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CLIMATE-SMART AGRICULTURE (CSA)-BASED ASSESSMENT OF A RICE CULTIVATION SYSTEM IN GIMJE, KOREA

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

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BY
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INTERDISCIPLINARY PROGRAM IN
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CLIMATE-SMART AGRICULTURE (CSA)-BASED ASSESSMENT OF A RICE CULTIVATION SYSTEM IN GIMJE, KOREA

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PROFESSOR JOON KIM, Ph.D.

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ABSTRACT

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

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Food and Agriculture Organization (FAO)'s climate-smart agriculture (CSA) challenges to avert world hunger through triple-win solutions: (1) sustainably increasing agricultural productivity and income, (2) reducing greenhouse gas (GHG) emission, and (3) building resilience to climate change. These are related to the United Nation's sustainable development goals (SDGs) such as SDG1 (reduce poverty), SDG2 (zero hunger), SDG12 (responsible consumption and production), SDG13 (climate action), and SDG15 (life on land). However, the paucity of appropriate (1) conceptual framework, (2) holistic indicators, and (3) quantitative measurement data hinders farmers, researchers, and policy makers from making measurable assessment of the progress and the impact of CSA.

The overarching question of this study is how a typical rice cultivation system in Korea is keeping up with the triple-win challenge of CSA. To answer this question, we have employed (1) a conceptual framework of 'self-organizing hierarchical open system with visioneering' (SOHO-V)' based on complex systems perspective; (2) quantitative data from direct measurement of energy, water, carbon and information flows in and out of a rice cultivation system, and (3) 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*), crop coefficient (*Kc*), 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.

The data obtained from the three growing seasons provided a wide range of contrasting environmental conditions and system states for our scrutiny. In terms of growing season averages from three years' monitoring, growing season length was ~122 days, solar radiation (*Rs*) was 1,852 MJ m^{-2} $season^{-1}$, air temperature was 22.4°C, and precipitation (*P*) was 830 mm. *GPP* was on average 889 g C m^{-2}, *RE* was 565 g C m^{-2}, grain yield was 588 g m^{-2}, *LUE* was 1.94 g C MJ^{-1}, *WUE* was 1.97 g C kg H_2O^{-1}, *Kc* was 1.26, *CUE* was 1.58, F_{CO2} was 324 g C m^{-2}, F_{CH4} was 21.1 g C m^{-2}, F_{N2O} was 1.65 mg N_2O m^{-2}, and S_{AVG} was 0.40 (for half-hourly time series) and 0.09 (for daily time series). These results for GRK are mostly within the middle to upper ranges of those reported from other studies, except GHG. GRK sequestered less CO_2 and emitted more CH_4 and N_2O than those reported from other studies.

Overall, the results of this study demonstrated that the rice cultivation system at GRK was not fulfilling the CSA's triple-win challenges. In fact, the competing goals and trade-offs among productivity, resilience, and GHG mitigation were found within individual years as well as between the three years, causing clashes and difficulties in achieving seamless harmony under the triple-win scenarios. 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., the purpose-driven visioneering.

The employed SOHO-V framework was useful for understanding of the complex interactions in ecological-societal systems and the CSA visioneering but difficult to use for practical application to prioritize the triad goals. An improved framework is proposed, in which economy is embedding within social systems and the UN's 17 SDGs are also included. This will provide diverse stakeholders with opportunity to unifying the issues and options under one coherent vision - a healthy and sustainable world. The results from this study would facilitate a paradigm shift in agriculture from 'climate-smart' to 'climate-wise', which will transform ourselves from 'being resilient' to 'becoming antifragile' so that agriculture may gain from volatility, shocks, and uncertainties.

Key words Climate-smart agriculture, Rice, Productivity, GHG mitigation, Resilience, Self-organization, Complexity, Conceptual framework, Eddy covariance technique, Flux measurement, CSA indicator, Sustainable development goals, Paradigm shift.

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LIST OF ABBREVIATIONS

C	Complexity (normalized to range from 0 to 1)
C_{AVG}	Composite **C**
CH_4	Methane
CO_2	Carbon dioxide
CUE	Carbon uptake efficiency
E	Emergence (normalized to range from 0 to 1)
E_{AVG}	Compopsite **E**
EBR	Energy balance ratio
EC	Eddy covariance
ET	Evapotranspiration (mm)
ET_0	Reference evapotranspiration (mm)
F	Flux (g m^{-2} per day or season)
FAO	Food and Agriculture Organization (UN)
FAO-PM	Food and Agriculture Organization-Penman Monteith equation
GHG	Greenhouse gases
GPP	Gross primary productivity (g C m^{-2})
H	Sensible heat flux (Wm^{-2})
IPCC	The Intergovernmental Panel on Climate Change
Kc	Crop coefficient
KoFlux	Korean network of tower flux measurement
LUE	Light use efficiency
MSD	Mid-season drainage
NEE	Net ecosystem exchange (g C m^{-2})
N_2O	Nitrous oxide
P	Precipitation (mm)
Pa	Atmospheric pressure (kPa)
Rs	Incoming shortwave radiation (Wm^{-2})
R_N	Net radiation (Wm^{-2})
S	Self-organization (normalized to range from 0 to 1)
S_{AVG}	Composite **S**
SHF	Soil heat flux (Wm^{-2})
SOHO	Self-Organizing Hierarchical Open systems
SOHO-V	Self-Organizing Hierarchical Open systems with Visioneering
T	Air temperature (°C)
WS	Wind speed (ms^{-1})
WUE	Water use efficiency (g C Kg H_2O^{-1} or g grain kg H_2O^{-1})
β	Bowen ratio
λE	Latent heat flux (Wm^{-2})

1. INTRODUCTION

1.1 Concerns and Motive

In order to meet the world's future food security and sustainability needs, on one hand, food production must grow substantially to provide a certain level of food demands from population growth. On the other hand, agricultural environmental footprint also must reduce substantially (e.g., Foley *et al*., 2011). Current agricultural management practices have been developed in a way that demands higher resource intensity and causes significant environmental degradation. Globally, agriculture is the largest consumer (*i.e.* around 70 %) of all freshwater withdrawals. There is a pressing demand for a new paradigm that combines the continued development of societal system and the maintenance of the ecological system in a resilient and accommodating condition (Steffen *et al.*, 2015). Under the framework of planetary boundary, at least four domains such as biogeochemical flows, biosphere integrity, land-system change and freshwater use are affected by agriculture, and the first two already have crossed the boundary that humanity is not supposed to cross over (http://www.stockholmresilience.org).

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 vision of climate-smart agriculture (CSA) 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 incomes, (2) reducing and/or removing greenhouse gas (GHG) emissions, where possible, and (3) adapting and building resilience to climate change. These triad goals of CSA are related to the United Nation's sustainable development goals (SDGs), particularly focused on reduce poverty (SDG1), zero hunger (SDG2), responsible consumption and production (SDG12), climate action (SDG13), and life on land (SDG15) (http://sdgs.un.org).

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 social-ecological 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 imperative. However, the paucity of appropriate (1) conceptual framework, (2) holistic indicators, and (3) 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).

1.2 Challenges in Climate-Smart Rice Farming

Rice is a leading food crop in the world (Ricepedia, n.d.). Usually, rice paddy acts as carbon sink by sequestering CO_2 (Diaz *et al*., 2019). On the contrary, rice paddies are also one of the major sources of CH_4 and its global warming potential (GWP) per unit mass is 25 times greater than that of 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 N_2O; the GWP per unit mass is 298 times greater than that of CO_2 (Forster *et al.,* 2007; Sun *et al*., 2016).

South Korea has been striving to reinforce its agricultural production, and yet the amount of import has been increasing (KOSIS, 2015). In addition, the pressure on water resources has been substantially expanding throughout the Peninsula (e.g. Jang *et al.*, 2010). Hence, improved water use efficiency would become an important feature under the projected water scarcity scenarios. Regarding the preparedness of Korean agriculture to be transformed to be climate-smart, there are some concerns including the lack of relevant tools to evaluate the biophysical and socio-economic impacts connected with changing climate and environmental conditions (e.g., Yoo and Kim, 2007).

Intermittent irrigation is the technique of alternately irrigating and passively or actively drying the field for several days (e.g., Keiser *et al.*, 2002). It generally starts about two weeks after transplanting and lasts for about 10-15 weeks until the plants reach maturity. Alternate wetting and drying (AWD) is one of the technologies of intermittent irrigation. In this technique, farmers maintain the 150-mm subsurface water level threshold for re-flooding in five days interval (Lampayan *et al.*, 2009). It is not suitable for wet season rice paddy cultivation due to monsoon. Therefore, the study site was intermittently irrigated with mid-season drainage (MSD) (Kim *et al.*, 2016). MSD reduces the CH_4 emissions since drainage affects the soil condition to change from anaerobic to aerobic, hence increasing CH_4 oxidation (Nishimura *et al.*, 2004; Wassmann *et al.*, 2000; Sass *et al.*, 1992). Rainfall during the MSD was reported as the major factors for causing inter-annual variations of CH_4 emission from a rice paddy site at Gimje (Kim *et al.*, 2016). Monitoring with the strength of smart farm technology could increase the effectiveness of MSD with intermittent irrigation.

Strategic and quantitative monitoring of rice paddy ecosystem is necessary to find out whether the current setting of rice paddy management is a proper configuration toward sustainable management in terms of productivity, GHG emission and system resilience to climate change (e.g., Indrawati *et al*., 2018). It is particularly challenging to assess resilience which is associated with functionality, directionality and consequence of interaction (Nielsen and Jørgensen, 2013). 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). Currently, information-theoretic approaches attain more recognition for evaluating self-organization capacity in terms of normalize spectral entropy, for example (Zaccarelli *et al*., 2013; Zurlini *et al*., 2013). Alternatively, thermodynamics indicators have been proposed such as energy capture (ratio of incoming radiation to net radiation), energy dissipation (Lin et al., 2009; Lin et al., 2011) and thermodynamic entropy budget (Svirezhev, 2010; Brunsell *et al*., 2011; Cochran *et al*., 2016; Yang *et al*., 2020).

Micrometeorological eddy covariance (EC) technique provides a quantitative assessment of energy, matter, and information flows in and out of ecosystems (*e.g.* Yun *et al.,* 2014; Kang *et al.,* 2017; Kim *et al*., 2018; Yang *et al*., 2020). 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 framing the situation, describing the dynamics, and synthesizing the understanding of ecosystem-environment interactions. 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.

1.3 Question, Goals and Strategies

In this study, we question, “how are rice cultivation systems in Gimje, Korea keeping up with the triple-challenge of CSA?” For the scrutiny of this assessment, we hypothesized that a typical Korean rice cultivation system is ‘climate-smart’, i.e., the triad goals are not only concurrently achieved but also generally met within the levels that are from the mid to upper ranges of results reported in the literature regarding productivity, GHG uptake and release, and resilience. Accordingly, a representative study site was selected from one of the Korean network of tower flux measurement (KoFlux, see Kang *et al*., 2018 for details) sites located at Gimje in the southwestern Korean Peninsula, which was managed by National Academy of Agricultural Science, Rural Development Administration. This study site represents one of the most typical rice farming systems in South Korea (Kim and Yeom, 2012) and the region has been designated as a 'rice town" due to the role of country's largest and oldest artificial irrigation facilities 'Byeokgolje reservoir' (Shim, 2009).

In order to establish quantitative database for the assessment of various CSA indicators, fluxes of energy, water, carbon dioxide (CO_2) and methane (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*), crop coefficient (*Kc*), and carbon uptake efficiency (*CUE*). The GHG mitigation was assessed by quantifying directly measured fluxes of carbon dioxide (F_{CO2}) and methane (F_{CH4}) along with indirectly estimated flux of nitrous oxide (F_{N2O}) following the IPCC guideline (IPCC, 2006). For the resilience indicator, using information-theoretic approach, self-organization was quantified for the three most comprehensive processes in rice cultivation system (i.e., *GPP*, CH_4 exchange, and evapotranspiration). The data obtained from the three growing seasons provided a wide range of contrasting environmental conditions and various system states for our scrutiny.

Finally, in order to streamline the processes of the CSA-based assessment, we have adopted a conceptual framework, *i.e.*, 'self-organizing hierarchical open systems (SOHO)' combined with 'visioneering' feedback loops (SOHO-V) (Waltner-Toews *et al*., 2008; Kim *et al*., 2018). This is a conceptual model to bring together an ecological understanding with human desire to make healthy and sustainable world, which manifests the fundamental properties of ecological-societal systems. Here, the term ‘hierarchical’ means both holarchic (i.e., made up of nested levels of focus, such as the CSA triad challenges) and viewed from different and multiple perspectives (such as diverse stakeholders). Human communities as well as ecosystems are open systems and their functions and structures are organized hierarchically (e.g., Jørgensen, 2006). A nested system from multiple perspectives is a hierarchical description. The SOHO-V framework is a synthesis between traditional ways of framing both ecological problems and environmental management based on complex systems theories and the engineering of purpose-driven vision, which was used as our guide for the CSA-based assessment of rice cultivation system (see sec. 2.1 for details).

2. MATERIALS AND METHODS

2.1 Conceptual Framework

2.1.1 Self-organizing hierarchical open systems (SOHO)

Conceptual framework is an abstract representation, connected to the research purpose and goals that direct the collection, analysis and synthesis of data, which helps diverse practitioners and stakeholders to translate comprehensive understanding into a streamlining of priorities and strategies toward the mission and vision. In this study, we adopted a framework called 'self-organizing hierarchical open systems (SOHO)', which provides a heuristic basis for systems thinking and a better understanding of the interactions between ecosystems and societal systems as coupled self-organizing systems. The self-organization concept implies open systems (exchanging energy, matter and information with surrounding environment) that are made up of components whose properties and behaviors are defined prior to organization itself. The term, 'self' implies the absence of centralizing ordering or external forcing whereas 'organization' involves a decrease in internal entropy or an increase in complexity (hence, increase in resilience) (Correia, 2006; Prokopenko *et al*., 2009; Kim *et al*., 2018).

The core assumption in the SOHO framework for the application to CSA is that a sustainable rural system maintains itself in the context of the larger ecological systems of which it is a part. The SOHO requires the integration of ecological integrity with social values and preference into a potential narrative (i.e., CSA's triad goals), thereby resolving a shared communal vision for climate-smart agriculture. In essence, it must involve the process of 'visioneering' - the engineering of a clear vision (Kim and Oki, 2011). Here, engineering implies skillful direction and creative application of scientific principles and experiences to develop structures, processes, or heuristics. Visioneering stands as the cooperative triad of governance (i.e., the process of strategic CSA vision casting, resolving tradeoffs and obstacles, and systematic celebration of progress), management (i.e., translating CSA vision into operation by developing and implementing priorities and strategies), and monitoring (i.e., synthesizing observations and analyses of CSA indicators into narratives, providing feedback, and promoting adaptive learning) (e.g., Boyle *et al*., 2001; Kim and Oki, 2011; Kim *et al*., 2018).

2.1.2 Coupling of SOHO with CSA Visioneering

Envisioning a climate-smart agriculture which fulfills the triple challenge is an important step. However, without the engineering of the CSA vision, it will not stick and would remain as a daydream. Figure 2.1 represents the combined SOHO-Visioneering (SOHO-V) frame work. Sustainability of CSA is all about maintaining the integrity of the combined ecological (i.e., rice agricultural)-societal (i.e., rural) systems. Integrity is preserved when the rice cultivation system's self-organizing processes are preserved, something that happens naturally if we maintain the context for self-organization in agricultural ecosystems, which, in turn, will maintain the context for the sustainability of the rural systems (e.g., Kay and Boyle, 2008; Ash *et al*., 2010; Kim *et al*., 2018). Kim *et al*. (2018) further suggested that the SOHO framework should be coupled with CSA visioneering processes through feedback/feedforward loops. And these 'nudged (or guided) self-organization' processes must be subject to first principles such as the entropy principle (as the most probable state) and the least action principle (as the most probable path/trajectory) toward sustainability.

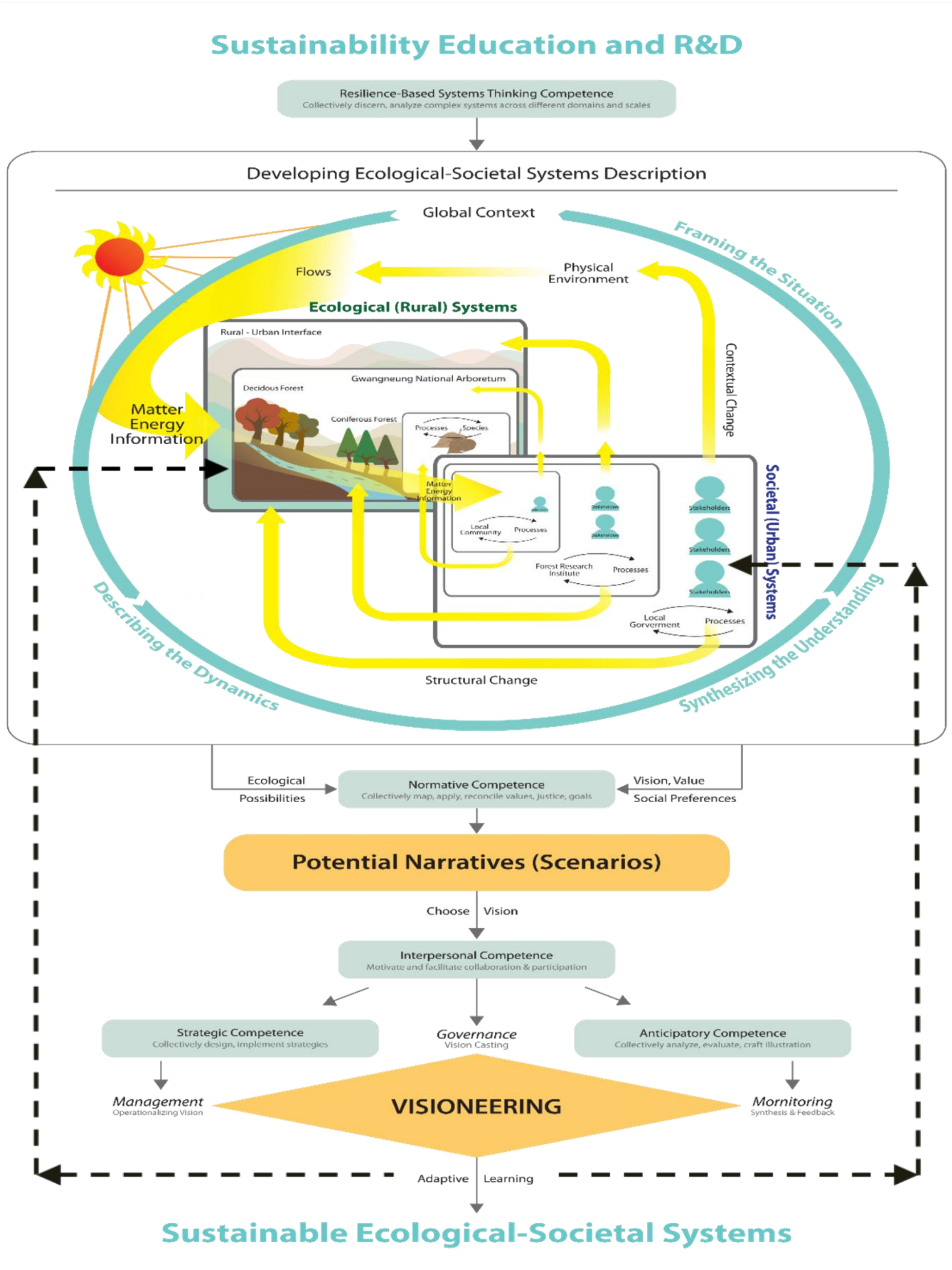

Figure 2.1 Self-organizing hierarchical open systems with visioneering (SOHO-V) framework (Kim *et al*., 2018). Dotted arrows describe feedback loops for adaptive learning.

