*) and light use efficiency (*LUE*). In this study, *LUE* is calculated as (e.g., Gitelson and Gamon, 2015):

$$LUE = \frac{GPP}{APAR} \qquad \text{(Eq. 3)}$$

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 GRK and estimation of *PAR.*

2.3.2. Indicators for GHG mitigation

2.3.2.1. Direct measurement of CO_2 and CH_4 fluxes

Measurement of *GHG* mitigation was assessed by the growing season-long monitoring of fluxes of CO_2 and CH_4 at GRK during 2011, 2012 and 2014. The time series of CO_2 and CH_4 fluxes were directly measured by eddy covariance techniques as described in the section 2.2.

2.3.2.2. Estimation of N_2O emission

Nitrous oxide emission from Gimje site was estimated using the revised 1996 IPCC guidelines for National Greenhouse gas inventories as (IPCC, 1997; Mosier *et al*.,1998) as.

N_2O emissions = Direct emissions (N_2O_{DIRECT}) + indirect emissions ($N_2O_{INDIRECT}$), (Eq. 4)

$N_2O_{DIRECT} = [(F_{SN} + F_{CR}) \text{ x } EF_{1FR}] \times 44/28$, and (Eq. 5)

$N_2O_{INDIRECT} = [(N_2O_{(G)}) + (N_2O_{(L)})] \times 44/28$, (Eq. 6)

where (i) F_{SN} is the nitrogen (N) fertilizer applied annually to soils adjusted to account for the amount that volatilizes as NH_3 and NOx [kg N ha^{-1}], and calculated as F_{SN} = N inputs x (1 - $Frac_{GASF}$) where $Frac_{GASF}$ (volatilization factor) is 0.1 kg NH_3-N/kg N_2O-N; (ii) F_{CR} is N in crop residues returned to soils [kg N ha^{-1}], and calculated as F_{CR} = weight of below ground part of the rice paddy (*kg* ha^{-1}) × N content of the residues (0.0067 kg N kg^{-1} of dry biomass) where the weight of below ground part of the rice paddy was given as 87% of rice grain yield; (iii) EF_{1FR} is the direct emission factor for N_2O emissions from N inputs to flooded rice field [kg N_2O-N/kg N inputs], and the country-specific coefficient is 0.003 kg N_2O-N/kg N; (iv) $N_2O_{(G)}$ is the indirect N_2O emissions by atmospheric vaporization and estimated as $N_2O_{(G)} = (F_{SN} \text{ x } Frac_{GASF}) \text{ x } EF_4$ where EF_4 is the emission factor for N_2O emissions from N volatilization and re-deposition [kg N_2O-N/kg NH_3-N] and default value is 0.01 kg N_2O-N/kg N; and (v) $N_2O_{(L)}$ is the indirect N_2O emissions by the outlet water and estimated as $N_2O_{(L)} = [(F_{SN}+F_{CR}) \text{ x } Frac_{LEACH}] \text{ x } EF_5$, where $Frac_{LEACH}$ (default value = 0.3) is the fraction of N inputs losses by leaching and runoff and EF_5 is the emission factor for N_2O from N leaching and runoff [kg N_2O-N / kg N], and the country-specific coefficient is 0.0135 kg N_2O-N / kg N.

2.3.2.3. Carbon uptake efficiency

Carbon uptake efficiency (*CUE*) is defined as the ratio of *GPP* and ecosystem respiration (*RE*) (Indrawati *et al*., 2018):

$$CUE = \frac{GPP}{RE} \quad \text{(Eq. 7)}$$

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

2.3.3. Resilience Indicator

Resilience is associated with 'self-organizing capacity' which produces a global order out of the local interactions of the system components. Such systems increase their organization in time from their own internal dynamics (Gershenson and Fernamdez, 2012). Here, information theory can be used to measure such organization (Shannon, 1948). For example, ordered/organized time series has less uncertainty (i.e., low information entropy) than chaotic, disorganized time series. In other words, if information entropy is reduced when self-organization occurs, whereas self-disorganization results in an increase of information entropy.

Complex systems are known to be equipped with stability and flexibility in harmony. From an information-theoretic point of view, 'regularity' ensures that useful information is maintained while 'change' enables the systems to be flexible to explore new possibilities that are essential for adaptation and evolution. Following Lopez-Ruiz *et al.* (1995), complexity can be defined as the balance between change (disorder) and stability (order), for which emergence (E) and self-organization (S) can be its measure, respectively. Here, E describes emergent (new) global patterns that are not present in the system's components, which measures the indeterminacy a process produces as a consequence of changes in process dynamics or scale.

For continuos distributions, E interpretation is constrained to the average uncertainty a process produces under a specific set of the distribution parameters (e.g., the standard deviation value for a Gaussian distributions). Formally, the continuous E is defined, following Santamaria-Bonfil *et al.* (2016) as:

$$E = -K\,(\lim_{\Delta \to 0} H(X^{\Delta}) + log_2\,(\Delta)) \quad \text{(Eq. 8)}$$

which is a quantized version of the differential entropy, where X^{Δ}corresponds to discretized version of random variable X, and Δ is the integration step. Here, K is a normalizing constant that constrains E within the range $0 \leq E \leq 1$, and is estimated as

$$K = {}^{1}/_{log_2(b)} \quad \text{(Eq. 9)}$$

where b corresponds to the states that satisfy $P(x_i) > 0$. Hence, $log_2(b)$ corresponds to the maximum entropy for a distribution function with number b of possible states that a system can take.

