Estimation of methane emission from rice paddy soils in Japan using the diagnostic ecosystem model

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Abstract

It is needed to accurately evaluate the methane emission from paddy fields at a national scale for both scientific and political purposes. The existing approaches have shared a common issue with obtaining the realistic information on spatiotemporal variations of crop management. Satellite sensor could possibly detect them, but the methodology to link the satellite observations to the methane emission has not been established. In this study, we enhanced the existing diagnostic satellite-driven paddy ecosystem model, the Biosphere model integrating Eco-physiological And Mechanistic approaches using satellite data for regional Cropland (BEAMS-C) (Sasai et al., 2012), by integrating the methane processes and examined the potential of this approach by comparing the estimated nation-wide methane emission with that by the existing approaches. The carbon flux estimations had good agreements with the measurements at the Mase paddy flux site. In regional-scale analyses in Japan, methane emission averaged from 2001 to 2010 was 15.0 gC m⁻² year⁻¹, which was similar to the Tire-1 and -2 results. If we have a continuing improvement of the diagnostic approach, it could be one of the most efficient tools for estimating the methane flux at national scales.

Key words: Carbon cycle, Diagnostic ecosystem model, Methane, Remote sensing, Rice paddy

1. Introduction

A paddy field is a greenhouse gas source in global warming, and especially plays a role of methane source (IPCC AR4, 2007). Methane is produced by the anaerobic soil during the irrigation period (Aulakh et al., 2001; Han et al., 2005; Nishimura et al., 2008), and emitted to the atmosphere via a rice plant and paddy water (Butterbach-Bahl et al., 1997; Jia et al., 2001). The methane emission from paddy fields accounts for 27% of the whole anthropogenic methane emission in the world (Yasuf et al., 2012). Therefore, it is needed to estimate the methane emission at a national scale for both scientific and political purposes.

To estimate the methane emission from paddy fields at national scales, IPCC AR4 (2007) proposed the Tier 1 method (Tier-1) as an efficient method in the guidelines for national greenhouse gas inventories. Tier-1 was derived from emission and scaling factors based on rough inventory, and can be adopted to any country which has little information about rice cultivation (Yan et al., 2009). For Japan, the Greenhouse Gas Inventory Office of Japan (GIO) report (2009) adopted the revised Tier-1 method more fit to rice paddy (Tier-2). However, Tier-1 and -2 were developed without a temporal change of soil water, the effect of meteorology and rice plant dynamics (e.g., photosynthesis, autotrophic respiration, phenology), so the estimation do not always reflect actual ecosystem feature along with agricultural activities. And, there are several paddy models for estimating the plant-mediated methane emission (e.g., Li et al., 2004; Ito and Inatomi, 2012). Since the process-based models especially have the versatility of the spatial and temporal calculation, they are one of the efficient tools for the national scale estimation. However, the existing studies suggest that the model have necessarily simulated different results from the actual emission by averaging parameters associated with the crop calendar (e.g., Bodegom et al., 2000).

The existing approaches have shared a common issue of obtaining a spatial information of crop management, which is essentially determined by each farmers depending on the climate, rice growth, and other conditions (Bachelet and Neue, 1993); each region and each paddy field have their own characteristics in agricultural practices in response to several agrometeorological conditions. The regional-scale database relevant to soil profile, climate, and agricultural practices needs to be constructed (Cao et al., 1995; Fumoto et al., 2010), but there is no means to sufficiently collect information emerging from farmers. To this end, we propose the use of a satellite-driven approach that simulates the ecosystem carbon and water processes by using satellite observations in a diagnostic model. A satellite sensor can detect some spatial parameters for the crop management of paddy fields (e.g., irrigation water and rice biomass) (e.g., Kim et al., 2014; Zhang et al., 2016), and the satellite products will be created as time-series datasets in the future. Moreover, if directly linking such satellite products to agricultural processes, we might overcome the common challenge of obtaining realistic information of paddy field conditions. It strongly motivates us to positively have a continuing need to develop such diagnostic approach for the realistic methane emission estimate.
We improved the existing diagnostic ecosystem model for estimating the methane emission from paddy fields. The improved point is the introduction of the ecosystem methane process, which is linked to the temporal change of the plant biomass and crop management. The model estimation was validated at the Mase paddy flux site (MSE), and applied to paddy field over Japan from 2001 to 2010.