2.2 Study Site

The study site was located in the Sinyong-ri, Buryang-myeon, Gimje, Jeollabuk in the Republic of Korea (35°44′42.4″N, 126°51′8.8″E, and 4.2 m above m.s.l.) (Fig. 2.2). The dominant land use was cropland characterized by relatively wide plains with a moderate oceanic climate. The topography was flat and homogeneous with the prevailing wind direction from northwest. 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 soil porosity was ~0.52. 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. A 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).

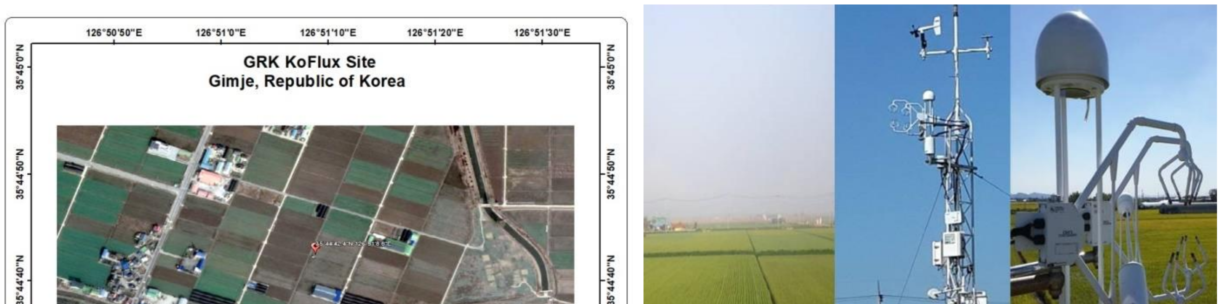

Figure 2.2 The map of the study site and the eddy covariance flux measurement tower in the rice paddy in Gimje, Korea.

The dates of transplanting, mid-season drainage (MSD), and harvesting along with the growing season length (GSL) are summarized in Table 2.1. Thirty-day old seedlings were transplanted (5-6 seedling per hill) mechanically at a density of 30 x 15 cm with 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. For irrigation, the water from the Bayeokgolgae reservoir was used. Flooded irrigation was carried out from early-June to mid-July, and then the paddy field was fully drained from mid-July to mid-August (i.e., mid- season drainage). After the MSD, intermittent irrigation practice was applied from mid-August to mid-September (Kim *et al*., 2016).

Table 2.1 Transplanting, mid-season drainage, and harvesting dates (in day of year, DOY) and growing season length (in days) 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

2.3 Biometeorological Measurements

2.3.1 Theoretical background

2.3.1.1 Eddy Covariance technique

The ambient atmosphere in and above plant canopies contains turbulent motions of upward and downward moving air that transport energy and gases. The eddy covariance (EC) technique samples these turbulent motions to determine the net flux across the canopy-atmosphere interface by statistical analysis of the instantaneous vertical mass flux density ($F = w\rho_c,\ in\ \mu mol\ m^{-2}s^{-1}$), using Reynolds' rules of averaging (Reynolds, 1895). The product of this operation is a relationship which expresses the mean flux density of a scalar averaged over some time span as the covariance between fluctuations in vertical velocity (w) and the scalar mixing ratio ($c = {}^{\rho_c}/_{\rho_a}$, where ρ_a is air density and ρ_c is scalar density):

$$F = \overline{\rho_a} . \overline{w^{'}c^{'}} \qquad (1)$$

where the overbars denote time averaging and the primes represent fluctuations from the mean ($c^{'} = c - \bar{c}$). Positive (or negative) covariance represents flux into (or from) the atmosphere.

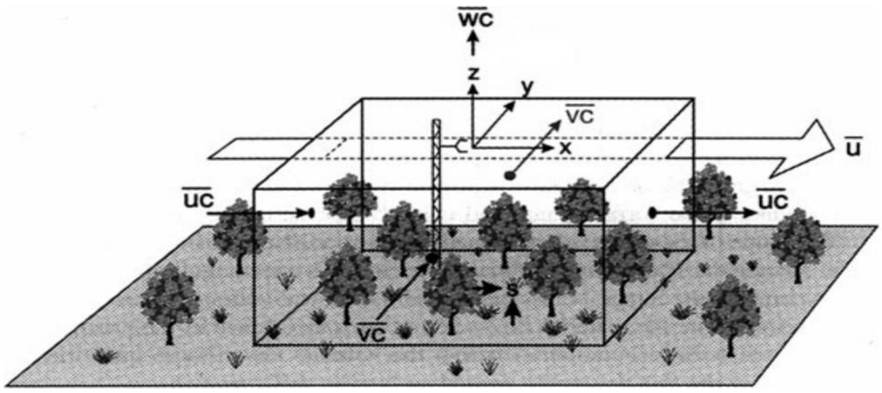

Figure 2.3 Schematic diagram of an eddy flux tower on a control volume in homogeneous flat land terrain (Finnigan *et al*. 2003).

The analytical method used to measure scalar (e.g., H_2O, CO_2, and CH_4 concentrations) also has an impact on the computation of flux covariance. In practice, scalar is measured with a non-dispersive, infrared spectrometer. This sensor does not measure mixing ratio, c. Instead, it samples molar density, ρ_c (moles per unit volume). In principle, changes in molar density can occur by adding molecules to or removing them from a controlled volume or by changing the size of the controlled volume, as is done when pressure, temperature and humidity change in the atmosphere. By measuring the eddy flux covariance in terms of molar density, the net flux density of a scalar across the canopy-atmosphere interface can be written as:

$$F = \overline{\omega\rho_c} = \overline{\omega'\rho_c'} + \omega\rho_c \ . \tag{2}$$

The new term, on the right hand side of Eq. (2), is the product of the mean vertical velocity and a scalar density. The mean vertical velocity is non-zero and arises from air density fluctuations (Webb *et al*., 1980; Kramm *et al*., 1995). In practice, the magnitude of $\overline{\omega}$ is too small (<1mms^{-1}) to be detected by anemometry, so it is usually computed on the basis of temperature (T) and humidity density (ρ_v) fluctuations using the Webb-Pearman-Leuning (WPL) correction (1980):

$$F_c = \overline{\omega'\rho'} + \frac{m_a}{m_v}\frac{\overline{\rho_c}}{\overline{\rho_a}}\overline{\omega'\rho_v'} + (1 + \frac{\overline{\rho_v}m_a}{\overline{\rho_a}m_v})\frac{\overline{\rho_c}}{T}\overline{\omega'T'} \ . \tag{3}$$

The derivation of the above equation ignores effects of pressure fluctuations, which may be significant under high winds (Massman and Lee, 2002), and covariances between temperature and pressure (Fuehrer and Friehe, 2002). It also ignores advection (Paw *et al*., 2000), which is important over sloping terrain.

2.3.1.2 Energy balance

Energy balance equation can be expressed as (e.g., Kang *et al*., 2009):

$$\int_0^{24h}(R_N - G - S)\,dt \approx \int_0^{24h} R_N = \int_0^{24h}(\lambda\mathrm{E} + H)\,dt, \tag{4}$$

where R_N is the net radiation, G is the ground heat flux, S is the energy storage, λE is the latent heat flux (Wm^{-2}) and H is the sensible heat flux. Daily integrated values of G and S are negligible (Hong and Kim, 2008). The energy balance closure was assessed using the energy balance ratio (*EBR*) as:

$$EBR = \frac{\sum(\lambda\mathrm{E+H})}{\sum R_N} \tag{5}$$

where the daily integrated values of λE and H and R_N were used. The advantage of *EBR* is that it gives an overall evaluation of energy balance closure at longer time scales by averaging over random errors in the half-hourly measurements. A disadvantage of *EBR* is the potential to overlook biases in the half-hourly data, such as the tendency to overestimate positive fluxes during the day and underestimate negative fluxes at night (Mahrt, 1999). The *EBR* values that are differet from the unity may result from such reasons, among other factors, as mismatch of flux footprint, sampling error, instrument biases, and advection effect.

For Gimje rice paddy site, *EBR* was examined by linear regression (through the origin) using the daily integrated values of (H+ λE) against the daily R_N during the study period. The daily integrated values of G and S were negligible. The *EBR* at GRK site was on average 0.96

(±0.09), and varied with the extent and frequency of sensible heat advection over irrigated rice paddy (i.e., positive *H*) mostly during mid to late afternoon period.

2.3.2 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 EC technique has the advantage of observing energy and gas fluxes over a long period with minimal disturbance to plants (e.g., Kim *et al*. 2000). The LI-7700 open-path CH_4 analyzer (LI-COR Biosciences), the LI-7500 open-path H_2O/CO_2 analyzer (LI-COR Biosciences), and the CSAT3-three-dimensional sonic anemometers (Campbell Scientific Inc.) 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) 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 0.05m depth were measured with thermometers (TCAV, Campbell Scientific Inc.) and tensiometers (CS616, Campbell Scientific Inc.) at 2 locations, respectively. Soil heat flux was measured with soil heat flux plates (HFP01, Hukseflux Thermal Sensors, Delft, 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 low 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.) was used to store and compile both turbulence and meteorological data.

2.4 Bio-Meteorological Data Processing

2.4.1 Quality control

For the slow-response bio-meteorological variables, the data logger output (i.e., the 30-minutes 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.*, 2017), the L0 data were processed with quality control to produce L1 dataset.

2.4.2 Gap-filling

In order to provide seamless dataset (i.e., L2 data), the combination approach (including interpolation, mean diurnal variation, linear regression) was applied for the gap filling of the missing meteorological variables (Kang *et al.*, 2017). These L2 data set was also used for the gap-filling of flux data measured by EC technique.

2.5 Flux Data Processing

2.5.1 Raw data processing

To improve the data quality by correcting and eliminating undesirable data, the collected flux data were examined by the quality control 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), Frequency response correction (Horst and Lenschow, 2009; Fratini *et al*., 2012), humidity correction of sonic temperature (Van

Dijk *et al*., 2004), spectroscopic correction for LI-7700 (Burba, 2013), steady state/developed turbulent conditions test (Mauder and Foken, 2011) were conducted using the EddyPro® software (Version 5.2.1, LI-COR Biosciences). The flux and bio-meteorological 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.

2.5.2 Spike Detection of Fluxes

EC data are often affected by spikes due to different bio-physical and instrumental reasons. Spike detection was conducted following Papale et al. (2006). Single point measurement storage term was added to the fluxes and then spikes were removed. The spikes in the high frequency raw data (10 *Hz*) are removed before the half-hourly average flux is calculated by EddyPro. However, spikes could also occur in the time series of the half hourly flux values. KoFlux protocol was used for detecting these spikes in the half-hourly data (Hong *et al.*, 2009) followed by Papale *et al.*(2006) after some modification. The algorithm used in the matlab program to detect the spikes is based on the position of each half hourly value with respect to the values just before and after and it is applied to blocks of 28 days and separately for daytime and night-time data. Night-time data were selected according to a global radiation threshold of 20 Wm^{-2}.

For each half-hourly data, the d value is calculated as:

$$d_i = (F_i - F_{i-1})(F_{i+1} - F_i) \qquad (6)$$

and the scalar or flux value is flagged as spike if:

$$d_i < Md - \left(\frac{z.MAD}{0.6745}\right) \qquad (7)$$

or

$$d_i > Md + \left(\frac{z.MAD}{0.6745}\right) \qquad (8)$$

where Md is the median of differences; median of absolute deviation (MAD) is defined as $MAD = \text{median}(|d_i - M_d|)$ and z is a threshold value.
Papale *et al.*(2006) used three threshold *(z)* values (4, 5.5 and 7; less conservative to more conservative) to assess the effect on the data and the sensibility of the method. Seven was used as the threshold value in KoFlux protocol.

2.5.3 Gap-filling of flux data

Gap-filling was applied to 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 (u*) filtering method, 2) light response curve (LRC) method, and 3) modified van Gorsel (mVGF) 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 these three methods.

MDS method calculates a median fluxes under similar meteorological conditions within a time window of 14 days and replaces the missing values with the median. The intervals of the similar meteorological conditions were 50Wm^{-2} for the *Rs*, 2.5 ^{0}C for the air temperature, and 5.0 hPa for the vapor pressure deficit (VPD). If similar meteorological conditions were unavailable within the time window, its interval increased in increments of 7 days before and after the missing data point (i.e., 14-days window size) until it reached 56 days (i.e., before and after 7 days→14 days→21 days →28 days). When the missing fluxes values could not be filled in a time window of less than 56 days, *Rs* was exclusively used following the same approach (i.e., calculating a median of fluxes under similar *Rs* conditions within a time window).

Latent heat fluxes were gap-filled by modified lookup table method (Reichstein *et al*., 2005) and Penman-Monteith equation with Kalman filter whereas sensible heat fluxes were gap-filled by modified lookup table method (Reichstein *et al*., 2005).

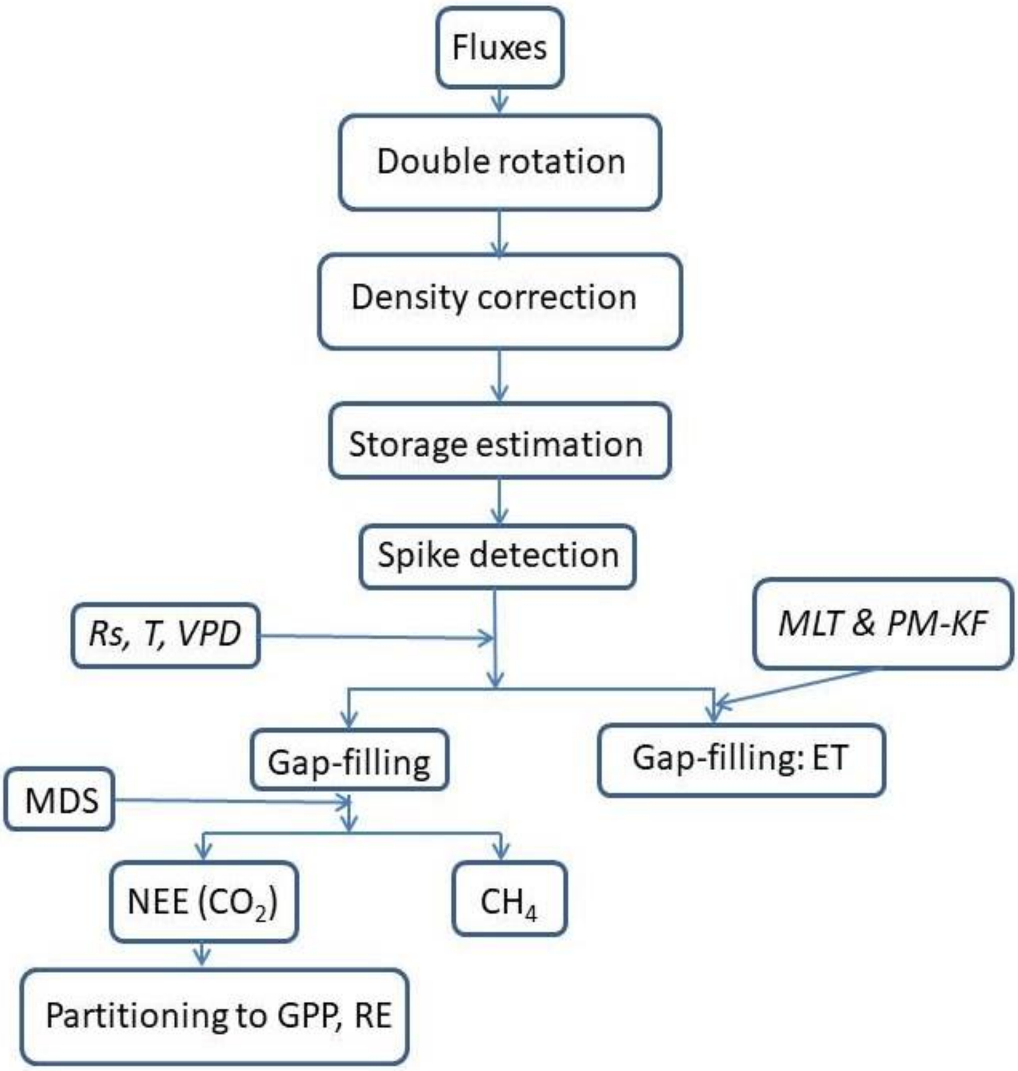

Figure 2.4. Flowchart of data processing of GRK site EC fluxes adopted from standardized KoFlux protocol (Hong et al., 2009). Here, *Rs* is incoming solar radiation, *T* is air temperature, *VPD* is vapor pressure deficit, MDS is marginal distribution sampling method, MLT is modified lookup table method and PM-KF is Penman-Monteith equation with Kalman filter.