Now, as resilience indicator, self-organization (S) can be seen as a reduction of entropy. Thus, S is considered as the compliment of E, that is:

$$S = 1 - E, \quad \text{(Eq. 10)}$$

such that $0 \leq S \leq 1$. S is related to order and regularity due changes in the process dynamics and scale. Hence, an entirely random process (e.g., uniform distribution) has the lowest S (= 0) whereas a completely deterministic process has the highest S (= 1).

Finally, S, as an indicator for system's resilience, was quantified for the three most comprehensive processes in rice cultivation system: 1) gross primary production (biochemical), 2) methane production/ oxidation and transport (biogeochemical), and 3) evapotranspiration (biophysical). Using the MATLAB code of Santamaria-Bonfil *et al.* (2017), computations and analyses were done in two ways by using (1) the time series data with half-hourly interval and (2) the time series data with daily interval. Then, the composite values (i.e., E_{AVG}, S_{AVG}) were calculated by taking the average of the individual indicator's values for the above-mentioned three processes (i.e., GPP, F_{CH4}, and ET). Finally, S_{AVG} was considered as an overall resilience indicator for the rice cultivation systems at GRK site for the growing seasons of 2011, 2012 and 2014.

III. Results

3.1. Climatic Conditions

As summarized in Table 2, the growing season mean air temperature (T) was 22.7±4.4°C, 22.5±4.8°C and 22.1±2.9°C during 2011, 2012 and 2014, respectively, all comparable with the 30-year (growing season) normal (22.7±3.8°C). For the growing season total P, 2011 and 2012 were above normal (i.e., 804±278 mm) whereas 2014 was much below normal. As expected from the observed differences in P among the three growing seasons, incoming solar radiation (R_S) was highest in 2014. Such an interannual variability in P and R_S provided a broad range of conditions needed for the examination of CSA indicators among the three years under study.

3.2 Assessment of Climate-Smart Agriculture (CSA)

3.2.1. Indicators for productivity

3.2.1.1. Gross primary productivity (*GPP*)

For the three growing seasons, GPP averaged to be 889 (±35) g C m^{-2} with an averaged growing

Table 2. Climatic conditions, phenology, and indicators for the triad goals (i.e., productivity, GHG mitigation, and resilience) of climate-smart agriculture (CSA) during the three growing seasons in 2011, 2012 and 2014 at the GRK rice cultivation site

Parameters (Unit)	2011	2012	2014
Climatic conditions			
T (°C)	22.7	22.5	22.1
P (mm)	893	976	620
Solar radiation, R_S (MJ m^{-2})	1703	1894	1958
Phenology			
Growing season length, *GSL* (days)	119	121	125
Productivity indicators			
Gross primary production, *GPP* (g C m^{-2})	938	860	868
Grain yield (g grain m^{-2})	649	513	603
Light use efficiency, *LUE* (g C MJ^{-1})	2.09	1.93	1.80
Water use efficiency, *WUE* (g C kg H_2O^{-1})	1.91	2.06	1.95
Evapotranspiration, *ET* (mm)	514	440	494
GHG mitigation indicators			
Net CO_2 uptake, F_{CO2} (g CO_2 m^{-2})	-1,349	-931	-1,280
CH_4 emission, F_{CH4} (g CH_4 m^{-2}) (CO_2 equivalent F_{CH4} in g CO_2e m^{-2})	25.5 (2,142)	24.0 (2,016)	34.7 (2,912)
N_2O emission, F_{N2O} (mg N_2O m^{-2}) (CO_2 equivalent F_{N2O} in g CO_2e m^{-2})	1.39 (0.41)	1.32 (0.39)	1.36 (0.41)
Total CO_2 equivalent emission of CO_2, CH_4 & N_2O per grain yield (g CO_2e / g grain yield)	1.22	2.12	2.83
Carbon uptake efficiency, *CUE*	1.65	1.42	1.67
Ecosystem respiration, *RE* (g CO_2 m^{-2})	570	607	519
Resilience indicators using half-hourly (daily) time series			
Self-organization of *GPP* (S_{GPP})	0.97 (0.93)	0.96 (0.93)	0.97 (0.93)
Self-organization of F_{CH4} (S_{FCH4})	0.95 (0.93)	0.97 (0.95)	0.96 (0.94)
Self-organization of *ET* (S_{ET})	0.95 (0.93)	0.95 (0.94)	0.95 (0.94)
Composite self-organization (S_{AVG})	0.95 (0.93)	0.96 (0.94)	0.96 (0.93)

season length (*GSL*) of ~122 days. In 2011, despite being the year with the lowest R_S, *GPP* was 938 g C m^{-2}, higher than those in 2012 and 2014. *GPP* was lowest in 2012. The growing season-integrated *RE* was on average 565 (±36) g C m^{-2} with interannaul variation of ~6%. Among the three growing seasons, *RE* was highest in 2012 which showed the lowest *GPP*.

3.2.1.2. Evapotranspiration (*ET*)

As summarized in Table 2, evapotranspiration (*ET*) from the three growing seasons was different and the daily rate ranged from 3.6 to 4.3 mm day^{-1}. The maximum *ET* was 8.78 mm d^{-1}, 6.6 mm d^{-1} and 7.2 mm d^{-1} in 2011, 2012 and 2014, respectively. As noted earlier, the energy source for *ET* (i.e., R_S) was lowest in 2011, and yet *ET* was highest among the three growing seasons.

3.2.1.3. Water use efficiency (*WUE*)

Water use efficiency is simply the ratio of *GPP* to *ET*, therefore it can be intuitively guessed from the above values of *GPP* and *ET*. As shown in Table 2, mean daily *WUE* in 2012 was highest despite the lowest *GPP* because the relative amount of reduction in *ET* was much greater than that in *GPP*. On the contrary, *GPP* was highest in 2011 but *WUE* was lowest because of greater increase in *ET* (likely due to more frequent occurrence of sensible heat advection).

3.3.1.4. Light use efficiency (*LUE*)

The growing season-integrated photosynthetically active radiation (*PAR)* was on average 807±44 MJ m^{-2} with the absorbed fraction of *PAR* (*fPAR*) varying from 0.54 to 0.60. For the three growing seasons, the daily *LUE* ranged from 1.80 to 2.09 g C $MJ^{-1}d^{-1}$ with an average of 1.94±0.12 g C $MJ^{-1}d^{-1}$. As expected, 2011 showed the highest *LUE* with the highest *GPP* and the lowest *APAR*. The opposite was the case in 2014 when lower *GPP* with the highest *APAR* produced the lowest *LUE*.

3.3.2. Indicators for Greenhouse Gas (GHG) mitigation

3.3.2.1. Carbon dioxide (CO_2) uptake

The growing season-integrated CO_2 uptake was on average 1,118 (±183) g CO_2 m^{-2} (equivalent to a daily rate, F_{CO2} of~9.9 g CO_2 m^{-2} d^{-1}). The highest net uptake rate of F_{CO2} (~11.0 g CO_2 m^{-2} d^{-1}) was observed in 2011, corresponding with the highest *GPP* and grain yield. The lowest F_{CO2} was observed in 2012 when *RE* was highest, resulting lowest carbon uptake efficiency (Table 2). More efficient carbon uptake was observed in 2011 and 2014. In Table 2, F_{CO2} was given with negative sign, indicating that negative flux means absorption by rice paddy and positive flux means emission into the atmosphere.

3.3.2.2. Methane (CH_4) emission

The growing season-accumulated methane emission, F_{CH4} was on average 28.1±4.7 g CH_4 m^{-2} (equivalent to a daily rate of 231 mg CH_4 m^{-2} d^{-1}). In Table 2, the values of F_{CH4} are also given in CO_2 equivalent (g CO_2e m^{-2}). For this conversion, instead of using the 100-year global warming potential (GWP), we used the 20-year GWP of 84 × CO_2 because of relatively short (less than 20 years) residence time of methane in the atmosphere. Despite the lowest *P* in 2014, methane emission was highest. Furthermore, for the years with ample precipitation (2011 and 2012), methane emission was much lower. As pointed out later in the discussion, the proper timing of mid-season drainage played more important role than total amount of season-long *P* in methane emission.

3.3.2.3. Nitrous Oxide (N_2O) emission

For the three growing seasons (with an averaged GSL of~122 days), the total emission of N_2O was on average 0.165±0.004 g N_2O m^{-2} (equivalent to 1.36 mg N_2O m^{-2} d^{-1}). The difference in F_{N2O} among the three growing season was small (< 2%) and negligible when considering the uncertainties associated with indirect estimation based on the IPCC guideline. In terms of its CO_2 equivalent (using the GWP of 298 × CO_2), the contribution of F_{N2O} was negligibly small (see Table 2).

3.3.3. Indicators for Resilience

Table 2 also presents the results of *S* (self-organization, a resilience indicator) for the three growing seasons. It would be useful to recall the definition of *S* which is the compliment of *E* (i.e., $S = 1 - E$) where E measures the uncertainty (hence, an increase of entropy) a process produces as a consequence of changes in process dynamics or scale. *S* is related to order and regularity due changes (hence, a reduction of entropy). The time series of *GPP*, F_{CH4}, and *ET* were analyzed with two different sampling rates (i.e., half-hourly and daily) but the results were not much different as shown in Table 2. All the values of S_{GPP}, S_{FCH4}, and S_{ET} for the three growing seasons were between 0.93 to 0.97, suggesting the rice cultivation system had high level of resilience with little interannual variability. However, further test of this approach is needed with different parameter settings and assumptions.

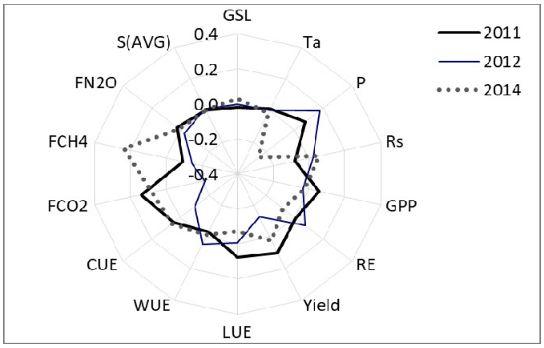

Fig. 2. Radial plot showing the relative changes (from -40 to 40%) in CSA indicators that are normalized against the mean values. F_{CO2} is uptake whereas $F_{CH4,}$ F_{N2O}, and RE are all emission.

IV. Discussion

As shown in Table 2, a variety of conditions encountered for the three year's growing season period provided an opportunity to examine the CSA indicators under different constraints as well as from different perspectives.

In order to distinguish the observed conflict and/or tradeoff between the triad goals of CSA, all the indicators were normalized based on their mean values for the three growing seasons. Their relative changes are presented in a radial plot in Fig. 2. It is clearly demonstrated that all the indicators were varying during the three growing seasons except the resilience indicator, S and nitrous oxide emission, F_{N2O}.