2.6 Assessment of Climate-Smart Agriculture (CSA)

2.6.1 Indicators for productivity and efficiency

2.6.1.1 Gross primary productivity (*GPP*) and grain yield

The gross primary productivity (*GPP*) 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 as the sum of *NEE* and ecosystem respirations (*RE*, extrapolated from the nighttime temperature-response equation with daytime temperature) as:

$$GPP - RE = - NEE, \tag{9}$$

where -NEE is equal to but opposite in sign to net ecosystem productivity (*NEP*). The nighttime ecosystem respiration was corrected using friction velocity, light response curve and modified Van Gorsel methods.

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'.

2.6.1.2 Crop coefficient

Crop coefficient (K_c) is a concept introduced to study the evaporative demand of the atmosphere independently of crop type, crop development, and management practices. It is the ratio of actual evapotranspiration (ET) to reference evapotranspiration (ET_0) on a daily scale:

$$K_c = \frac{ET}{ET_0} \quad , \tag{10}$$

where ET was directly measured by the eddy covariance technique and ET_0 was estimated using the globally accepted procedure - the FAO-Penmen Monteith equation (FAO-PM; Allen *et al*., 1998) for humid conditions (Shuttleworth and Wallace, 1985). Here, we used $(H + \lambda E)$ instead of $(R_N$ - $G)$ for the calculation of ET_0 as:

$$ET_0 = \frac{0.408\Delta(H+\lambda E)+\gamma\frac{900}{T+273}u_2(e_s-e_a)}{\Delta+\gamma(1+0.34u_2)} \quad , \tag{11}$$

where ET_0 is in mm d^{-1}; H is sensible heat flux (MJ m^{-2} d^{-1}); λE is latent heat flux (MJ m^{-2} d^{-1}); T is mean daily air temperature at 2 m height (°C); u_2 is wind speed at 2 m height (m s^{-1}); e_s is saturation vapor pressure (kPa); e_a is actual vapor pressure (kPa); $e_s - e_a$ is saturation vapor pressure deficit (kPa); Δ is the slope of T-e_s curve (kPa °C^{-1}); and γ is psychrometric constant (kPa °C^{-1}). The wind speed at 2 m was calculated using the logarithmic wind profile equation (Rosenberg *et al*., 1983; Indrawati, 2015):

$$\frac{u_2}{u_1} = \frac{\ln\ (Z_2-d)-ln\ z_0}{\ln\ (Z_1-d)-ln\ z_0} \quad , \tag{12}$$

where $u_1$and u_2 are the mean wind speeds at elevation Z_1 and Z_2, respectively. The d is the zero-plane displacement and z_0 is the roughness parameter. This wind profile equation has two major assumptions: (i) the existence of neutral atmospheric stability and (ii) the availability of adequate fetch which were satisfied at this study site.

2.6.1.3 Water use efficiency *(WUE)*

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

$$WUE = \frac{GPP}{ET} \text{ ,} \tag{13}$$

where GPP and ET are the daily sums of half-hourly fluxes from the eddy covariance measurement (e.g. Reichstein *et al*., 2007; Yu *et al*., 2008). ET was calculated by dividing the 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}.

2.6.1.4 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 PAR ($APAR$) and light use efficiency (LUE). In this study, LUE is calculated as (*e.g.* Gitelson and Gamon, 2015):

$$LUE = \frac{GPP}{APAR} \tag{14}$$

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.

2.6.2 Indicators for GHG mitigation

2.6.2.1 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 to 2.4.

2.6.2.2 Estimation of N_2O emission

Nitrous oxide emissions from Gimje site were estimated following the revised 1996 IPCC guidelines for National Greenhouse gas inventories as (IPCC, 2006):

$$N_2O \text{ emissions} = \text{Direct emissions } (N_2O_{DIRECT}) + \text{indirect emissions } (N_2O_{INDIRECT}) \quad (15)$$

$$N_2O_{DIRECT} = [(F_{SN} + F_{CR}) \times EF_{1FR}] \times 44/28, \quad (16)$$

$$N_2O_{INDIRECT} = [(N_2O_{(G)}) + (N_2O_{(L)})] \times 44/28 \quad (17)$$

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 ($kg\ ha^{-1}$) x 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 $N_2O_{(G)} = (F_{SN} \times Frac_{GASF}) \times EF_4$ 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 $N_2O_{(L)} = [(F_{SN}+F_{CR}) \times Frac_{LEACH}] \times EF_5$, 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.

2.6.2.3 Carbon uptake efficiency

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

$$CUE = \frac{GPP}{RE} \tag{18}$$

where *RE* (in g C m^{-2}) was 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 (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 carbon-neutral.

2.6.3 Resilience Indicator

Based on the SOHO framework, resilience is associated with 'self-organizing capacity' which produces a global pattern from the interactions of the components of self-organizing systems. 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, then self-organization occurs, while an increase of information entropy accompanies self-disorganization.

Complex systems are known to be equipped with stability and flexibility concurrently. 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. Given a time series X (composed by a sequence of values of variable x), emergence is defined as (e.g., Santamaria-Bonfil *et al*., 2017):

$$E = -K \sum_{i=1}^{N} p_i \ log_2 \ p_i, \tag{19}$$

where K is a normalizing constant that constrains E within the range between 0 and 1 and p_i = $P(X = x)$ is the probability of element i. When $p_i \approx 1$, future of x is almost certain, and $E \approx 0$; then when $p_i \approx 0$, future of x is almost surely absent, so that again $E \approx 0$. It is only for intermediate, less determinate values of p_i that E remains appreciable.

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:

$$S = 1 - E, \tag{20}$$

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 whereas a completely deterministic process has the highest S.

For the sake of completeness, we propose complexity (C) as a system state indicator, which describes a system's behavior in term of average uncertainty produced by emergent and regular global patterns described by its probability distribution. Thus, C can be defined as (e.g., Fernandez *et al*., 2014):

$$C = 4 \cdot I \cdot S \tag{21}$$

where the relationship meets the following requirements: (1) C is normalized to range from 0 to 1, (2) $C = 1$ if and only if $E = S = 0.5$, and (3) $C = 0$ if and only if $E = 0$ or $S = 0$.

Finally, S, as an indicator for system's resilience, was quantified for the three most comprehensive processes in rice cultivation system, namely, gross primary production (biochemical), methane production/oxidation and transport (biogeochemical), and 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} and C_{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.

3. RESULTS

3.1 Climatic Conditions

3.1.1 Air temperature

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, which were higher than that of the 30-year (growing season) normal (21.7±0.7°C), reflecting the gradual warming effect due to climate change. In terms of seasonality, 2014 was cooler in July and August and warmer in September and October than other years, whereas 2012 was the opposite, and 2011 was in between (Fig. 3.1). Such a distinct temperature difference in seasonality would result in altered responses of temperature-sensitive processes such as photosynthesis and respiration, causing more complicated carbon dynamics, as will be shown later.

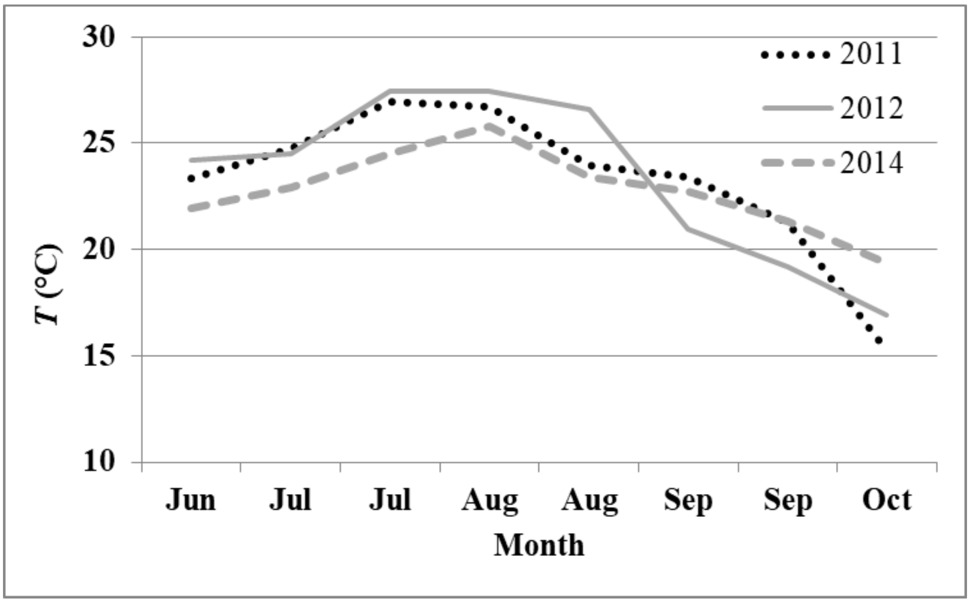

Figure 3.1 Bi-weekly mean daily air temperature during the growing seasons in 2011, 2012 and 2014 at GRK site.

3.1.2 Precipitation (*P*)

In comparison with the 30-year normal for the growing season total *P* (i.e., 804±278 mm), 2011 and 2012 were above normal by 89 and 172 mm, respectively; whereas 2014 was much below normal by 184 mm. In addition to the differences in magnitude, distinctly different seasonality among the three growing seasons caused more complexity in understanding and analyzing their impact. In terms of seasonality, *P* in 2011 was positively skewed (or right-skewed), meaning that more *P* occurred during the first half of the growing season, whereas in 2014 *P* was left-skewed (i.e., more *P* in the later season). In 2012, *P* spread out through the season (except in mid to late July) with near normal distribution with maximum in early to mid August (Fig. 3.2). The presence or absence of *P* during the period of mid-season drainage (MSD) played an important role in terms of CH_4 emission during MSD and afterwards, as will be shown later.

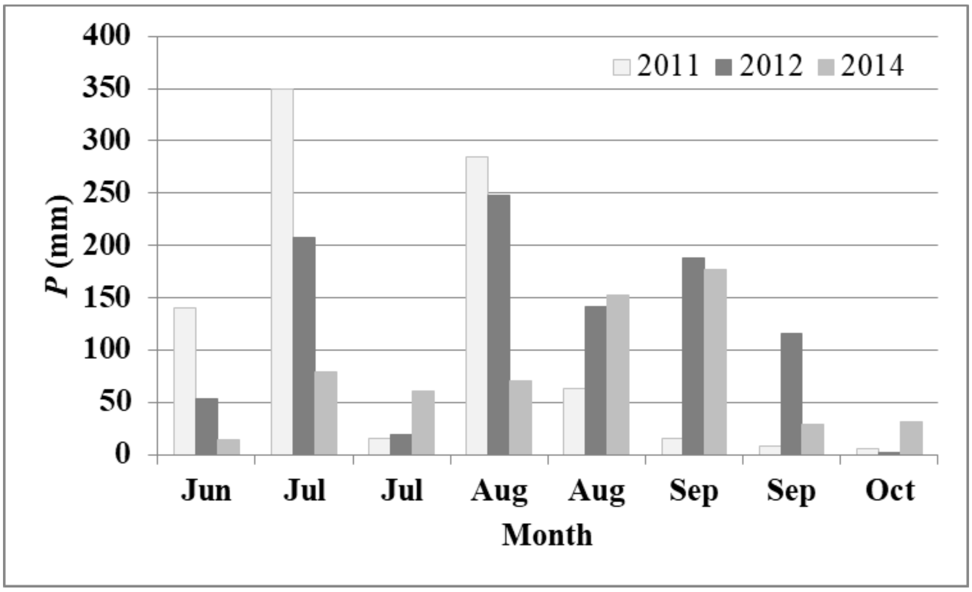

Figure 3.2 Bi-weekly sum of precipitation (*P*) during the growing seasons in 2011, 2012 and 2014 at GRK site.

Bi-weekly averaged soil moisture was near saturation throughout the seasons in all three years except during the MSD in early August in 2012 when soil moisture dropped down to 0.25 m^3m^{-3} (Fig. 3.3). As will be shown in Fig. 3.12, the successful MSD in 2012 resulted in the minimal methane emission. On the other hand, well-watered conditions during the MSD in 2011 and 2014 resulted in more methane emission.

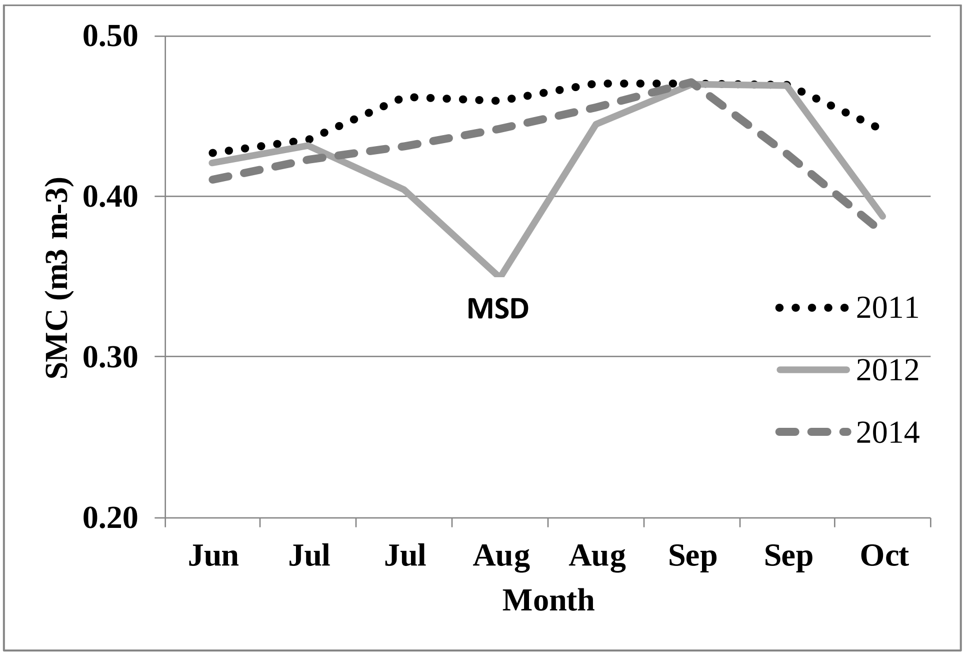

Figure 3.3 Bi-weekly average of daily soil moisture content (SMC) during the growing seasons in 2011, 2012 and 2014 at GRK site. Also shown is the mid- season drainage (MSD) period (i.e., 21 July to 9 August 2012).

3.1.3 Radiation

As expected from the observed differences in *P* among the three growing aseasons, incoming solar radiation (R_S) was also different in terms of magnitude and seasonality (Fig. 3.4) The growing season daily mean of R_S in 2011 was 14.2±7.7 MJ m^{-2}, lower by 9% than those in 2012 and 2014 (~15.5±7.2 MJ m^{-2}). In terms of seasonality, however, R_S in 2011 was much lower in early growing season and higher in later season compared to those in 2012 and 2014. R_S in 2012 fluctuated throughout the season whereas R_S in 2014 gradually decreased throughout the season. Such distinct differences in magnitude and seasonality provided a broad range of conditions needed for the examination of CSA indicators. For example, the highest *Rs* coincided with the lowest SMC during the MSD (late July to Early August) in 2012, thereby producing the largest net CO_2 uptake (Fig. 3.11) as well as the largest CH_4 emission (Fig. 3.12).

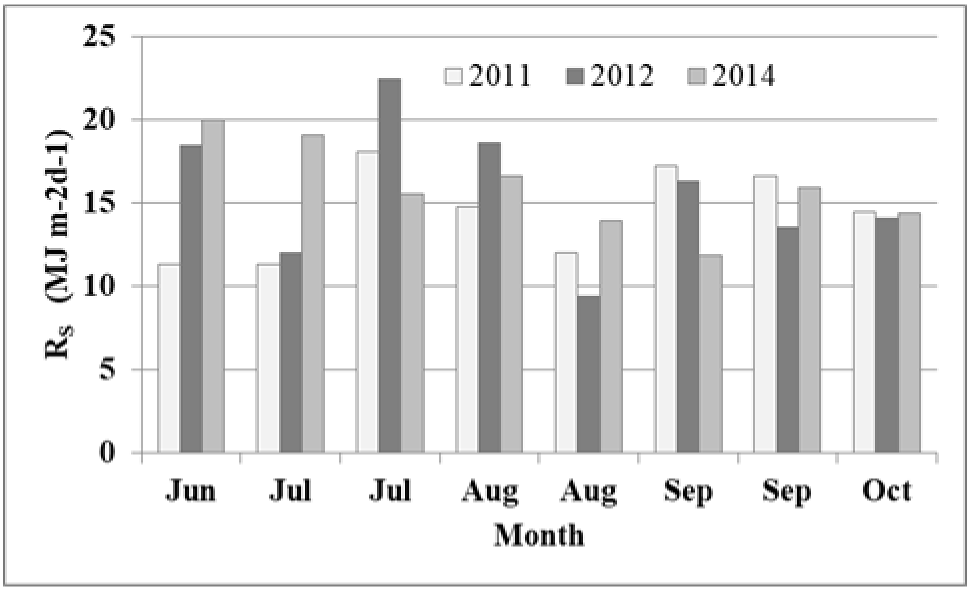

Figure 3.4 Bi-weekly averaged daily incoming solar radiation (MJ m^{-2} d^{-1}) during the growing seasons in 2011, 2012 and 2014 at GRK site.

The efficiency of energy capture (i.e., the ratio of net radiation, R_N, to R_S) ranged from 0.63 to 0.68. Despite the differences in magnitude and seasonality of radiation, R_N/Rs showed no significant differences among the three growing seasons (Fig. 3.5).