In 2011, despite having the lowest R_S, more efficient use of light resulted in higher productivity (thus, higher *CUE*) than in other two years. However, it was at the expense of using more water (i.e., lower *WUE*) while the system resilience remained with little change. In 2012, despite receiving the greatest amount of P, the mid-season drainage was effective because of the absence of P during the MSD period with greater R_S (not shown). The resulting aerobic soil conditions produced better mitigation of overall CH_4 emission as indicated in Fig. 2. The increase in RE (hence, reduced F_{CO2}) resulted in the lowest productivity. Despite all these changes, S remained with little change. In 2014, higher R_S and lower P than other two years resulted in intermediate level of *GPP* as well as grain yield, which are reflected in the lowest *LUE*. However, rainfalls during the MSD period maintained the soil moisture near saturation (not shown) and nullified the drainage effect, thereby resulting in significantly more CH_4 emission than in other years.

Table 3 represents a qualitative comparison of the relative achievement of triad goals among the three growing seasons at Gimje site using a simplified three-level categorization (i.e., high, intermediate, low) based on Table 2 and Fig. 2. Several features are worth noting: (1) the rice cultivation in 2011 was ‘climate-smart’ by achieving the ‘high’ level in all three goals of CSA, but the reason for such a success is unclear and deserves further investigation, (2) neither 2012 nor 2014 maintained ‘climate-smart’ cultivation due to reduced productivity and increased GHG emission, and (3) there appears to be trade-offs between productivity and GHG mitigation within a growing season as well as between different growing seasons.

In terms of productivity, the range of *GPP* at GRK site was comparable to those reported from other sites in Korea as well as those from Japan and the Philippines (e.g., Hwang *et al*., 2020; Alberto *et al*.,

Table 3. Qualitative comparison of the triad goals (productivity, GHG mitigation, resilience) of climate-smart agriculture (CSA) at GRK rice cultivation site for the growing seasons of 2011, 2012 and 2014

CSA triad goal	2011	2012	2014
Productivity	High	Low	Intermediate
GHG mitigation	High	Intermediate	Low
Resilience	High	High	High

2011), but higher than those reported from China and Bangladesh (e.g., Wang *et al*., 2017; Hossen *et al*., 2011; 2012). Productivity is dependent on the efficiency of light use, among other factors. The *LUE* at GRK site was higher than those reported from a few rice paddy sites in Japan (Indrawati *et al*., 2018; Ikawa *et al*. 2017). In terms of water use, the range of *WUE* at GRK was in the middle to upper range of those reported from other rice paddy studies (e.g., Hossen *et al*., 2011; 2012 ; Alberto *et al*., 2009; 2011; Diaz *et al*., 2019).

In terms of GHG, F_{CO2} at GRK was within low range of those reported in the literature for rice paddies under various practices and climate conditions (e.g., Alberto *et al*., 2012; Miyata *et al*., 2005; Diaz *et al*., 2019). Carbon uptake efficiency at GRK was similar to *CUE* in a rice paddy at Cherwon in central Korea (1.62; Indrawati *et al*., 2018) but lower than those in Japan and Philippines (1.76～2.25; Alberto *et al*., 2011; Ikawa *et al*., 2017). Methane emission at GRK was significant, which was in the mid to upper range of F_{CH4} reported in the literature (e.g., Knox *et al*., 2016; Miyata *et al*., 2005; Meijidae *et al*., 2011; Chun *et al*., 2015). Nitrous oxide emission also was in the upper range of the F_{N2O} reported in the literature (e.g., Knox *et al*., 2016; Miyata *et al*., 2005; Meijidae *et al*., 2011; Chun *et al*., 2015).

V. Summary and Conclusions

This study is the first attempt to examining a typical rice cultivation system in Gimje, Korea under the framework of CSA. The ultimate purpose is to mobilize people and nation toward healthy and sustainable agriculture through the engineering of the CSA vision. Main objectives were (1) to select an archetypal rice cultivation system, (2) to monitor the flows of energy, H_2O, CO_2, CH_4, N_2O, and information in and out of system, (3) to evaluate the indicators for productivity, resilience, and GHG mitigation, and finally (4) to assess how the progress is achieved on the triad goals of CSA.

The data obtained from the three growing seasons provided a unique and wide range of environmental conditions to scrutinize the state of rice cultivation system in the context of CSA. The main results of the assessment of a suite of indicators for the triad goals of CSA can be summarized as: (1) productivity was within the middle to upper ranges of those reported in the literature; (2) GHG mitigation was substandard because of low F_{CO2} (i.e., lower CO_2 uptake) and moderate to high F_{CH4} and F_{N2O} (i.e., higher emission) than those reported from other studies; and (3) resilience was high but unable to assess due to the lack of quantitative data in the literature, (4) only one of the three growing seasons examined in this study achieved the CSA’s triple win whereas other two growing seasons failed to become climate-smart due to reduced productivity as well as increased GHG emission, and (5) overall, the rice cultivation system at GRK was not fulfilling the CSA’s triad goals, particularly in the challenge of GHG mitigation which requires substantial improvement in all three gases (i.e., CO_2, CH_4, N_2O).

The apparent competing goals and trade-offs (between increasing productivity and mitigating GHG emission) within individual years as well as between years would hinder farmers from achieving seamless harmony under the triple-win scenarios. Therefore, the pursuit of CSA requires for stakeholders to prioritize their goals (i.e., governance) and to practice opportune interventions (i.e., management) based on the feedback from real-time assessment of the CSA indicators (i.e., monitoring) - i.e., a purpose-driven visioneering. On one hand for example, developing countries require an intensification of agricultural production to close yield gaps and meet sharply rising food demands. In this context, there are fewer possibilities to reduce GHG emissions, and it makes sense to target efforts to food security and resilience. On the other hand, for developed countries with intensive agriculture, it may not be a priority to increase production, but to reduce emissions while enhancing resilience to climate change.

적 요

본 연구에서는 '한국 김제의 전형적인 벼 경작 시스템이 기후스마트농업(CSA)의 삼중 도전에 어떻게 부합하고 있는가?'라는 질문에 답하기 위해, (1) 벼 경작 시스템의 에너지, 물, 탄소 및 정보의 흐름을 직접 관측하였고, (2) 생산성/효율성, 온실가스 방출/흡수 및 회복성을 평가할 수 있는 다양한 측정도구(metrics)를 사용하여 기후스마트농업의 관점에서 평가하였다. 국내 플럭스 관측망인 KoFlux 관측지의 하나인 김제의 대표적인 벼 경작 시스템에서 3년간(2011, 2012, 2014)의 생육기간 동안 에디공분산 기술을 사용하여 에너지, 물, 이산화탄소 및 메탄 플럭스의 흐름을 모니터링하였다. 생산 효율성 평가를 위해서는 총일차생산량(*GPP*), 생태계 호흡량(*RE*), 곡물 수확량, 빛사용효율(*LUE*), 물사용효율(*WUE*), 및 탄소흡수효율(*CUE*)을 지표로 사용하였다. 온실가스 정량화를 위해서는, 이산화탄소 플럭스(F_{CO2})와 메탄 플럭스(F_{CH4})의 경우 직접 관측한 자료를 사용하였고, 아산화질소 플럭스(F_{N2O})는 IPCC지침에 따라 간접적으로 산출한 자료를 사용하였다. 회복성 평가를 위해서는 자기-조직화(self-organization, *S*) 지표를 사용하였으며, 벼 경작 시스템에서 가장 포괄적인 세 과정(총일차생산, 메탄 플럭스, 증발산)을 대상으로 정보이론을 사용하여 정량화 하였다. 결과에 따르면, 3년 간의 생육 기간 중 2011년이 상대적으로 CSA 삼중 목표를 모두 성취하였으나, 이어지는 2012년과 2014년에 모두 생산량이 감소하고 온실가스 방출이 크게 증가하여 기후스마트한 관리가 이루어지지 않은 것으로 보인다. 3년 생육기간을 평균한 CSA 지표의 값과 범위의 경우, 생산성에 관련된 지표들은 문헌에 보고된 다른 연구 결과와 비교할 때 대부분 중-상위의 범위에 속했으나, 온실가스 완화의 경우 평균 이하였고, 회복성은 높았지만 보고된 자료가 없어 비교하지 못했다. 기후스마트한 벼 재배를 위해서는, 1) 이해 관계자들이 함께 목적에 맞게 목표의 우선순위를 정하고('거버넌스'), 2) CSA 지표를 분석한 결과로부터 얻어진 되먹임(feedback)('모니터링') 정보를 기반으로, 3) 상황에 맞는 적절한 개입('관리'), 즉 거버넌스/관리/모니터링의 삼합으로 이루어지는 비저니어링이 필요함을 시사한다.

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REFERENCES

Alberto, M. C. R., R. Wassmann, T. Hirano, A. Miyata, A. Kumar, A. Padre, and M. Amant, 2009: CO_2/heat fluxes in rice fields: Comparative assessment of flooded and non-flooded fields in the philippines. *Agricultural and Forest Meteorology* **149**(10), 1737-1750.

Alberto, M. C. R., R. Wassmann, T. Hirano, A. Miyata, R. Hatano, A. Kumar, A. Padre, and M. Amant, 2011: Comparisons of energy balance and evapotranspiration between flooded and aerobic rice fields in the philippines. *Agricultural Water Management* **98**(9), 1417-1430.

Alberto, M. C. R., T. Hirano, A. Miyata, R. Wassmann, A. Kumar, A. Padre, and M. Amante 2012: Influence of climate variability on seasonal and interannual variations of ecosystem CO_2 exchange in flooded and non-flooded rice fields in the Philippines. *Field Crops Research* **134**, 80-94.

Aubinet, M., B. Chermanne, M. Vandenhaute, B. Longdoz, M. Yernaux, and E. Laitat, 2001: Long term carbon dioxide exchange above a mixed forest in the Belgian Ardennes. *Agricultural and Forest Meteorology* **108**(4), 293-315.

Brunsell, N. A., S. J. Schymanski, and A. Kleidon, 2011: Quantifying the thermodynamic budget of the land surface: is this useful? *Earth System Dynamics* **2**(1), 87-103.

Burba, G., 2013: Eddy Covariance Method for

Scientific, Industrial, Agricultural and Regulatory Applications: A Field Book on Measuring Ecosystem Gas Exchange and Areal Emission Rates. Li-Cor Biosciences, Lincoln.

Choi, S.-W., J. Kim, M. Kang, S. H. Lee, N. Kang, and K.-M. Shim, 2018: Estimation and Mapping of Methane Emissions from Rice Paddies in Korea: Analysis of Regional Differences and Characteristics. *Korean Journal of Agricultural and Forest Meteorology* **20**(1), 88-100. (in Korean with English abstract).

Chun, J. A., K.-M. Shim, S. H. Min, and Q. Wang, 2015: Methane mitigation for flooded rice paddy systems in South Korea using a process-based model. *Paddy and Water Environment* DOI 10.1007/s10333-015-0484-0.

Cochran, F.V., N. A. Brunsell, and A. E. Suyker, 2016: A thermodynamic approach for agroecosystem sustainability. *Ecological Indicators* **67**, 204-214.