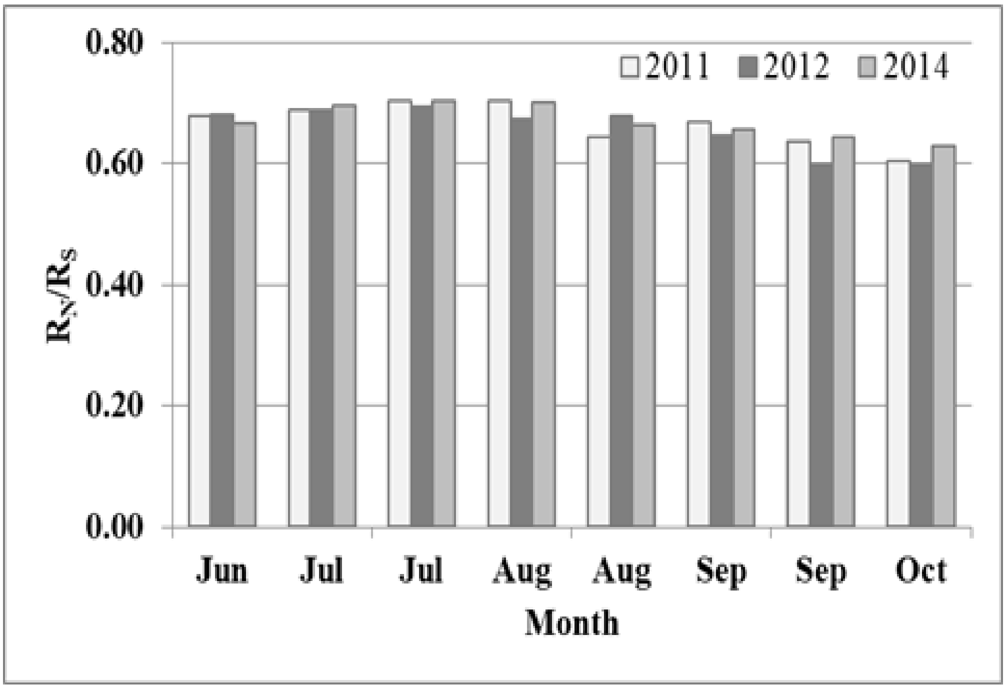

Figure 3.5 Bi-weekly averaged ratios of net radiation (R_N) to incoming solar radiation (R_S) for the growing seasons in 2011, 2012 and 2014 at GRK site.

3.2 Energy Balance and the Bowen ratio

The closure of the measured energy balance components is shown in Fig. 3.6 and Table 3.1. The footprint (i.e., source area) of R_N component was relatively small compared to that of λE and H that were measured by EC technique. And yet, the rice paddy site was large and homogeneous. The same instruments and the standardized KoFlux data processing protocol were used, resulting in the EBR values that are closer to 1 than other agricultural sites reported (ranging from 0.34 to 1.69 with an average of 0.84; Wilson *et al*., 2002). The regression (through the origin) yielded the EBR values (i.e., the slope in Fig. 3.6) of 1.06 in 2011, 0.89 in 2012, and 0.93 in 2014 with an average of 0.96.

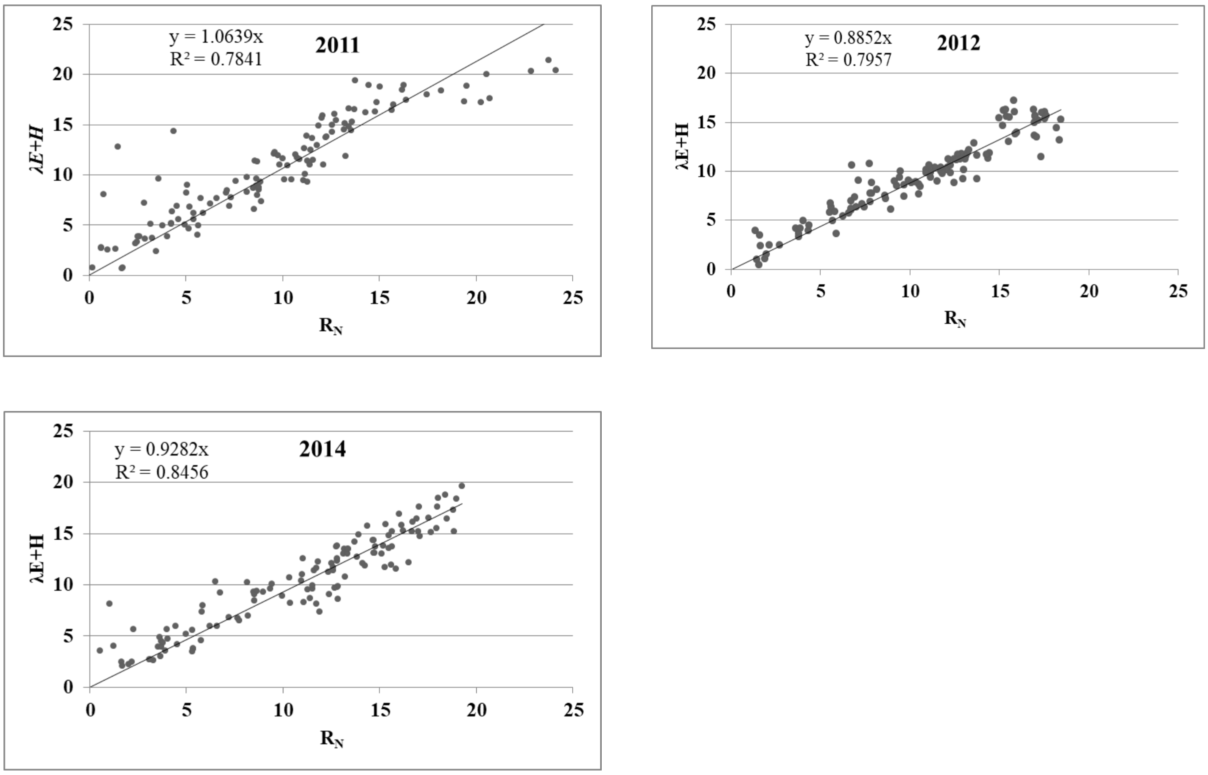

Figure 3.6 Energy balance ratio (*EBR*) with regression (through the origin) using the daily integrated values of R_N and $\lambda E+H$ during the growing seasons in 2011, 2012 and 2014.

Table 3. 1 Energy balance ratio (*EBR*), coefficient of determination (r^2), and the Bowen ratio (β) from Gimje (GRK) site during the growing seasons in 2011, 2012 and 2014.

Growing season	*EBR*	r^2	β
2011	1.06	0.78	0.03±0.13
2012	0.89	0.80	0.05±0.17
2014	0.93	0.85	0.07±0.11

The 2011 growing season showed more negative daily β (~ 42%) than 2012 (~30%) and 2014 (~21%), indicating more frequent occurrence of sensible heat advection in 2011. As a result, the growing season average of β was lower in 2011 than 2012 and 2014 (Table 3.1). β ranged from -0.50 to 0.36,-0.58 to 0.58, and -0.30 to 0.43 in 2011, 2012 and 2014, respectively. Overall, β at GRK site was comparable for flooded rice paddies reported in other studies in Philippines (0.14; Alberto *et al*., 2009), in Bangladesh (0.06; Hossen *et al*., 2012) and in Taiwan (0.18; Tsai *et al*., 2007).

Table 3.2 Comparision of eddy covariance based energy balance ratio *(EBR)* among different rice paddy ecosystems reported in the literature

Location	*EBR*	References
GRK	0.96	This study
CA, USA	0.81~0.94	Hatala *et al*., 2012; Baldocchi *et al*., 2016
IRRI, Philipines	0.72~0.89	Alberto *et al*., 2011, 2014
Southern Brazil	0.75	Timm *et al*., 2014
Ibaraki, Japan	0.72	Ikawa *et al*., 2017
Bangladesh	0.69	Hossen *et al*., 2012

3.3 Assessment of Climate-Smart Agriculture (CSA)

3.3.1 Indicators for productivity

3.3.1.1 Gross primary productivity (*GPP*)

For the sake of completeness, the results on *GPP* are presented along with those of *RE* (Fig. 3.7) because net CO_2 exchange (F_{CO2}) is a result of a delicate balance between *GPP* and *RE* and their ratio represents carbon uptake efficiency. For the three growing seasons, *GPP* averaged to be 889 (± 35) g C m^{-2}. The three growing seasons showed differences not only in magnitude but also in seasonality as seen in Fig. 3.7. In 2011, despite being the year with the lowest Rs, the greater *GPP* of 938 g C m^{-2} was observed. The lowest *GPP* of 860 g C m^{-2} in 2012 was associated with greater *RE* along with higher *T* and lower *P* (hence, lower SMC).

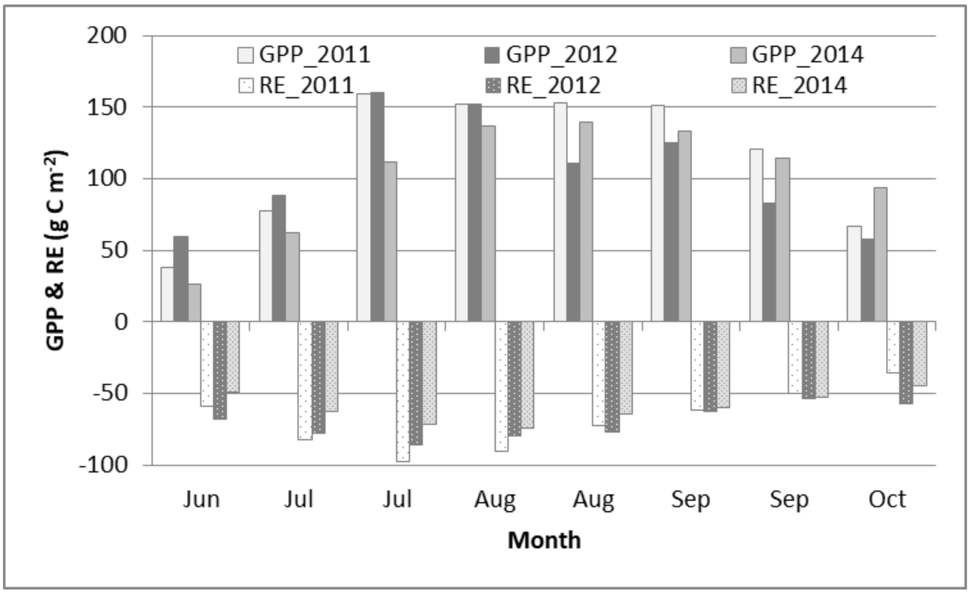

Figure 3.7 Bi-weekly sum of gross primary productivity (*GPP*) and ecosystem respiration (*RE*) during the growing season in 2011, 2012 and 2014 at GRK site.

The growing season-integrated *RE* was on average 565 (±36) g C m^{-2} with interannaul variation of ~6%. Among the three growing seasons, the highest *RE* of 607 g C m^{-2} was observed in 2012 (thereby decreasing the productivity) whereas the lowest *RE* of 519 g C m^{-2} in 2014. The seasonality of *RE* was different from that of *GPP*.

3.3.1.2 Evapotranspiration (*ET*) and crop coefficient (*Kc*)

Evapotranspiration (*ET*) from the three growing seasons was different through the lens of daily mean and maximum values as well as the ratio of *ET* to *P*. The mean *ET* was 4.3±2.1 mm d^{-1} in 2011, 3.6±1.6 mm d^{-1} in 2012, and 3.9±1.7 mm d^{-1} in 2014. 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., *Rs*) was lowest in 2011, and yet *ET* was highest among the three growing seasons. This can be explained partly because of more frequent occurrence of sensible heat advection (via oasis effect) over well-watered rice paddy, which is supported by above-normal *P* and the SMC near saturation throughout the growing season in 2011. This further substantiated by the lowest value of β (the Bowen ratio shown in Table 3.1) in 2011.

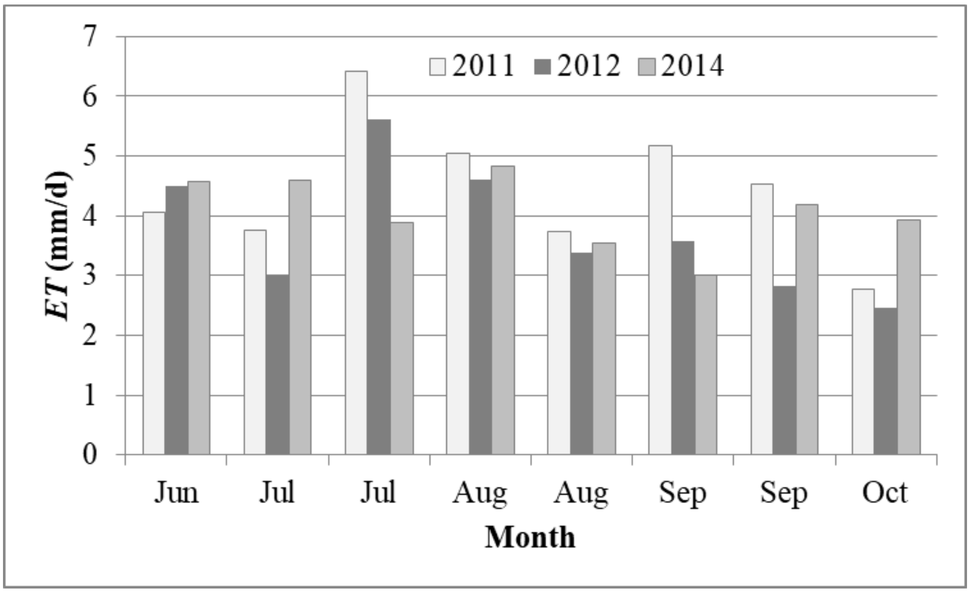

Figure 3.8 Bi-weekly averaged daily evapotranspiration (mm d^{-1}) during the growing seasons in 2011, 2012 and 2014.

In terms of the ratio of *ET* to *P* (and disregarding the amount of irrigated water), about 58 % of *P* returned to the atmosphere by *ET* (514 mm) in 2011. It is note that in 2012 *P* was highest (~ 976 mm) and *Rs* was higher than in 2011 but *ET* was lowest (440 mm), thereby resulting in *ET/P* of 0.45. The below normal *P* (~ 620 mm) in 2014 yielded the highest *ET/P* of 0.80.

The magnitude as well as the seasonality of *Kc* were quite different for the three growing seasons. For the entire period of the three growing seasons, *Kc* was on average 1.26. As expected from the highest *ET* rate (Fig. 3.8), *Kc* in 2011 was highest with an average of 1.31 (±0.21). In terms of seasonal variation, the *Kc* in 2011 was maintained high throuout the season except October, whereas those in 2012 and 2014 started with much lower values (~1.12) and progressively increased through the growing seasons except in October 2012 (Fig. 3.9).

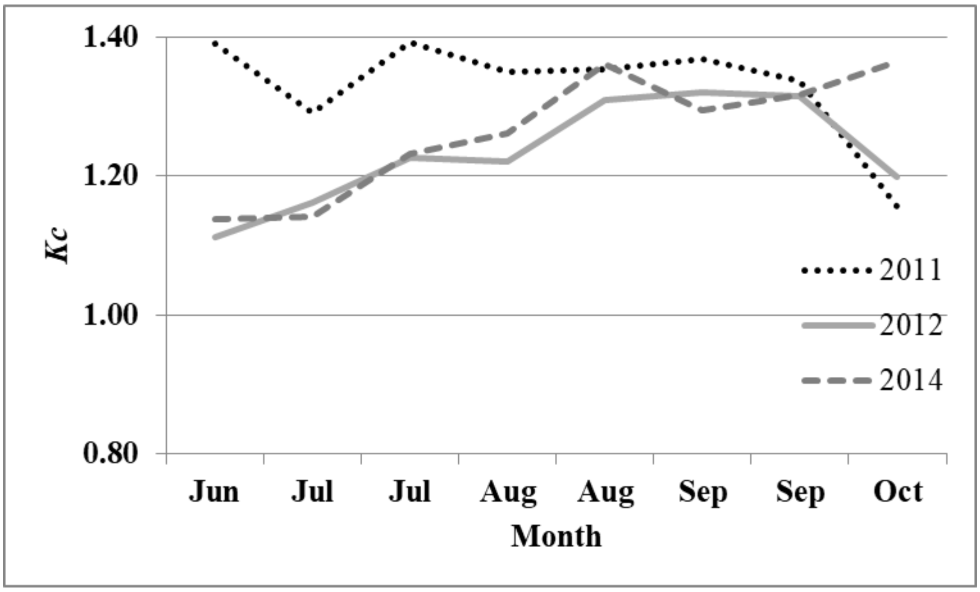

Figure 3.9 Bi-weekly averaged daily crop coefficient (*Kc*) during the growing seasons in 2011, 2012 and 2014.

3.3.1.3 Water use efficiency (*WUE*)

Water use efficiency is the ratio of *GPP* to *ET*, therefore it could be intuitively guessed from the above-reported results of *GPP* and *ET*. However, it was not that straightforward to deduce and was dependent on the amount of relative changes. For example, despite its lowest *GPP*, the mean daily *WUE* in 2012 was highest (2.06±0.82 g C kg H_2O^{-1} d^{-1}, Fig. 3.10) 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* turned out to be lowest (1.91±0.82 g C kg H_2O^{-1} d^{-1}) because of much greater increase in *ET* (owing to more frequent advection of sensible heat under well-watered conditions throughout the growing season). The *WUE* in 2014 was on average 1.95±1.0 g C kg H_2O^{-1} d^{-1}.

In terms of seasonality, *WUE* gradually increased until it reached the maxima between mid-August and mid-September. The three growing seasons showed seasonal variations that were different from one another.

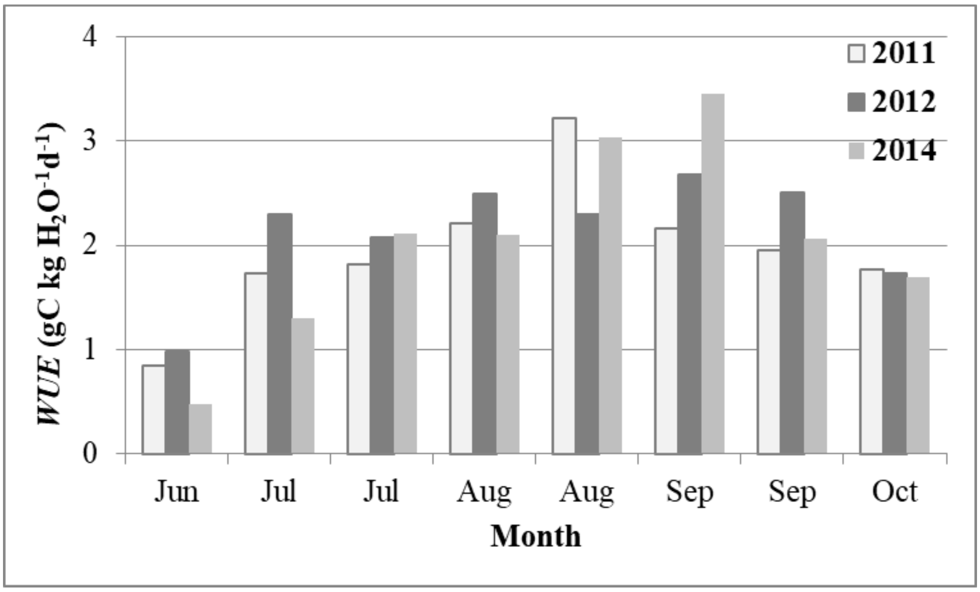

Figure 3.10 Bi-weekly averages of the daily water use efficiency (*WUE*, in g C kg H_2O^{-1} d^{-1}) during the growing seasons of 2011, 2012 and 2014.