Diaz, M. B., D. R. Roberti, J. V. Carneiro, V. d. A. Souza, and O. L. L. de Moraes, 2019: Dynamics of the superficial fluxes over a flooded rice paddy in southern Brazil. *Agricultural and Forest Meteorology* **276**(277), 107650. doi:10.1016/j.agrformet.2019.107650

Fernandez, N., C. Maldonado, and C. Gershenson, 2014: Information measures of complexity, emergence, self-organization, homeostasis, and autopoiesis. In *Guided self-organization: Inception*, Springer, 19-51.

Forster, P., V. Ramaswamy, P. Artaxo, T. Bernsten, R. Betts, D. W. Fahey, J. Haywood, J. Lean, D. C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz, and R. Van Dorland, 2007: *Changes in atmospheric constituents and in radiative forcing.* In: Climate Change. 2007. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Solomon S, D Qin, M Manning et al.), 130-234. Cambridge University Press, Cambridge, UK.

Fratini, G., A. Ibrom, N. Arriga, G. Burba, and D. Papale, 2012: Relative humidity effects on water vapour fluxes measured with closed-path eddy-covariance systems with short sampling lines. *Agricultural and Forest Meteorology* **165**, 53-63.

Gershenson, C., and N. Fernández, 2012: Complexity and information: Measuring emergence, selforganization, and homeostasis at multiple scales. *Complexity* **18**(2), 29-44.

Gitelson, A. A., and J. A. Gamon, 2015: The need for a common basis for defining light-use efficiency: Implications for productivity estimation. *Remote Sensing of Environment* **156**, 196-201.

Gitelson, A. A., A. Viña, S. B. Verma, D. C. Rundquist, T. J. Arkebauer, G. G. Burba, and A. E. Suyker, 2006: Relationship between gross primary production and chlorophyll content in crops: Implications for the synoptic monitoring of vegetation productivity. *Journal of Geophysical Research: Atmospheres* **11**(D8).

Hong, J. K., H. J. Kwon, J.-H. Lim,Y. H. Byun, J. H. Lee, and J. Kim, 2009: Standardization of KoFlux eddy-covariance data processing. *Korean Journal of Agricultural and Forest Meteorology* **11**(1), 19-26.

Horst, T. W., and D. H. Lenschow, 2009: Attenuation of scalar fluxes measured with spatially-displaced sensors. *Boundary Layer Meteorology* **130**(2), 275-300.

Hossen, M. S., M. Mano, A. Miyata, A. Baten, and T. Hiyama, 2012: Surface energy partitioning and evapotranspiration over a double-cropping paddy field in bangladesh. *Hydrological Processes* **26**, 1311-1320.

Hossen, M. S., M. Mano, A. Miyata, M. A. Baten, and T. Hiyama, 2011: Seasonality of ecosystem respiration in a double-cropping paddy field in Bangladesh. *Biogeosciences Discussions* **8**, 8693-8721.

Hwang, Y., Y. Ryu, Y. Huang, J. Kim, H. Iwata, and M. Kang, 2020: Comprehensive assessments of carbon dynamics in an intermittently-irrigated rice paddy. *Agricultural and Forest Meteorology* **285**,107933.

Ikawa, H., K. Ono, M. Mano, K. Kobayashi, T. Takimoto, K. Kuwagata, and A. Miyata, 2017: Evapotranspiration in a rice paddy field over 13 crop years. *Journal of Agricultural Meteorology* **73**(3), 109-118.

Indrawati, Y. M., J. Kim, and M. Kang, 2018: Assessment of Ecosystem Productivity and Efficiency using Flux Measurement over Haenam Farmland Site in Korea (HFK). *Korean Journal of Agricultural and Forest Meteorology* **20**(1), 57-72. doi:10.5532/KJAFM.2018.20.1.57

IPCC (Intergovernmental Panel on Climate Change), 2007: Nitrous oxide and carbon dioxide in agriculture; OECD/IPCC/IEA phase II development of IPCC guidelines for natural greenhouse gas inventory methodology, Workshop Report, 4-6 December, 1995, OECD, IPCC, IEA (Geneva), 1997.

Kang, M., J. Kim, S. H. Lee, J. Kim, J. H. Chun, and S. Cho, 2018: Changes and improvements of the standardized eddy covariance data processing in KoFlux. *Korean Journal of Agricultural and Forest Meteorology* **20**(1), 5-17.

Kang, M., J. Kim, B. Malla Thakuri, J. Chun, and C. Cho, 2018: New gap-filling and partitioning technique for H_2O eddy fluxes measured over forests. *Biogeosciences* **15**, 631-647.

Kang, M., J. Kim, H.S. Kim, B. Malla Thakuri, and J.-H. Chun, 2014: On the nighttime correction of CO_2 flux measured by eddy covariance over temperate forests in complex terrain. *Korean Journal of Agricultural and Forest Meteorology* **16**(3), 233-245.

Kang, N., J. Yun, M. S. A. Talucder, M. Moon, M. Kang, K.-M. Shim, and J. Kim, 2015: Corrections on CH_4 fluxes measured in a rice paddy by Eddy covariance method with an open-path wavelength modulation spectroscopy. *Korean Journal of Agricultural and Forest Meteorology* **17** (1), 15-24.

Kim, J., M. Kang, T. Oki, E. W. Park, K. Ichii, Y. M. Indrawati, S. Cho, J. Moon, W. C. Yoo, J. Rhee, H. Rhee, K. Njau, and S. Ahn, 2018: Rural Systems Visioneering: Paradigm Shift from Flux Measurement to Sustainability Science. *Korean Journal of Agricultural and Forest Meteorology* **20**(1), 101-116. doi:10.5532/KJAFM.2018.20.1.101

Kim, Y., M. S. A. Talucder, M. Kang, K.-M. Shim, N. Kang, and J. Kim, 2016: Interannual variations in methane emission from an irrigated rice paddy caused by rainfalls during the aeration period. *Agriculture, Ecosystems & Environment* **223**, 67-75. doi:10.1016/j.agee.2016.02.032

Knox, S. H., J. H. Matthes, C. Sturtevant, P. Y. Oikawa, J. Verfaillie, and D. Baldocchi, 2016: Biophysical controls on interannual variability in ecosystem-scale CO_2 and CH_4 exchange in a California rice paddy. *Journal of Geophysical Research: Biogeosciences* **121**, doi:10.1002/2015JG003247.

LI-COR Inc. 2014: Eddypro-eddy covarience software: Version 5.2.1 user’s guide and reference.

Lin, H., M. Cao, P. C. Stoy, and Y. Zhang, 2009: Assessing self-organization of plant communities a thermodynamic approach. *Ecological Modelling* **220**(6), 784-790.

Lin, H., M. Cao, and Y Zhang, 2011: Self-organization of tropical seasonal rain forest in southwest China. *Ecological Modelling* **222**(15), 2812-2816.

Lipper, L., P. Caron, F. Kossam, R. Sessa, P. Thornton, A. Cattaneo, W. Mann, R. Shula, B. M. Campbell, D. Garrity, N. McCarthy, A. Tibu, T. Baedeker, K. Henry, A. Meybeck, R. Hottle, and E. F. Torquebiau, 2014: Climate-smart agriculture for food security. *Nature Climate Change* **4**(12), 1068-1072.

Lopez-Ruiz, R., H. L. Mancini, and X. Calbet, 1995: A statistical measure of complexity. *Physics Letters A* **209**(5-6), 321-326.

Mauder, M. and T. Foken, 2011: Documentation and Instruction Manual of the Eddy-covariance Software Package TK3. Univ., Abt. Mikrometeorologie, 46:60.

McMillen, R. T., 1988: An eddy correlation technique with extended applicability to non-simple terrain. *Boundary Layer Meteorology* **43**(3), 231-245.

Meijide, A., G. Manca, I. Goded, V. Magliulo, P. di Tommasi, G. Seufert, and A. Cescatti, 2011: Seasonal trends and environmental controls of methane emissions in a rice paddy field in Northern Italy. *Biogeosciences* **8**, 3809-3821.

Min, S.-H., K.-M. Shim, Y.-S. Kim, M.-P. Jung, S.-C. Kim, K.-H. So, 2013: Seasonal Variation of Carbon Dioxide and Energy Fluxes During the Rice Cropping Season at Rice-barley Double Cropping Paddy Field of Gimje. *Korean Journal of Agricultural and Forest Meteorology* **15**(4), 273-281. doi:10.5532/kjafm.2013.15.4.273

Miyata, A., R. Leuning, O. T. Denmead, J. Kim, and Y. Harazono, 2000: Carbon dioxide and methane fluxes from an intermittently flooded paddy field. *Agricultural and Forest Meteorology* **102**(4), 287-303. doi:Doi 10.1016/S0168-1923(00)00092-7

Miyata, A., T. Iwata, H. Nagai, T. Yamada, H. Yoshikoshi, M. Mano, K. Ono, G. Han, Y. Harazono, and E. Ohtaki, 2005: Seasonal variation of carbon dioxide and methane fluxes at single cropping paddy fields in central and western Japan. *Phyton* **45**(4), 89-97.

Monteith, J. L., and C. Moss, 1977: Climate and the efficiency of crop production in Britain [and discussion]. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* **281**(980), 277-294.

Mosier, A. R., C. Kroeze, C. Nevison, O. Oenema, S. Seitzinger, and O. Van Cleemput, 1998: Closing the global N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. OECD/IPCC/IEA phase II development of IPCC guideslines for national greenhouse gas inventory methodology. *Nutrient Cycling in Agroecosystems* **52**, 225-248.

Neufeldt, H., M. Jahn, B. M. Campbell, J. R. Beddington, F. DeClerck, A. De Pinto, J. Gulledge, J. Hellin, M. Herrero, A. Jarvis, and D. LeZaks, 2013: Beyond climate-smart agriculture: toward safe operating spaces for global food systems. *Agriculture & Food Security* **2**(1), 12.

Nielsen, S. and S. Jørgensen, 2013: Goal functions, orientors and indicators (GoFOrtIt's) in ecology. Application and functional aspects-Strengths and weaknesses. *Ecological Indicators* **28**, 31-47.

Odum, E., 1969: The strategy of ecosystem development. *Science* (New York, NY), **164**(3877), 262-270.

Papale, D., M. Reichstein, M. Aubinet, E. Canfora, C. Bernhofer, W. Kutsch, B. Longdoz, S. Rambal, R. Valentini, T. Vesala, and D. Yakir, 2006: Towards a standardized processing of net ecosystme exchange measured with eddy covariance technique: algorithms and uncertainty estimation. *Biogeosciences* **3**, 571-583.

Pereira, J., N. Figueiredo, P. Goufo, J. Carneiro, R. Morais, C. Carranca, J. Coutinho, and H. Trindade, 2013: Effects of elevated temperature and atmospheric carbon dioxide concentration on the emissions of methane and nitrous oxide from Portuguese flooded rice fields. *Atmospheric Environment* **80**, 464-471.