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* (*APAR*) varying from 0.54 to 0.60. For the three growing seasons, the daily *LUE* was on average 1.94±0.12 g C $MJ^{-1}d^{-1}$ with a range from 1.80 to 2.09 g C MJ^{-1} d^{-1}. As expected, 2011 showed the highest *LUE* because of the highest *GPP* and the lowest *APAR* in comparison to those in other two growing seasons. The opposite was the case for *LUE* in 2014 when the lower *GPP* along with the highest *APAR* produced the lowest *LUE*. The highest *LUE* in 2011 was consistent with the observed maixima of *GPP* and grain yield in 2011. However, the lowest *LUE* in 2014 did not necessarily correspond to the lowest *GPP* nor the lowest grain yield (which occurred not in 2014 but in 2012 with intermediate *LUE*).

3.3.2 Indicators for Greenhouse Gas (GHG) mitigation

3.3.2.1 Carbon dioxide (CO_2) uptake

The net CO_2 uptake (*NEE*, or F_{CO2}) showed a moderate interannual variability of ~15%, and the growing season-integrated CO_2 uptake was on average 324 (±50) g C m^{-2} (equivalent to a daily rate, F_{CO2} of ~2.7 g C m^{-2} d^{-1}) (Fig. 3.11). Until late June, the rice paddy was a source of CO_2 and then turned into a sink in July. The highest net uptake rate of F_{CO2} (~3.0 g C m^{-2} d^{-1}) was observed in 2011, coinciding with the highest *GPP* and the grain yield.

As expected, changes in ecosystem respiration played a role. For example, the lowest F_{CO2} of 2.1 g C m^{-2} d^{-1} in 2012 was associated with the highest *RE*, resulting in the lowest productivity among the three growing seasons. Consequently, the carbon uptake efficiency in 2012 was lowest (~1.42). Much more efficient carbon uptake of ~1.66 was observed in both 2011 and 2014, resulting in the averaged *CUE* of 1.58 (±0.11) for the three growing seasons. The seasonality of F_{CO2} was significant within as well as between the individual years.

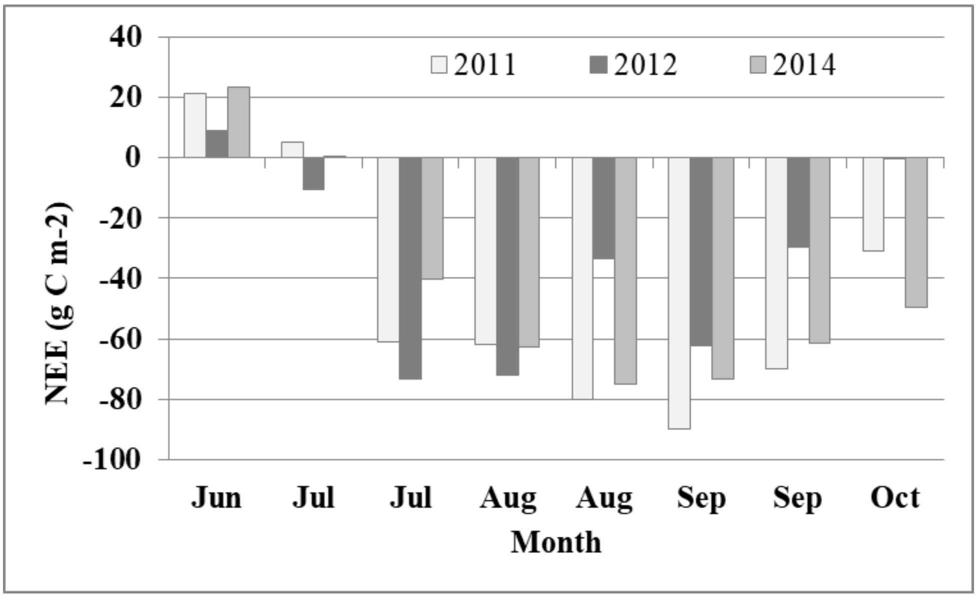

Figure 3.11 Bi-weekly sum of net ecosystem exchange (*NEE*) of CO_2 (in g C m^{-2}) during the growing seasons of 2011, 2012 and 2014.

3.3.2.2 Methane (CH_4) emission

The growing season-accumulated methane emission was on average 21.1±3.5 g C m^{-2} (equivalent to a daily rate, F_{CH4} of 173 mg C m^{-2} d^{-1}) with significant interannual variability. The highest F_{CH4} of 214 mg C m^{-2} was observed in 2014, whereas the lowest F_{CH4} of 148 mg C m^{-2} was observed in 2012.

The patterns of seasonal variation of F_{CH4} were quite different between the three growing seasons and was significantly affected by soil hydrology: (1) the effectiveness of mid-summer drainage and (2) amount and seasonality of *P*. For example, the growing season in 2012 was characterized by very dry conditions (see Fig. 3.3) during the MSD period due to the absence of rainfall. Figure 3.12 shows that the successful MSD in 2012 resulted in a dramatic reduction of F_{CH4} in August and the emission never recovered its strength for the remaining season in spite of ample rainfall. On the other hand, rainfalls during the mid summer in 2014 annihilated the effect of MSD and the following ample rainfalls in Augusut and September caused ~40% more CH_4 emission than other two growing seasons.

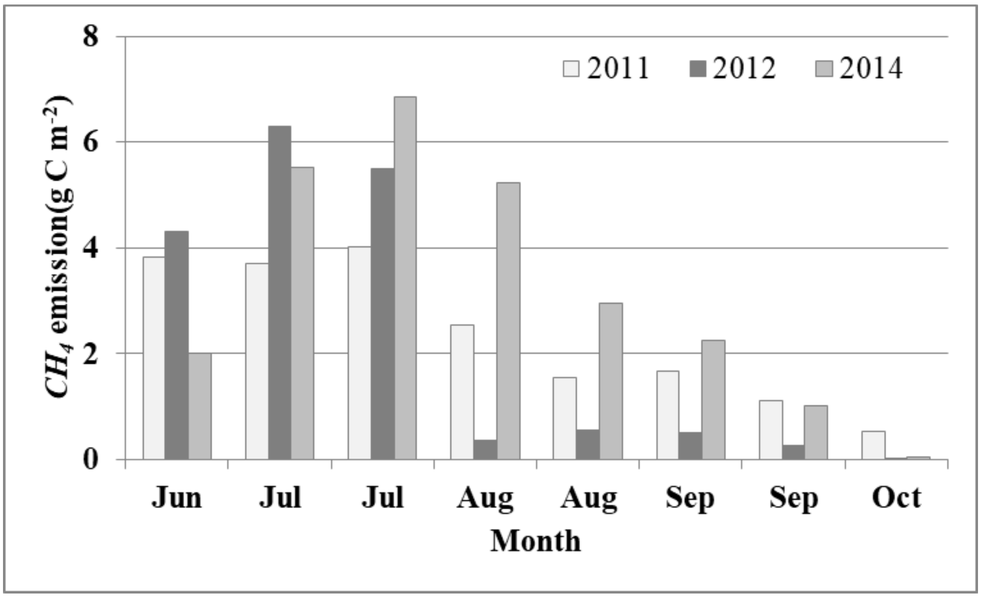

Figure 3.12 Bi-weekly sum of methane emission (in g C m^{-2}) during the growing seasons of 2011, 2012 and 2014.

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 a daily rate of F_{N2O} of 1.36 mg N_2O m^{-2} d^{-1}). The F_{N2O} in 2011was highest with 1.39 mg N_2O m^{-2} d^{-1} and was lowest (1.32 mg N_2O m^{-2} d^{-1}) in 2012. However, considering the uncertainties associated with indirect estimation based on the IPCC guideline, the interannaul variability of F_{N2O} was not significant (~2%).

3.3.3 Indicators for Resilience

Table 3.3 presents the summary of *E* (emergence), *S* (self-organization, a resilience indicator) and *C* (complexity) computed from the three growing seasons. It would be useful to recall the definition of these indicators. *E* describes new (emergent) global patterns that are not present in the system's components, which measures the uncertainty (hence, an increase of entropy) a process produces as a consequence of changes in process dynamics or scale. A resilience indicator, *S* is the compliment of *E* (i.e., $S = 1 - E$) and is related to order and regularity due changes. Therefore, *S* can be seen as a reduction of entropy. *C* is employed as an alternative indicator for system state, which results from a delicate balance between *E* (i.e., change) and *S* (i.e., regularity). The former leads to the exploration of new possibilities whereas the latter ensures the survival of information. In other words, *C* describes the behavior of a system as the average uncertainty produced by emergent and regular global patterns as described by its probability distribution (Correa, 2020).

First, the time series data of *GPP*, F_{CH4}, and *ET* were analyzed with two different sampling rates (i.e., half-hourly and daily) to compute E_{GPP}, E_{CH4}, *and* E_{ET}, respectively. The half-hourly time series produced *E* ranging from 0.46 to 76, which is smaller (less uncertain) than *E* of daily time series which ranged from 0.72 to 97 (more irregular). Consequently, in terms of self-organization (hence, resilience), the half-hourly time series of *GPP*, F_{CH4} and *ET* showed much higher *S* (0.24 to 0.54) (stable and thus more resilient) than *S* from the daily time series (0.03 to 0.28). In terms of composite S_{AVG} (average of S_{GPP}, $S_{F_{CH4}}$, *and* S_{ET}), both half-hourly and daily time series showed that the growing season of 2012 was somewhat more resilient (with S_{AVG} of 0.42 and 0.12, respectively) than other two years. Also, it was noted that the process of CH_4 exchange was most resilient whereas that of *ET* was least resilient and that of *GPP* was in between. For *GPP* and *ET*, self-organization occurred predominantly within hourly time scale whereas for F_{CH4} it occurred from hourly to daily time scales.

Table 3.3 Summary of emergence (*E*), self-organization (*S*), and complexity (*C*). Results are given for half-hourly time series and those from daily time series are provided in parenthesis. The subscripts *GPP*, F_{CH4}, and *ET* represent the processes associated with gross primary production (biochemical), methane production/oxidation and transport (biogeochemical), and evapotranspiration (biophysical), respectively. The composite values (i.e., E_{AVG}, S_{AVG} and C_{AVG}) were computed by taking the average of the indicators for three processes (i.e., *GPP*, F_{CH4}, and *ET*), which are considered as overall *E*, *S*, and *C* indicators for the rice cultivation systems at GRK site for the growing seasons of 2011, 2012 and 2014.

Indicators	2011	2012	2014
E_{GPP}	0.61 (0.97)	0.59 (0.95)	0.58 (0.97)
E_{FCH4}	0.51 (0.88)	0.52 (0.72)	0.46 (0.83)
E_{ET}	0.76 (0.97)	0.62 (0.97)	0.72 (0.97)
E_{AVG}	0.63 (0.94)	0.58 (0.88)	0.59 (0.92)
S_{GPP}	0.39 (0.03)	0.41 (0.05)	0.42 (0.03)
S_{FCH4}	0.49 (0.12)	0.48 (0.28)	0.54 (0.17)
S_{ET}	0.24 (0.03)	0.38 (0.03)	0.28 (0.03)
S_{AVG}	0.37 (0.06)	0.42 (0.12)	0.41 (0.08)
C_{GPP}	0.96 (0.12)	0.97 (0.18)	0.98 (0.12)
C_{FCH4}	1.00 (0.41)	1.00 (0.81)	0.99 (0.56)
C_{ET}	0.72 (0.12)	0.94 (0.11)	0.81 (0.11)
C_{AVG}	0.89 (0.27)	0.97 (0.49)	0.93 (0.34)

Finally, in terms of *C*, half-hourly and daily time series produced more contrasting results. On the one hand, half-hourly time series-based C_{AVG} was near the maximum of unity (0.89~0.97) because of near balance between *E* (~0.6) and *S* (~0.4). On the other hand, daily time series-based C_{AVG} was in the range of the other end (between 0 and 0.5) due to the dominance of *E* (~0.9) over *S* (~0.1). However, both time series produced the highest C_{AVG} in 2012 and the lowest in 2011, indicating that the 2012 growing season was not only more resilient but also more flexible to explore new possibilities with changes.

4. DISCUSSION

The conditions encountered for the three-year study period provided wide ranges of changes in the rice cultivation system's state and its surrounding environment for the assessment of CSA. First of all, three key variables (i.e., *T*, *P* and *Rs*) representing the climatic conditions provided characteristic and contrasting environment for the three growing seasons used in this study in terms of their differences in magnitude and in seasonality. Regarding phenology, the growing season length (i.e., number of days from transplanting to harvest) was not significantly different for the three growing season, which was on average 122 (± 3) days.

As seen in Table 4.1, the growing season in 2011 had above normal *P*, and R_S was low (by about 10% compared with *Rs* of other two growing seasons). Yet, *LUE* was highest (i.e., most efficient use of light), thereby resulting in the highest *GPP*, grain yield, and F_{CO2} among the three growing seasons. With moderate level of *RE*, *CUE* was also higher. However, the highest productivity, most efficient light use and carbon uptake were accompanied with the highest *ET* (and *Kc*), the lowest *WUE* (i.e., using more water), and the lowest S_{AVG} (therefore, least resilient due to minimized self-organization). In comparison with the averaged emissions of CH_4 and N_2O of the three growing seasons, the F_{CH4} was 10% lower but F_{N2O} was ~2% higher in 2011.

In comparison with 2011, the growing season in 2012 received 11% more *Rs* along with even more *P* (by 83 mm). Despite having excessive *P*, the mid-season drainage (*MSD*) was effective (owing to the absence of *P* and greater R_S during the *MSD* period) and provided better mitigation of CH_4. As a result, both F_{CH4} and F_{N2O} were lowest among the three growing seasons. Particularly, enhanced organization of methane exchange process (i.e., S_{FCH4}) resulted in overall increase in S_{AVG} up to 0.12 (i.e., the highest resilience). However, increased *RE* resulted in lowest F_{CO2}. *ET* (and *Kc*) was also lowest, and so were *GPP* and grain yield.

The highest *WUE* observed in 2012 was an artifact of the greater reduction of *ET* than that of *GPP*.

Table 4.1 Summary of climatic conditions, phenology, and indicators for 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
Evapotranspiration, *ET* (mm)	514	440	494
Water use efficiency, *WUE* (g C kg H_2O^{-1})	1.91	2.06	1.95
Crop coefficient (K_C)	1.31	1.21	1.25
GHG mitigation indicators			
Net CO_2 uptake, F_{CO2} (g C m^{-2})	368	254	349
CH_4 emission, F_{CH4} (g C m^{-2})	19.1	18.0	26.0
N_2O emission, F_{N2O} (mg N_2O m^{-2})	1.39	1.32	1.36
Carbon uptake efficiency, *CUE*	1.65	1.42	1.67
Ecosystem respiration, *RE* (g C m^{-2})	570	607	519
Resilience indicators (using daily time series)			
Self-organization of *GPP* (S_{GPP})	0.03	0.05	0.03
Self-organization of F_{CH4} (S_{FCH4})	0.12	0.28	0.17
Self-organization of *ET* (S_{ET})	0.03	0.03	0.03
Composite self-organization (S_{AVG})	0.06	0.12	0.08

The growing season in 2014 received the highest *Rs* and the lowest *P*. However, sufficient amount of rainfalls occurred during the mid-seaon and nullified the practice of MSD. In addition, the subsequent and continued ample amount of *P* throughout the rest of the growing season caused 40% more emission of CH_4 than other two growing seasons. *ET*, *Kc* and *WUE* were moderate, and *LUE* was lowest. Hence, productivity was moderate but F_{CO2} and *CUE* were high mainly because of low *RE*. Resilience was also moderate (S_{AVG} of 0.08) among the three growing seasons.

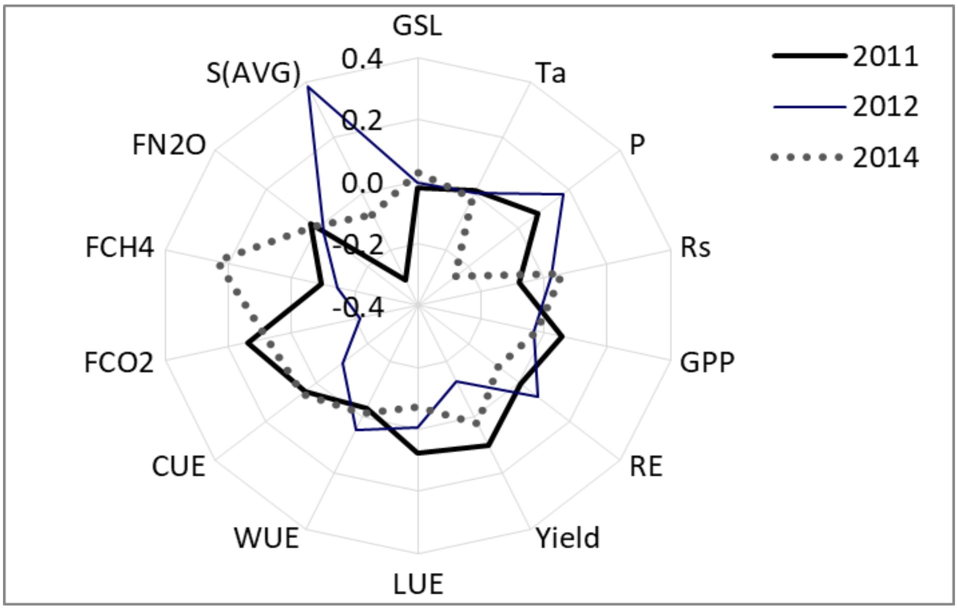

Figure 4.1 Radial plot showing the relative changes (from -50 to 40%) in CSA indicators that are normalized against the mean values against where F_{CO2} is uptake and other fluxes (F_{CH4}, F_{N2O}, *RE*) are emission.