Prokopenko, M., F, Boschetti., and A. J. Ryan, 2009: An information-theoretic primer on complexity, self-organization, and emergence. *Complexity* **15**(1), 11-28.

Reichstein, M., P. Ciais, D. Papale, R. Valentini, S. Running, N. Viovy, W. Cramer, A. Granier, J. Ogee, V. Allard, and M. Aubinet, 2007: Reduction of ecosystem productivity and respiration during the European summer 2003 climate anomaly: a joint flux tower, remote sensing and modelling analysis. *Global Change Biology* **13**(3), 634-651.

Ricepedia. Retrieved 08 December 2019, from http://ricepedia.org/rice-as-a-crop

Rosenstock, T. S., C. Lamanna, S. Chesterman, P. Bell, A. Arslan, M. Richards, J. Rioux, A. O. Akinleye, C. Champalle, Z. Cheng, C. Corner-Dolloff, J. Dohn, W. English, A. S. Eyrich, E. H. Girvetz, A. Kerr, M. Lizarazo, A. Madalinska, S. McFatridge, K. S. Morris, N. Namoi, N. Poultouchidou, M. Ravina da Silva, S. Rayess, H. Ström, K. L. Tully, and W. Zhou, 2016: The scientific basis of climate-smart agriculture: A systematic review protocol. CCAFS Working Paper no. 138. Copenhagen, Denmark: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Santamarı́a-Bonfil, G., N. Fernández, and C. Gershenson, 2016: Measuring the complexity of continuous distributions *Entropy* **18**(3), 72.

Santamarı́a-Bonfil, G., C. Gershenson, and N. Ferná ndez, 2017: A package for measuring emergence, self-organization, and complexity based on shannon entropy. *Frontiers in Robotics and AI* **4**(10), 1-12.

Shannon, C. E., 1948: A Mathematical Theory of Communication. *The Bell System Technical Journal* **27**,379-423, 623-656.

Shindell, D., G. Faluvegi, D. M. Koch, G. A. Schmidt, N. Unger, and S. E. Bauer, 2009: Improved attribution of climate forcing to emissions. *Science* **326**(5953), 716-718.

Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'mara, C. Rice, B. Scholes, O. Sirotenko, M. Howden, T. McAllister, G. Pan, V. Romanenkov, and U. Schneider, S. Towprayoon, 2007: Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture *Agriculture, Ecosystems & Environment* **118**(1), 6–28.

Sun, H., S. Zhou, Z. Fu, G. Chen, G. Zou, and X. Song, 2016: A two-year field measurement of methane and nitrous oxide fluxes from rice paddies under contrasting climate conditions. *Scientific Reports* **6**, 28255. doi:10.1038/srep28255

Svirezhev,Y., 2010: Entropy and Entropy Flows the Biosphere. *Global Ecology* **154**.

Van Dijk, A., A. F. Moene, and H. A. R. De Bruin, 2004: The principles of surface flux physics: theory, practice and description of the ECPACK library. *Meteorology and Air Quality Group*. Wageningen University, Wageningen, The Netherlands, 99.

Van Gorsel, E., N. Delpierre, R. Leuning, A. Black, J. W. Munger, S. Wofsy, M. Aubinet, C. Feigenwinter, J. Beringer, D. Bonal, and B. Chen, 2009: Estimating nocturnal ecosystem from the vertical turbulent flux and change in storage of of CO_2. *Agricultural and Forest Meteorology* **149** (11), 1919-1930.

Van Groenigen, K. J., C. Van Kessel, and B. A.

Hungate, 2013: Increased greenhouse-gas intensity of rice production under future atmospheric conditions. *Nature Climate Change* **3**(3), 288-291.

Wang, Y., L. Zhou, Q. Jia, and W. Yu, 2017: Water use efficiency of a rice paddy field in Liaohe Delta, Northeast China. *Agricultural Water Management* **187**, 222-231.

Webb, E. K., G. Pearman, and R. Leuning, 1980: Correction of flux measurements for density effects due to heat and water vapor transfer. *Quarterly Journal of Royal Meteorological Society* **106**, 85-100.

Yang, H., Y. M. Indrawati, A. E. Suyker, J. Lee, K.-d. Lee, and J. Kim, 2020: Radiation, Energy, and Entropy Exchange in an Irrigated-Maize Agroecosystem in Nebraska, USA. *Korean Journal of Agricultural and Forest Meteorology* **22**(1), 26-46. doi:10.5532/KJAFM.2020.22.1.26

Yu, G., X. Song, Q. Wang, Y. Liu, D. Guan, J. Yan, X. Sun, L. Zhang, and X. Wen, 2008: Water-use efficiency of forest ecosystems in eastern China and its relations to climatic variables. *New Phytologist* **177**(4), 927-937.

Zaccarelli, N., B. L. Li, I. Petrosillo, and G. Zurlini, 2013: Order and disorder in ecological time-series: introducing normalized spectral entropy. *Ecological Indicators* **28**, 22-30.

Zhang, Y., M. Xu, H. Chen, and J. Adams, 2009: Global pattern of NPP to GPP ratio derived from MODIS data: effects of ecosystem type, geographical location and climate. *Global Ecology and Biogeography* **18**(3), 280-290.

Zurlini, G., I. Petrosillo, K. B. Jones, and N. Zaccarelli, 2013: Highlighting order and disorder in social-ecological landscapes to foster adaptive capacity and sustainability. *Landscape Ecology* **28**(6), 1161-1173.