In order to distinguish the observed conflict and/or tradeoff between the triad of CSA challenges, the indicators in Table 4.1 were normalized against the averages of the three growing seasons and their relative changes are described in a radial plot in Fig. 4.1. It is clearly demonstrated that the rice cultivation system at GRK was not fulfilling the CSA's triple challenge. In fact, it should be noted that the competing goals and trade-offs among productivity, GHG mitigation, and resilience within individual years as well as among the three years caused clashes and difficulties in achieving seamless harmony under the triple-win scenarios in which conflicts of interest are assumed to be absent. Table 4.2 further confirms such competing goals and trade-offs in the rice cultivating system at GRK site. None of the growing seasons examined in this study either achieved the CSA triple win within individual years or maintained the status for the three-year period.

Table 4.2 Conflicts and trade-offs among the triple challenge of climate-smart agriculture (CSA) at GRK site for the growing seasons of 2011, 2012 and 2014.

CSA triple goal	2011	2012	2014
Productivity	High	Low	Moderate
GHG mitigation	Moderate	High	Low
Resilience	Low	High	Moderate

Below, to evaluate the relative success of the rice cultivation system at GRK site, the averaged values of individual CSA indicators for the three growing seasons at GRK site are compared with those reported from other rice paddy studies. In terms of productivity, the growing season-integrated *GPP* at GRK site was comparable to those reported from other site in Korea as well as those from Japan and the Philippines, but higher than those reported from China and Bangladesh (Table 4.3).

Table 4.3 Comparison of the growing season-integrated gross primary productivity (*GPP*, in g C m^{-2}) at GRK site to *GPP* reported from other rice paddy studies.

Location	***GPP* (g C m^{-2})**	**References**
CRK, Korea	921	Choi *et al*., 2018
IRRI, Philippines	905	Alberto *et al*., 2011
MSE, Japan	895	Ikawa *et al*., 2017
GRK, Korea	***889***	***This study***
Liaohe Delta, China	823	Wang *et al*., 2017
Bangladesh (dry season)	711	Hossen *et al*., 2011, 2012
Bangladesh (wet season)	601	Hossen *et al*., 2011, 2012

Productivity is dependent on the efficiency of light use, among other factors. Table 4.4 provides the comparison of *LUE* among a few rice paddy sites available in the literature and shows that *LUE* at GRK site was higher.

Table 4.4 Comparison of growing season-averaged light use efficiency (*LUE*) at GRK site to *LUE* reported from other rice paddy studies.

Location	***LUE***	**References**
GRK, Korea	***1.94***	***This study***
MSE, Japan	1.52	Ikawa *et al*. 2017
HFK, Korea	1.49	Indrawati *et al*., 2018

In terms of water requiremt for rice cultivation, evapotranspiration (*ET*) and crop coefficient (*Kc*) are worth mentioning here. The seasonal daily mean *ET* ranged from 3.6 to 4.3 mm d^{-1} in during 2011, 2012 and 2014. The seasonal daily mean *ET* in the study site was comparable with the range reported from other studies. For example, Alberto *et al*. (2011)

using eddy covariance technique, reported the *ET* of 3.8 to 4.3 mm d^{-1} for an aerobic to flooded rice paddy in the Philippines. Tomar and O'Toole (1980) reported that the seasonal average of *ET* in Asian rice paddy fields was in the range of 4 to 7 mm d^{-1}.

The maximum *ET* was 7.0, 6.6 and 7.2 mm d^{-1} in 2011, 2012 and 2014 growing season, respectively. The observed *ET* maxima in our study are well within those reported for various rice paddies in the literature. For example, Tyagi *et al*. (2000) reported a maximum *ET* of 6.6 mm d^{-1} under semi-arid conditions in Karnal, India using Lysimeters. Hossen *et al.* (2012) also reported the maximum ET of 6.6 mm d^{-1} in Banglasdesh. In southern Brazil, Timm *et al.* (2014) reported the maximum *ET* of ~ 7 mm d^{-1} during the rice paddy growing season using eddy covariance technique. On the other hand, Hatala *et al*. (2012) observed *ET* up to 10 mm d^{-1} from rice paddy in Sacramento-San Joaquin Delta, California.

Table 4.5 Comparison of growing season averaged ET (mm) at GRK site to ET reported from their rice paddy studies

Location	**(mm)**	**References**
Liaohe Delta, China	823~608	Wang *et al*., 2017
India	587	Tyagi *et al*., 2000
Brazil	562	Timm *et al*., 2014
IRRI, Philipines	400~556	Alberto *et al*., 2011
GRK, Korea	***483***	***This study***
CRK, Korea	426	Choi *et al*., 2018
HFK, Korea	352	Indrawati *et al*., 2018
MSE, Japan	425	Ikawa *et al*., 2017
Bangladesh	307~370	Hossen *et al*., 2011, 2012

Form Table 4.5, *GRK* site seasonally-integrated *ET* was lower than the *ET* reported from China, India and Brazil (Timm *et al*., 2014; Tyagi *et al*., 2000; Timm *et al*., 2014) and higher than those reported from Bangladesh and Japan, (Hossen *et al*., 2011, 2012; Ikawa *et al*., 2017) and also HFK and CRK sites of Korea. However, the seasonal *ET* from our site was within the range of *ET* in Philipines reported Alberto *et al*. (2011).

Table 4.6 Comparison of growth stage wise mean *Kc* of rice paddy at GRK site to *Kc* of rice paddy reported from ten locations of Korea. Number of days used for growth stage wise *Kc* estimation in this study: $K_{c\text{-}ini}$ = 20; $K_{c\text{-}dev}$ = 30; $K_{c\text{-}mid}$ = 40; and $K_{c\text{-}end}$ = 30.

Location	**Estimation method**	**Growth stage wise *Kc***				$K_{c\text{-}mean}$	**References**
		$K_{c\text{-}ini}$	$K_{c\text{-}dev}$	$K_{c\text{-}mid}$	$K_{c\text{-}end}$		
Daejeon	Lysimeter	1.17	1.42	1.82	1.78	1.59	Yoo *et. al*., 2006
Daegu	Lysimeter	0.79	1.22	1.87	2.05	1.48	Yoo *et. al*., 2006
Cheongju	Lysimeter	0.98	1.26	1.56	1.57	1.36	Yoo *et. al*., 2006
Suwon	Lysimeter	0.75	1.31	1.56	1.30	1.30	Yoo *et. al*., 2006
Chuncheon	Lysimeter	1.17	1.17	1.54	1.11	1.28	Yoo *et. al*., 2006
Jinju	Lysimeter	0.88	1.00	1.57	1.45	1.27	Yoo *et. al*., 2006
GRK	***EC***	***1.21***	***1.26***	***1.33***	***1.21***	***1.26***	***This study***
Gwangju	Lysimeter	1.07	1.16	1.28	0.90	1.14	Yoo *et. al*., 2006
Jeonju	Lysimeter	0.59	1.09	1.34	1.18	1.11	Yoo *et. al*., 2006
Haenam	EC	0.87	1.02	1.02	0.77	0.92	Indrawati, 2015
Seoul	Lysimeter	0.51	0.94	0.93	1.07	0.88	Yoo *et. al*., 2006

Yoo *et. al*. (2006) documented mean *Kc* values of rice paddy at 9 locations from north to south and east to west part of Korean peninsula during 1982-86 using lysimeter (Table 4.6). Indrawati (2015) estimated mean *Kc* (0.98±0.08) of rice value from 2003 to 2012 at Haenam using EC method. Growth stage wise *Kc* was adopted from Yoo et. al. (2006) and Indrawati

(2015) for comparing *GRK* site mean *Kc* values during 2011, 2012 and 2014. Although, *Kc* values varied due to local climatic, management and crop condition; this analysis provided better understanding of water use status of Korea.

Three patterns of *Kc* were found from Yoo *et. al*. (2006) compared to *GRK* study site. First category showed increasing trend except mid-season but always lower than Gimje site which is found in Seoul. Second category showed increasing trend in all the growth stage but *Kc* values of these locations were lower than Gimje site until development stage and after that always higher than Gimje. This category found in Daegu, Daejeon and Cheongju. Third category locations showed the conventional seasonal pattern of *Kc* values in which *Kc* values sharply increased upto the development stage and still maintaining increasing trend until mid-season and finally showed decreasing trend. *Kc* values were lower than Gimje site upto development stage, then all site showed higher *Kc* values than Gimje site. And finally Gwangju and Chuncheon were again lower than *GRK* site while Jeonju, Suwon and Jinju were still maintained higher *Kc* values than the study site.

The seasonal mean *Kc* at GRK site was slightly above average compared to those from other locations in Korea, which was encouraging to compare the *Kc* values at *GRK* site with those from other countries' rice paddies as shown in Table 4.6. Study site mean *Kc* was at the upper range compared to other countries reported in the available literature (Table 4.7). For example, comparing with FAO recommended mid-stage *Kc* (Allen et al., 1998), *GRK* site *Kc* was on an average 11% higher and seasonally 18% higher. As seen in Table 4.1, *Kc* could be used as a proxy indicator for productivity (positively correlated) and for *WUE* (negatively correlated).

Table 4.7 Comparison of growth stage wise mean *Kc* of rice paddy at GRK site to Kc of rice paddy reported from other countries.

Location	**Estimation method**	**Growth stage wise *Kc***				**$K_{c\text{-mean}}$**	**References**
		$K_{c\text{-ini}}$	$K_{c\text{-dev}}$	$K_{c\text{-mid}}$	$K_{c\text{-end}}$		
Taiwan	Lysimeter	1.00	1.45	1.65	0.95	1.26	Kuo *et al.*, 2006
GRK, Korea	***EC***	***1.21***	***1.26***	***1.33***	***1.21***	***1.26***	***This study***
South & Southeast Asia	-	1.0	1.15	1.3	1.15	1.2	Tomar & O'toole, 1980
Karnal, India	Lysimeter	1.15	1.23	1.14	1.02	1.14	Tyagi *et al.*, 2000
FAO	-	1.05	1.12	1.20	0.90	1.07	Allen *et al.*, 1998
West java, Indonesia	Excel Solver	0.70	1.06	1.24	1.22	1.06	Arif *et al.*, 2012
IRRI, Philipines	EC	1.04	1.11	1.04	0.93	1.03	Alberto *et al.*, 2011
Montana, Spain	Surface renewal	0.92	1.06	1.06	1.03	1.02	Moratiel and Martinez-Cob, 2013
IRRI, Philipines	EC	0.83	0.95	1.10	1.07	0.99	Alberto *et al.*, 2014
Sardinia, Italy	Pan evaporation	0.90	1.07	0.97	0.97	0.98	Spanu *et. al.*, 2009

Table 4.8 Comparison of the growing season averaged water use efficiency (*WUE*, in g C kg H_2O^{-1}) at GRK site to WUE reported from other rice paddy studies.

Location	***WUE* (g C kg H_2O^{-1})**	**Reference**
CRK, Korea	2.16	Choi *et al.*, 2018
MASE, Japan	2.13	Ikawa *et al.*, 2017
GRK, Korea	***1.97***	***This study***
Bangladesh (wet season)	1.96	Hossen *et al.*, 2011, 2012
Bangladesh (dry season)	1.92	Hossen *et al.*, 2011, 2012
IRRI/flooded, Philippines	1.73	Alberto *et al.*, 2009, 2011
Southern Brazil	1.50	Diaz *et al.*, 2019
Liaohe Delta, China	1.36	Wang *et al.*, 2017
IRRI/aerobic, Philippines	1.03	Alberto *et al.*, 2009, 2011

Considering the projected water deficit in the future under the current climate change scenarios, efficient use of water is an important indicator for CSA. The growing season averaged daily *WUE* was in the middle to upper ranges of those reported from other rice paddy studies (Table 4.8).

Table 4.9 Comparison of the growing season-integrated net CO_2 uptake ($F_{CO2,}$ g C m^{-2}) among different rice paddy ecosystems.

Location	F_{CO2} (g C m^{-2})	References
Odisha, India (wet)	355 ~ 449	Bhattacharyya *et al*. (2013, 2014)
Southern Brazil	448	Diaz *et al*., 2019
Okayama, Japan	438	Miyata *et al*. (2005)
Ibaraki, Japan	400	Saito *et al*. (2005)
Odisha, India (dry)	383	Swain *et al*. (2016)
USA	363	Knox *et al*. (2016)
Ibaraki, Japan	354	Miyata *et al*. (2005)
Odisha, India (dry)	341	Bhattacharyya *et al*. (2014)
Philippines (wet)	334	Alberto *et al*. (2012)
GRK, Korea	***324***	***This study***
Philippines (dry)	318	Alberto *et al*. (2012)
Odisha, India (wet)	251	*Swain et al. (2016)*

Table 4.9 summarizes the growing season-integrated net CO_2 uptake (F_{CO2}, in g C m^{-2}) at various rice paddy sites reported in the literature (Table 4.9). Phenology makes difference in this kind of comparison because of the varying length of the growing season. Thus, daily rate of F_{CO2} may be used for more accurate comparison. However, total amount (regardless of the growing season length) is as important as a daily rate in the context of CSA regardlwss of GSL. Overall, F_{CO2} (324±50 g C m^{-2}) at GRK site was in the lower range of those reported from other rice paddy sites under various practices and climate conditions. Carbon uptake

efficiency at GRK site was on average 1.58, similar to *CUE* in other typical rice paddy at Cherwon, Korea (1.62, Choi *et al*., 2018). However, they were lower than those reported in other studies in Japan and Philippines (1.76~2.25; Alberto *et al*., 2011; Ikawa *et al*., 2017). *CUE* is the ratio of *GPP* to *RE* and therefore not only productivity but also the management of ecosystem respiration are certainly the places to intervene as the leverage points for transformation toward CSA.

Methane emission at GRK site is another important place which needs intervention. The growing season-integrated F_{CH4} at GRK site was in the mid to upper ranges of F_{CH4} reported in the literature (Table 4.10). As has been demonstrated earlier, soil hydrology associated with water management (e.g., intermittent irrigation and drainage) significantly affects not only magnitude but also seasonality of F_{CH4} (e.g., Kim *et al*., 2016).

Also was the case in nitrous oxide emission which was in the upper range of the reported F_{N2O}, requiring an appropriate management intervention (see Table 4.11).

Table 4.10 Comparison of the growing season-integrated net CH_4 emission ($F_{CH4,}$ g C m^{-2}) among different rice paddy ecosystems.

Location	**F_{CH4} (g C m^{-2})**	**References**
Bangladesh	91.7	Hossen *et al*. (2015)
GRK, Korea (chamber-based)	26.4~35.3	Chun *et al*. (2015)
Italy	27.9	Meijidae *et al*. (2011)
GRK, Korea (eddy covariance-based)	***21.0***	***This study***
IRRI (high organic input)	14.5	Wassmann *et al*. (1996)
India	8.4~12.9	Bhattacharyya *et al*. (2014)
Ibaraki, Japan	9.3	Miyata *et al*. (2005)
California, USA	6.6	Knox *et al*. (2016)
IRRI(low organic input)	3.8	Wassmann *et al*. (1996)

Table 4.11 Comparison of the growing season-integrated N_2O emission (F_{N2O}, g N_2O m^{-2}) among different rice paddy ecosystems.

Location	Estimation method	Applied N (kg N ha^{-1})	F_{N2O} ($g\ N_2O\ m^{-2}$)	References
Fengqiu, China	Chamber	365	0.48	Cai *et al*. (1999)
Tsukuba, Japan	Chamber	-	0.42	Kim *et al*. (2002)
GRK, Korea	***IPCC***	***110***	***0.17***	***This study***
Nanjing, China	Chamber	300	0.10	Cai *et al*. (1997)
Tsukuba, Japan	Chamber	100	0.09	Minami (1987)
Ehime, Japan	Chamber	-	0.07	Toma *et al*., 2016
Philippines	Chamber	200	0.06	Bronson *et al*. (1997)
Tsukuba, Japan	Chamber	90	0.01-0.03	Nishimura *et al*. (2011, 2004)
Hokkaido, Japan	Chamber	-	0.08	Nishimura *et al*. (2020)
Nanjing, China	Chamber	100	0.01	Cai *et al*. (1997)
Ryugasaki, Japan	Chamber	90	0.01	Yagi *et al*. (1996)

The above findings from the GRK site study are not surprising because the interactions among the CSA triad depend on the context. Many claims of triple-wins do not withstand detailed scrutiny because benefits for one CSA pillar often go hand in hand with disadvantages for other pillar(s) or compromises and negotiation in terms of ecological-societal sustainability (e.g. Smith *et al*., 2013; Steenwerth *et al*., 2014; Thornton and Herrero, 2014; Debaeke *et al*., 2017; Scherer and Verburg, 2017). The possible trade-offs and synergies between the CSA triad must be taken into account for policies to underpin pathways to CSA (Descheemaeker *et al*., 2020). To understand this complexity and find sustainable options, conceptual framework is essential, which enables more integrated and cross-scale analyses from diverse perspectives.

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. In contrast, for developed countries with intensive agriculture, it is not a priority to increase production, but to reduce emissions, while enhancing resilience to climate change. Taylor (2017) proposed an encompassing and progressive framework so-called 'climate-wise', an alternative to CSA framework, which emphasizes four key points. First, this framework must have access to sufficient and nutritious food. Second, it promotes shifts in consumption patterns. Third, a climate-wise food system would be predicated upon strong normative preference for ecological intensification in which biological processes in combination with human labour underscore productivity advances, rather than cheap energy inputs. And, fourth, climate-wise approaches must both be participatory and explicitly challenge the politics of knowledge production.

In this study, SOHO-V was adopted as a conceptual framework in the context of CSA. The merit of using SOHO-V lies at the conection (and interactions) between 'ecological-societal systems' and 'visioneering' via feedback loops (for details, see Kim *et al*., 2018). In the SOHO-V framework, stakeholders can identify 'a rice paddy' as 'ecological system', 'farmers/rural systems' as 'societal system', and 'CSA triad vision' as 'potential narratives (or scenarios)' in Fig. 2.1 (as shown in Fig. 4.2). This framework is theoretically and academically useful and insightful. And yet, it is practically difficult to apply SOHO-V in real life situation for prioritizing or decision making to resolve trade-offs and conflicts. Therefore, we propose a revised framework for ecological-societal systems, i.e., the upper portion of the SOHO-V framework. Here, societal systems are now included inside ecological systems in which the 21st century 'Doughnut Economics' theory is embedded along with 17 SDGs (Fig. 4.3) (Raworth, 2017).

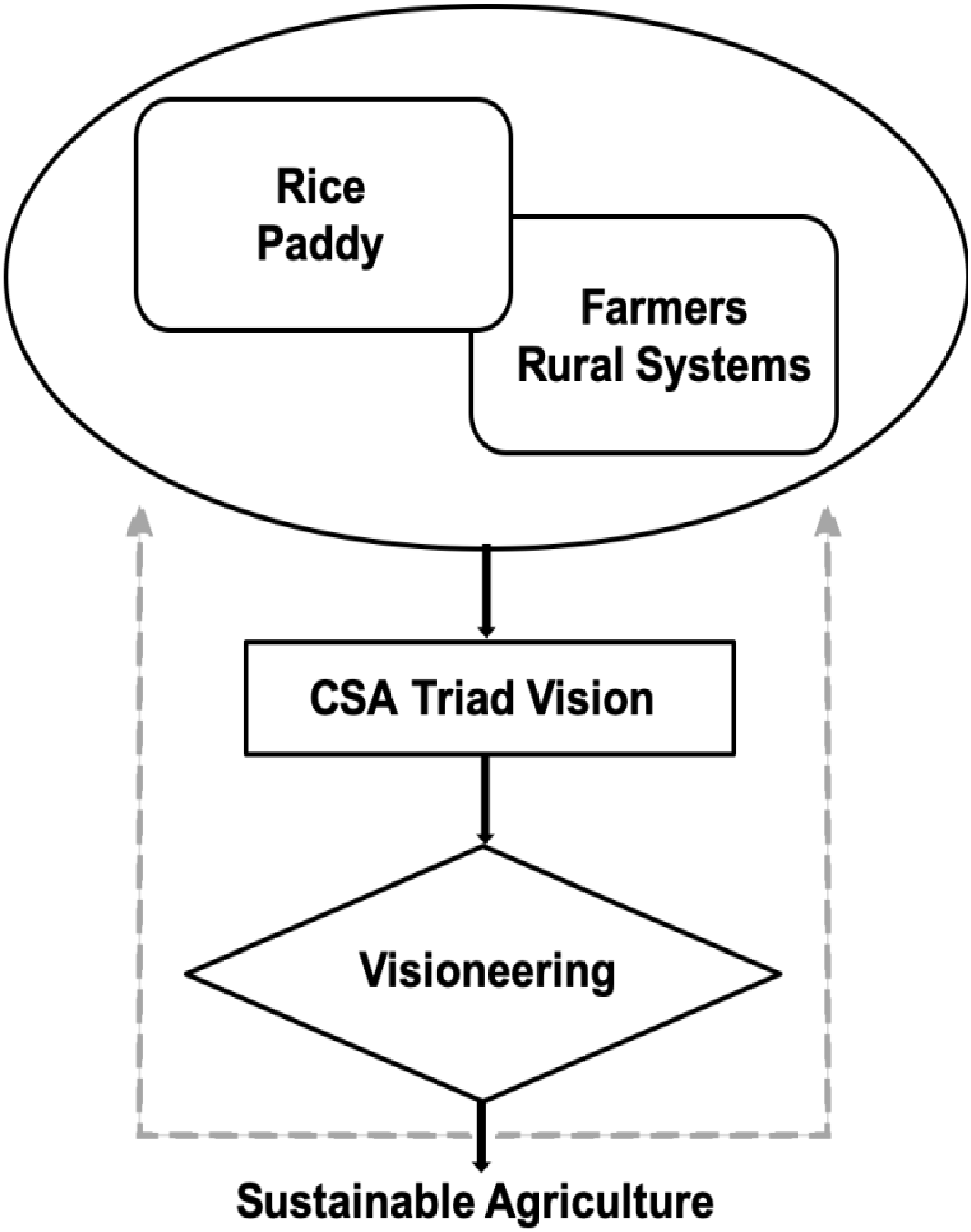

Figure 4.2 CSA triad vision applied to SOHO-V framework toward sustainable agriculture

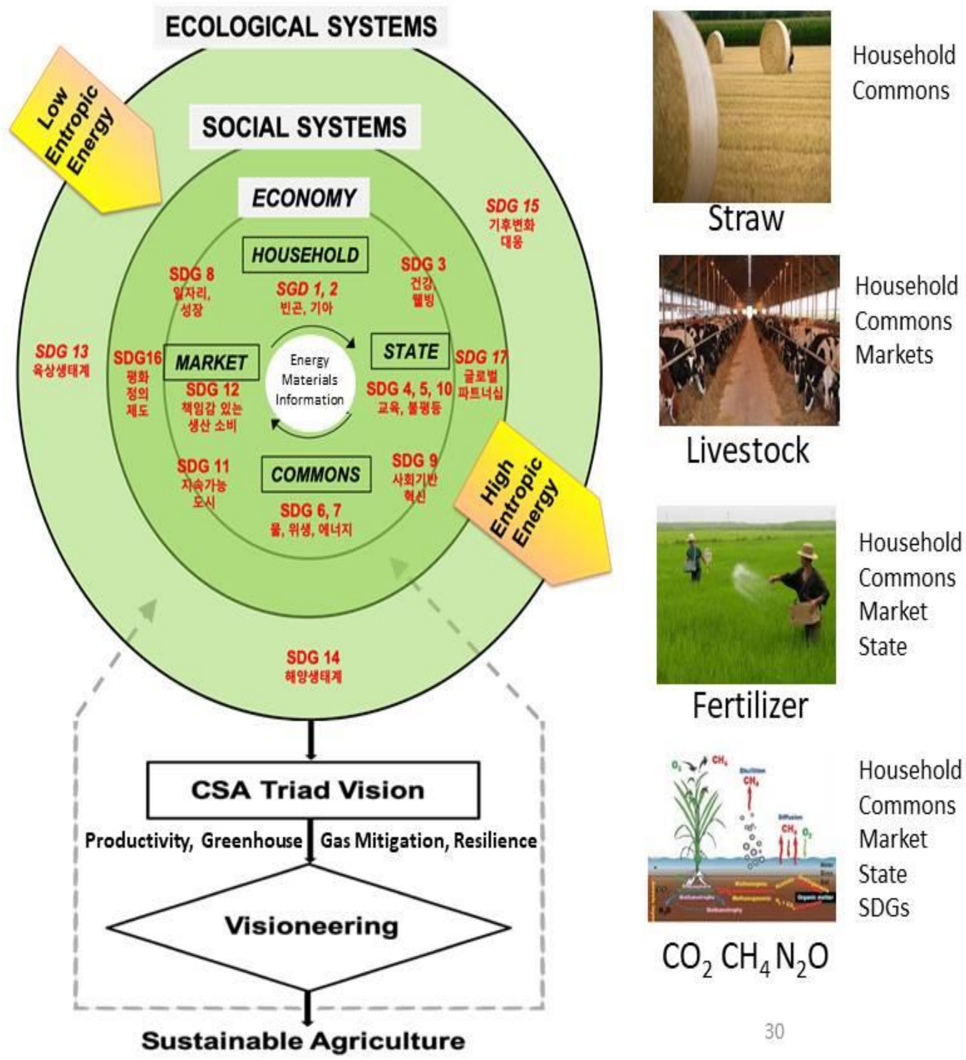

Figure 4.3 Ecological-Societal Systems (ESS) embedded with Doughnut Economics and 17 Sustainable Development Goals (SDGs).

As seen in Figs. 4.2 and 4.3, the newly proposed framework (i.e., economy embedded EES) is simpler yet practical so that it may be used in tandem with SOHO-V to help see a big picture (e.g., UN's SDGs) as well as to better address details (e.g., conficts and trade-offs in the pursuit of CSA triple-win). For example in Fig. 4.3, after rice harvest (SDG 2), farmers are supposed to return straws to their fileds to promote soil fertility as well as to store carbon in the soil for better management (SDG 13). Instead, livestock markets buy those straws to feed cows to produce meet product. In return, farmers get cash back. Such processes can be depicted in the new framework which has embedded the economy (consisting of household, market, commons, and state; see Fig. 4.3) and seem even circular and beneficial but they are not. Without straw, farmers have to apply more fertilizer to the soil, which produces more GHG. Moreover, cows' digestion of straws actually produces more emission of CH_4 which has much greater global warming potential than CO_2 (connected to SDG 15). And the rice and meet production become no longer responsible production and consumption (i.e., SDG 12). The new framework will help bring out more sustainable options that can be negotiated and reconciled through partnership among different players in economy and other stakeholders with different perspectives (i.e., SDG 17).

The revised conceptual framework would provide diverse stakeholders with opportunity to unifying the issues and options under one coherent vision - a healthy and sustainable world. We expect and hope that the proposed new framework, quantitative measurement and the exemplary CSA metrics from complex system perspectives would facilitate a paradigm shift in agriculture from 'climate-smart' to 'climate-wise' (e.g., Taylor, 2017).

5. SUMMARY AND CONCLUSIONS

This research has started with an overarching question, "How is a typical rice cultivation system in Korea keeping up with the triple challenge of climate-smart agriculture?" CSA is defined as agricultural practices that sustainably increase productivity and system resilience while reducing GHG emissions. It helps ensure that adaptation to and mitigation of climate change are properly incorporated into agricultural planning, development, and investment stargtegies with purpose-driven priorities. CSA has been promoted worldwide as the future of agriculture and a viable answer to many of the UN's sustainable development goals (SDGs).

This study is the first attempt to examining a typical rice cultivation system in Korea under the framework of CSA. The ultimate purpose of the study is to mobilize people and nation toward healthy and sustainable agriculture through the visioneering of CSA. Main objectives are (1) to select an archetypal rice cultivation system, (2) to adopt a conceptual model as a guiding framework for the CSA assessment based on complex systems approach, (3) to monitor the flows of energy, H_2O, CO_2, CH_4, N_2O, and information in and out of system, (4) to evaluate the indicators for productivity, resilience, and GHG mitigation, and finally (5) to assess how the progress is achieved on the triad goals of CSA.

First, 'self-organizing hierarchical open systems with visioneering (SOHO-V)' model was employed as a guide for strategic assessment of CSA's triple challenge. Then, as a representative study site, a Gimje rice paddy KoFlux site (GRK) was selected, which were managed by National Academy of Agricultural Science. At this GRK site, along with biometeorological measurement, fluxes of energy, GHG, and information were monitored using eddy covariance technique for the entire growing seasons in 2011, 2012 and 2014.

The indicators for the triad goals of CSA were selected as follows: (1) productivity: gross primary productivity (*GPP*), ecosystem respiration (*RE*), grain yield, light use efficiency (*LUE*), evapotranspiration (*ET*), water use efficiency (*WUE*), crop coefficient (*Kc*), and carbon uptake efficiency (*CUE*); (2) resilience: self-organization (*S*) for the processes of *GPP*, F_{CH4}, and *ET*; and (3) GHG mitigation: fluxes of carbon dioxide (F_{CO2}), methane (F_{CH4}) and nitrous oxide (F_{N2O}).

The data obtained from the three growing seasons provided a unique and wide range of environmental conditions to scrutinize the system state in the context of CSA. On average, length of the growing season (from June to October) was ~122 days, solar radiation (*Rs*) was 1,852 MJ m^{-2} $season^{-1}$, air temperature was 22.4°C, and *P* was 830 mm. *GPP* was on average 889 g C m^{-2}, *RE* was 565 g C m^{-2}, grain yield was 588 g m^{-2}, *LUE* was 1.94 g C MJ^{-1}, *WUE* was 1.97 g C kg H_2O^{-1}, *Kc* was 1.26, *CUE* was 1.58, F_{CO2} was 324 g C m^{-2}, F_{CH4} was 21.1 g C m^{-2}, F_{N2O} was 1.65 mg N_2O m^{-2}, and S_{AVG} (i.e., average of S_{GPP}, S_{FCH4}, and S_{ET}) was 0.40 (high resilience) with half-hourly time series and 0.09 (low resilience) with daily time series.

In terms of triad challenges of CSA, (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 low to high depending on the sampling rate of the time series but unable to assess due to the lack of quantitative data in the literature.

The key findings from the three individual growing seasons are summarized below:

(1) In 2011, despite having the lowest incoming solar radiation, 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*) and being least resilient (due to minimized self-organization;

(2) In 2012, despite receiving the greatest amount of precipitation, the mid-season drainage was effective because of the absence of *P* during the MSD period with greater *Rs*. The resulting aerobic soil conditions produced better mitigation of overall CH_4 emission. The concomitant increase in respiration (hence, reduced CO_2 uptake, F_{CO2}) resulted in the lowest productivity. However, enhanced self-organization (particularly in F_{CH4} process) increased the stability, thereby making the growing season of 2012 to be most resilient; and

(3) In 2014 being moderately resilient, higher *Rs* and the lowest *P* resulted in the highest grain yield and moderate *GPP* mainly due to the reduction in *RE* (as indicated by the lowest *LUE*). However, rainfalls during the MSD period maintained the soil moisture near saturation and nullified the drainage effect, resulting in 40% more CH_4 emission than in other years.

In conclusion, none of the three growing seasons examined in this study either achieved the CSA triple win within individual years or maintained the status during the three-years study period. Overall, the rice cultivation system at GRK was not fulfilling the CSA's triple challenge, particularly in the challenge of GHG mitigation and resilience building. The observed competing goals and trade-offs (among increasing productivity, building resilience and GHG mitigation) within individual years as well as between years caused clashes and difficulties in achieving seamless harmony under the triple-win scenarios in which conflicts of interest were not taken into account. Farmers in a pursuit of CSA must prioritize their goals by specific purpose-driven priorities, in which visioneering plays an essential role. The newly proposed conceptual framework, CSA metrics, and the insights learned from this study would help facilitate a paradigm shift in agriculture from "climate-smart' to 'climate-wise', in other words, from ‘being resilient’ to ‘becoming antifragile’ toward a global vision of healthy and sustainable agriculture.

6. SUGGESTIONS FOR FUTURE STUDY

1) The results of this study are limited to the past three years (i.e., 2011, 2012 and 2014) at one study site, and thus continuous monitoring is needed at this GRK site along with other sites under different conditions and management for futher investigation;

2) Self-organization (*S*, as resilience indicator) was assessed only for the three comprehensive processes associated with GHG gases (i.e., CO_2, CH_4, H_2O). More appropriate assessment of *S* is need for the whole system processes;

3) Future research should include the assessment for the entire year period for longer-term basis (e.g., decade-long) to consider whole cropping system (e.g., rotation of barley and rice cultivation at GRK);

4) The CSA metrics outlined in this study can be further improved with (1) thermodynamic analysis such as entropy accounting (e.g., Yang *et al*., 2020), (2) dynamic process network analysis (e.g., Yu *et al*., 2019), and (3) antifragility framework based on complex systems science (e.g., Equihua *et al.*, 2020);

5) Future research should focus on establishing the evidence based on holistic indicators, which can be used to develop protocols for provisioning incentives to promote practices and management towards CSA;

6) The lessons learned from this study are going to be applied to the agricultural sectors of Sylhet, Bangladesh by developing models of climate-smart villages in under-previliged rural areas. The center for trade-off analysis of climate-smart practices can be established under this flexible but comprehensive framework using geospatial and remote-sensing data combining with deep learning, IoT of smart farm technology for livelihood improvement as well as sustainable management of local ecological-societal systems; and

7) Education system would be transformed in Sylhet Agricultural University by promoting complex systems-based transdisciplinary education through the heuristic processes by achieving both IQ (Intelligence Quotient) and AQ (Adversity Quotient) from the visioneering of ecological-societal systems towards sustainability.

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APPENDIXES

A. 1 Physicochemical properties of soil at Gimje site

Properties	Value/type	Unit
Soil pH	4.9 to 5.3	-
Electrical conductivity	~0.74	ds m^{-1}
Total organic carbon	~1.69	%
Total nitrogen	~0.16	%
Cation exchange capacity	~17.17	%
Bulk density	~1.30	g cm^{-3}
Particle density	~2.57	g cm^{-3}
Soil porosity	~50	%
Soil texture	Silt loam	-

Soil sample tested from National Instrumentation Centre for Environmental Management (NICEM), Seoul National University

A.2 List of Instruments at Gimje tower flux measurement

Eddy Covariance measurement

Variables	Measurement height (m)	Instruments
Wind speed	5.2 m	3D sonic anemometer(CSAT3, Campbell Sci., Inc., USA)
Air temperature	5.2 m	3D sonic anemometer(CSAT3, Campbell Sci., Inc., USA)
Water vapor	5.2 m	Open path(LI-7500, Li-Cor, USA)
CO_2	5.2 m	Open path(LI-7500, Li-Cor, USA)
Sampling frequency	N/A	10 Hz
Averaging time	N/A	30 min
Data logger	N/A	CR3000 (Campbell, USA)
Data storage	N/A	HD
Original data	N/A	Statistics (Raw data is also available)

Meteorology

Variables	Measuring height (m)	Instruments
Global solar radiation(incoming)	2.0 m	Net radiometer (CNR1, Kipp & Zonen, Netherlands)
Global solar radiation (outgoing)	2.0 m	Net radiometer (CNR1, Kipp & Zonen, Netherlands)
Long-wave radiation(incoming)	2.0 m	Net radiometer (CNR1, Kipp & Zonen, Netherlands)
Long-wave radiation(outgoing)	2.0 m	Net radiometer (CNR1, Kipp & Zonen, Netherlands)
Net radiation	2.0 m	Net radiometer (CNR1, Kipp & Zonen, Netherlands)
Air temperature	3.25, 1.5 m	Temperature and RH probe (HMP45C, Vaisala, Finland)
Humidity	3.25, 1.5 m	Temperature and RH probe (HMP45C, Vaisala, Finland)
Soil temperature	0.1 m	Soil thermocouple probe (TCAV, Campbell Sci., Inc., USA)
Soil heat flux	0.1 m	Heat Flux plate (HFP-1, Campbell Sci., Inc., USA)
Soil water content	0.1 m	Water content reflectometer (CS-616, Campbell Sci. Inc., USA)
Wind speed	5.2 m	3D sonic anemometer (CSAT3, Campbell Sci., Inc., USA)
Wind direction	5.2 m	3D sonic anemometer (CSAT3, Campbell Sci., Inc., USA)
Barometric pressure	5.2 m	Open path infrared gas analyzer (LI-7500, Li-Cor, USA)
Precipitation	2.25 m	Tipping bucket rain gauge
CO_2 concentration	5.2 m	Open path infrared gas analyzer (LI-7500, Li-Cor Biogeosciences, USA)
H_2O concentration	5.2 m	Open path infrared gas analyzer (LI-7500, Li-Cor Biogeosciences, USA)
CH_4concentration	5.2 m	Open path laser spectroscopy gas analyzer (LI-7700, Li-Cor Biogeosciences, USA; instrument ownership: KRISS)

A. 3 Annual daily average temperature (°C)and total precipitation(mm) of surf 243 weater station in Buan (12.4 km south-east from the Gimje study site) during 1981-2010

Year	Daily average temperature (°C)	Total precipitation (mm)
1981	11.6	1297.1
1982	12.6	859.0
1983	12.6	1471.9
1984	12.1	1430.8
1985	12.4	1671.4
1986	11.7	1273.1
1987	12.1	1464.6
1988	12.3	705.6
1989	13.1	1222.4
1990	13.4	1111.5
1991	12.3	1077.6
1992	12.5	1039.1
1993	11.9	1341.8
1994	13.2	832.5
1995	12.3	838.5
1996	12.3	1030.3
1997	13.1	1302.0
1998	13.5	1600.9
1999	12.6	1358.8
2000	12.4	1231.6
2001	12.6	885.4
2002	12.9	1248.7
2003	12.8	1850.0
2004	13.2	1390.7
2005	12.2	1420.0
2006	13.6	1210.7
2007	14.0	2074.1
2008	13.4	881.5
2009	13.3	1136.1
2010	12.8	1253.6
Average	12.7	1250.4
Standard Deviation	0.6	308.6
Coefficient of Variation (%)	4.7	24.7

A. 4 Monthlydaily average temperature (°C) of surf 243 weater station in Buan (12.4 km South-East from the Gimje study site) during 1981-2010

Month/Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1981	-5.0	-0.3	5.7	10.8	16.6	21.1	25.9	24.5	19.4	13.5	4.7	1.0
1982	-1.5	0.4	5.3	10.7	18.4	21.0	24.2	25.5	19.8	15.2	9.2	2.2
1983	-0.8	-0.9	6.3	12.7	17.1	21.2	24.2	25.8	22.1	14.6	7.4	0.5
1984	-3.3	-2.1	3.2	11.4	17.2	22.0	25.2	26.8	20.3	14.2	8.2	1.2
1985	-3.3	1.2	4.2	11.3	17.8	21.2	25.3	26.5	21.1	15.0	7.9	-0.8
1986	-3.2	-1.4	4.7	11.0	16.1	21.5	23.9	25.2	19.3	12.9	6.4	3.2
1987	-0.6	1.5	3.9	9.9	15.9	21.1	23.6	24.7	19.2	14.8	8.0	2.3
1988	0.1	-0.7	3.5	10.1	16.7	21.3	25.6	25.6	21.2	15.2	6.8	1.9
1989	1.7	3.2	6.2	12.7	17.2	20.5	24.5	25.2	20.6	13.6	7.9	3.0
1990	-0.7	3.0	6.7	11.0	16.4	21.8	25.8	26.4	21.6	14.6	10.5	3.0
1991	-0.1	0.1	4.8	11.0	16.7	21.5	24.7	24.3	20.6	13.6	6.8	3.3
1992	1.2	1.1	6.5	11.0	15.5	20.0	25.0	24.9	20.6	13.9	7.1	3.1
1993	-1.1	1.9	5.1	10.4	16.5	20.5	22.9	22.6	20.3	13.1	8.7	1.7
1994	-0.4	0.9	3.7	13.0	17.3	20.6	28.1	27.0	20.5	14.9	9.5	2.7
1995	-0.5	1.0	6.1	9.8	16.1	20.9	24.8	26.7	19.7	14.7	7.0	0.2
1996	-0.6	-0.7	4.3	8.7	15.8	20.7	24.5	25.9	21.8	15.6	9.1	2.1
1997	-1.2	1.4	6.3	12.0	18.3	22.5	24.9	25.9	20.2	13.9	9.4	2.7
1998	0.0	3.7	6.4	14.4	17.2	20.6	25.0	25.3	21.8	16.0	8.3	2.9
1999	0.5	1.7	6.0	11.1	15.1	19.8	24.5	25.1	22.5	14.0	8.3	1.5
2000	-0.4	-0.6	4.9	10.5	15.6	20.6	25.4	25.6	19.5	15.1	8.4	3.5

Month/Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2001	0.3	2.8	5.1	11.0	16.8	20.7	25.3	25.1	20.3	14.8	7.3	1.4
2002	2.6	1.9	7.2	13.2	16.5	21.4	25.1	24.5	20.7	13.3	5.5	2.6
2003	-1.7	2.3	5.5	11.6	17.6	21.0	23.4	24.7	21.9	14.4	10.4	2.3
2004	-1.3	2.7	5.4	11.1	16.5	21.6	25.7	26.3	22.0	15.1	10.0	3.6
2005	-0.9	-0.8	3.8	12.4	16.2	21.6	24.9	25.2	21.9	14.1	9.2	-1.8
2006	1.3	1.6	5.9	11.2	17.7	22.0	24.8	27.3	20.4	17.4	10.1	3.0
2007	1.6	4.6	7.3	11.4	18.4	22.5	24.9	27.2	22.0	15.5	7.9	3.7
2008	-0.2	-0.4	6.6	12.2	17.3	21.3	26.3	25.6	22.8	16.4	8.9	3.2
2009	-0.2	3.7	6.6	11.5	17.9	22.2	24.5	25.5	21.5	16.4	8.8	1.2
2010	-1.3	2.5	5.5	9.1	16.7	21.9	25.7	27.2	22.6	14.3	7.7	1.6
Average	-0.6	1.2	5.4	11.3	16.8	21.2	24.9	25.6	20.9	14.7	8.2	2.1
Standard deviation	1.6	1.7	1.1	1.2	0.9	0.7	1.0	1.0	1.0	1.0	1.4	1.3
Coefficient of Variation (%)	-255	143	21	11	5	3	4	4	5	7	17	63

A. 5 Monthly total precipitation (mm) of surf 243 weather station in Buan (12.4 km south-east from the Ginje study site) during 1981-2010

Month/Year	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec
1981	32.7	36.3	11.2	54.9	38	89.8	396	356.6	156.3	79.2	22.9	23.2
1982	26.5	11	80.4	52.4	140.7	23	150.1	116.1	8.1	43.9	149.2	57.6
1983	28.9	62.7	95.2	132.4	68.5	165.6	287.8	387.8	131.2	40.7	49.7	21.4
1984	16.2	20.8	10.5	145.8	93.4	171.3	276.3	155.2	409	48.6	44.4	39.3
1985	14.9	38.6	91.5	66.3	95.7	126.6	352.1	276.8	290.2	126	147.9	44.8
1986	26.2	21.7	51.7	38.3	205.7	218	173	222	124.4	87.9	36.3	67.9
1987	61.7	43	36.1	62.5	68.2	129.8	432.1	437.6	24.2	93.8	72.1	3.5
1988	19	7.3	41	58.3	80.9	40.5	236.1	83.3	46.9	1.8	45.5	45
1989	106.1	68	69.2	41.5	24.6	177.1	250.5	144.8	245.4	18.4	67	9.8
1990	32.9	78.1	53.8	74	77.7	236.4	270.8	136.2	85.5	3.6	38.1	24.4
1991	20.9	49.7	80.4	69.5	49.9	166.9	257.6	97.4	209	22.2	20.1	34
1992	7.6	27.3	51.1	96.7	64.9	8	251.9	184.5	228.5	13.5	68.4	36.7
1993	26.5	76.1	34	25.9	89	265.4	317	281	69.5	30	99	28.4
1994	37.6	12.7	36.5	32.5	127.5	131.5	36.8	217	42	117.5	10	30.9
1995	38	27.2	23.5	83	55	42.5	136	346.5	33.5	14	16.7	22.6
1996	29.1	10	69	34.2	29	333	183	85.5	18	82	92.6	64.9
1997	21.3	43.7	50.5	63	123.5	137.5	418	187.5	10	18.5	174.5	54
1998	50.6	28.8	39.5	122.5	117.5	308	241.5	224.4	351.5	81	32.9	2.7
1999	28.9	31.7	82.5	85	95	189.5	174.2	199.5	284.5	133	15.5	39.5
2000	33.6	9.5	13.5	33.5	29.5	134	201	448	233	34	44	18

Month/Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2001	85.7	91	16.2	27	16.5	208	161	86	36	107	19	32
2002	62.7	11.5	41	137.5	134	63.5	187.5	380.5	47	62	55.5	66
2003	51.8	43.6	51	252.5	147.5	158.5	563	307.5	167.5	44	44	19.1
2004	20.5	32.9	16.7	73.5	97	272.5	266.5	269	199.5	7.5	85.5	47.3
2005	6.7	46.8	43.5	47	65	113.5	468.5	363	154	18	25.5	68.5
2006	27	27	12.4	104	142.5	142.5	484	88.5	31	47.5	57.5	46.8
2007	14.5	64.7	99.4	41	72.5	116	274	582	677	65.5	12.5	55
2008	37.8	5.4	48.6	41.1	109.5	196.5	107.7	208.3	29.5	26.5	37.5	27.1
2009	29	30.6	49.5	28.4	97.9	111.5	462.7	162	55	24	24.1	61.4
2010	34.7	93.1	68.5	79.1	119	21.8	266.6	362.6	116.5	32.3	11.7	47.7
Average	34.3	38.4	48.9	73.4	89.2	150.0	276.1	246.6	150.5	50.8	54.0	38.0
Standard deviation	21.7	25.1	26.2	47.9	43.1	83.2	124.0	128.2	147.9	38.1	42.6	18.9
Coefficient of Variation (%)	63	65	54	65	48	55	45	52	98	75	79	50

초록

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

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세계식량기구(Food and Agriculture Organization, FAO)는 기아종식을 위해 삼중도전, 즉 (1) 생산성과 농가 소득을 지속적으로 증가시키고, (2) 기후변화에 대한 회복력을 갖추면서, (3) 온실가스의 배출을 완화시키는 기후스마트농업 (Climate-Smart Agriculture, CSA)에 도전하고 있다. 유엔의 17 개 지속가능발전목표 (sustainable development goals, SDG)의 SDG1(빈곤퇴치), SDG2(기아종식), SDG12 (책임감 있는 소비와 생산), SDG13(기후변화 대응), SDG15(육상생태계)와 연결되는 이러한 노력은 코로나 19 팬데믹으로 인해 그 중요성과 시급성이 더욱 부각되고 있다. 그러나 전체적인 맥락을 볼 수 있는 적절한 개념적 틀과 총체적 지표 및 정량적인 측정 자료의 결핍이 농민, 연구자 및 정책입안자가 CSA 의 진행 상황을 파악하고 그 효과를 정량적으로 평가하는데 걸림돌이 되고 있다.

본 연구에서는 '한국의 전형적인 벼 경작 시스템이 CSA 의 삼중 도전에 어떻게 부합하고 있는가?'라는 질문에 답하기 위해, (1) 복잡계사고 기반의 '자기-조직화하는 계층구조의 열린 시스템과 비전의 엔지니어링이 연결(Self-Organizing, Hierarchical, Open systems with Visioneering, SOHO-V)된 개념 모델을 채택하고, (2) 벼 경작 시스템의 에너지, 물, 탄소 및 정보의 흐름을 직접 관측하였고, (3)

생산성/효율성, 온실가스 방출/흡수 및 회복력을 평가할 수 있는 다양한 측정 수단(metrics)을 사용하여 기후스마트농업의 관점에서 평가하였다.

연구 장소로서 국내 플럭스 관측망인 KoFlux 관측지의 하나인 김제의 대표적인 벼 경작 시스템을 선택하였다. 3 년간(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*), 작물계수(*Kc*) 및 탄소흡수효율(*CUE*) 지표를 사용하였다. 온실가스 정량화를 위해서는, 이산화탄소 플럭스(F_{CO2})와 메탄 플럭스(F_{CH4})의 경우 직접 관측한 자료를 사용하였고, 아산화질소 플럭스(F_{N2O})는 IPCC 지침에 따라 간접적으로 산출한 자료를 사용하였다. 회복력 평가를 위해서는 자기-조직화(self-organization, *S*) 지표를 사용하였으며, 벼 경작 시스템에서 가장 포괄적인 세 과정(총일차생산, 메탄 플럭스, 그리고 증발산)을 대상으로 정보이론을 사용하여 정량화 하였다. 3 년간의 생육기간으로부터 관측된 자료는 CSA 평가에 필요한 넓은 범위의 다양한 환경 조건과 시스템 상태를 제공하였다.

3 년간의 모니터링에서 얻은 생육기간 평균을 살펴보면, 생육기간은 ~122 일, 총일사량(*Rs*)은 1,852 MJ m^{-2}, 기온은 22.4°C, 총강수량(*P*)은 830 mm 였다. *GPP* 는 889 g C m^{-2}, *RE* 는 565 g C m^{-2}, 곡물수확량은 588 g m^{-2}, *LUE* 는 1.94 g C MJ^{-1}, *WUE* 는 1.97 g C kg $H2O^{-1}$, *Kc* 는 1.26, *CUE* 는 1.58, F_{CO2}는 324 g C m^{-2}, F_{CH4}는 21.1 g C m^{-2}, F_{N2O} 는 0.165 g N_2O m^{-2}, 그리고 *S* 는 30 분 단위 시계열 자료를 사용했을 경우에 0.40, 일(24 시간) 단위 시계열 자료를 사용하였을 경우에 0.09 이었다. 이러한 김제 벼 경작 시스템의 결과는, 대략 평균 이하의 범위를 보인 온실가스 F_{CO2} , F_{CH4} 및 F_{N2O} 를 제외하면, 전반적으로 선행연구에서 보고된 값들의 중-상위의 범위에 속하였다. 각 당해년도 생육기간의 주요 결과를 요약하면 다음과 같다:

(1) 2011 년의 경우, 일사량이 가장 낮았음에도 불구하고, 빛을 효율적으로 사용하여 다른 두 해보다 더 높은 생산성을 보여 탄소 흡수량이 가장 높았고, 메탄 방출량은 낮았다. 그러나 그 대가로 물 사용 효율이 다른 두 해보다 낮았고, 자기-조직화가 최소화되어 변화에 더 민감하게 반응하면서 회복력은 3 년 중에서 가장 낮았다;

(2) 2012 년의 경우, 강수량이 가장 많았으나 중간 물떼기(MSD) 기간 동안 강수가 발생하지 않았고 일사량이 높아 배수가 효과적이었다. 그 결과 호기성 토양이 메탄을 산화시켜 배출을 전반적으로 완화시켰다. 이에 수반되는 생태계 호흡 증가로 이산화탄소 흡수가 감소하여 생산성이 가장 낮았다. 반면 자기-조직화가 활성화되면서 3 년 중에서 회복력이 가장 높았다;

(3) 2014 년은 일사량이 높았고 가장 적은 강수량으로 인해 빛 사용 효율이 낮았으나, 생태계 호흡의 감소로 인해 곡물 수확량과 GPP 가 높았다. 그러나 MSD 기간 동안에 강수가 발생하여 중간 물떼기 효과가 최소화 되어, 다른 두 해보다 40% 더 많은 메탄을 배출하였다. 회복력은 다른 두 해의 중간 수준이었다;

(4) 3 년 자료의 연간 비교에서 뿐만 아니라 각 개별 연도 내에서도 나타난 CSA 의 세 목표 간 경쟁과 대립 관계가 (애초부터 이러한 이해 상충은 없다고 가정한) CSA 삼중 도전 시나리오에서 충돌을 야기하고 원활한 조화를 이끌어 내는데 어려움이 있음을 보여 주였다.

결론적으로, 본 연구에서 평가한 3 년 간의 생육 기간 중 기후스마트농업의 삼중 목표를 모두 성취한 경우는 단 한 해도 없었으며, 특정 해에 성취된 목표도 연구기간 동안 지속적으로 유지되지 않고 다양한 변화를 보였다. 또한, 3 년 간의 생육기간을 평균한 CSA 지표의 경우, 생산성에 관련된 지표들은 문헌에 보고된

다른 연구 결과와 비교할 때 대부분 중-상위의 범위에 속했으나, 온실가스 완화와 회복력 관련 지표들을 평균 이하였다. 따라서 김제의 벼 경작 시스템은 3 년의 연구기간 동안 기후스마트농업의 삼중 도전에 부합하지 못한 것으로 나타났다. 이러한 연구 결과는 기후스마트농업을 추구할 때 다양한 이해관계자가 비전의 엔지니어링을 통해 시작부터 명확한 목적에 따라 목표의 우선순위를 정하고 CSA 지표들을 지속적으로 모니터링하여 관리에 반영하여 함을 시사한다.

본 연구에서 사용한 개념적 틀인 SOHO-V 는 생태-사회시스템의 복잡한 상호작용을 학문적으로 이해하는 데는 유용하지만, 지속가능성을 지향하는 CSA 비전의 우선 순위를 실제로 적용하는 데에는 사용하기가 어려운 구조이다. 따라서 본 연구에서는 21 세기 '도넛 경제학' 이론과 UN 의 17 개 SDGs 를 함께 내재 시킴으로써 보다 개선된 개념적 틀을 제시하였다. 이 새로운 틀은 다양한 이해관계자들이 ‘건강하고 지속가능한 세상’이라는 하나의 일관된 비전 안에서 문제와 선택사양을 통합할 수 있도록 도울 것이다. 이러한 틀과 총체적인 CSA 측정 수단과 코로나 19 팬데믹으로부터 배운 교훈이 ‘기후스마트’에서 '기후와이즈 (climate-wise)’ 농업으로의 패러다임 전환, 즉 ‘회복력’을 지향하는 현재의 농업을 뛰어 넘어, 충격과 불확실성을 오히려 더 나은 성장과 발전으로 이끄는 복잡성 기반의 ‘반취약(antifragility)’ 농업으로의 변혁을 가져오길 희망한다.

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