2. Model Description for methane process

We used the model (Biome model integrating Ecophysiological And Mechanistic approaches using Satellite data for regional Cropland, BEAMS-C), which has been validated for regional and nation-wide rice production in Japan (Sasai et al., 2012). Since the original BEAMS-C consists of only CO2-related processes, we introduced the methane process related to seasonal change of the rice biomass compartments and crop management into BEAMS-C to calculate the methane flux (Fig. 1). The three major methane processes are (1) methane production in the anaerobic soil by methanogens, (2) methane oxidation by the methanotrophs, and (3) the three pathways for methane emission. The balances of the soil organic matter (CSOM) and soil methane (CCH4soil) (gC m⁻²) pools are given by

\[ \frac{dC_{\text{CSOM}}}{dt} = LF - \text{SD} - CH_{\text{pro}} \]  \hspace{1cm} (1)

\[ \frac{dC_{\text{CCH4soil}}}{dt} = CH_{\text{pro}} - (CH_{\text{anaer}} + CH_{\text{oxy}} + E_{\text{CH4}}) \] \hspace{1cm} (2)

where \( LF \) is the litter fall including straw composting and stubble plowing (gC m⁻² day⁻¹), \( SD \) is the aerobic decomposition (gC m⁻² day⁻¹), \( CH_{\text{pro}} \) is the methane production rate under an anaerobic soil (gC m⁻² day⁻¹), and \( CH_{\text{anaer}} \) and \( CH_{\text{oxy}} \) are the methane oxidation rates in rhizosphere and the soil surface layer where oxygen is transported from the atmosphere, respectively (gC m⁻² day⁻¹). \( E_{\text{CH4}} \) is the total methane emission from paddy field (gC m⁻² day⁻¹).

2.1. Methane production

A methane in anaerobic soils is produced from simple carbon substrates by methanogens. \( CH_{\text{pro}} \) is calculated from the methane production (gC m⁻² day⁻¹) from the rice plant biomass (\( CH_{\text{BPS}} \)) and from the soil organic matter (\( CH_{\text{soil}} \)) (Huang et al., 1998, 2004) \( CH_{\text{pro}} = CH_{\text{BPS}} + CH_{\text{soil}} \). Each production rate is given by

\[ CH_{\text{BPS}} = 0.27 \times F_{\text{EB}} \times Q_{\text{ir}}^{(\text{Tot} + 25.0)} / 10.0 \times C_{\text{EB}} \] \hspace{1cm} (3)

\[ CH_{\text{soil}} = 0.27 \times F_{\text{EB}} \times Q_{\text{ir}}^{(\text{Tot} - 25.0)} / 10.0 \times C_{\text{OM}} \] \hspace{1cm} (4)

where \( F_{\text{EB}} \) is the factor of soil redox potential on methane production, \( Q_{\text{ir}} \) is a temperature coefficient (=4.6 by Fumoto et al., 2008), \( T_{\text{soil}} \) is the soil temperature of the first layer (°C), \( C_{\text{EB}} \) is the biomass-derived carbon substrate (gC m⁻² day⁻¹), and \( C_{\text{OM}} \) is the soil-derived carbon substrate (gC m⁻² day⁻¹). We calculated methane production rate with the value of soil redox potential \( E_{\text{h}} \) (mV) (Zhang et al., 2002a). The negative and positive values of \( E_{\text{h}} \) mean anaerobic and aerobic condition, respectively (Han et al., 2005).

\begin{align*}
\text{If } W_{\text{p(t)}} &< 0.0
E_{\text{h}_{\text{(t)}}} &= E_{\text{h}_{\text{(t-1)}}} - D_{\text{h}} \times (A_{\text{h}} + \text{min}(1.0, C_{\text{EB}})) \times (E_{\text{h}_{\text{(t-1)}}} + 250.0), \hspace{1cm} (5) \\
\text{else}
E_{\text{h}_{\text{(t)}}} &= E_{\text{h}_{\text{(t-1)}}} - D_{\text{h}} \times (A_{\text{h}} + 0.7) \times (E_{\text{h}_{\text{(t-1)}}} - 300.0) \text{when } W_{\text{p(t)}} = 0.0 \hspace{1cm} (6)
\end{align*}

where \( E_{\text{h}_{\text{(t)}}} \) is the soil \( E_{\text{h}} \) value at time \( t \) (mV), \( A_{\text{h}} \) and \( D_{\text{h}} \) are constant parameters (= 0.23 and 0.16), and \( W_{\text{p(t)}} \) is the water depth of the paddy field at time \( t \) (mm). \( F_{\text{EB}} \) is given by;

\[ F_{\text{EB}} = \exp(-1.7 \times (150.0 + E_{\text{h}})/150.0) \] \hspace{1cm} (7)

The part of the photosynthetically fixed carbon exuded from roots (\( C_{\text{r}} \)) is given by following equations (Huang et al., 2004).

\[ C_{\text{r}} = \alpha \times vi \times s_{i} \times C_{\text{above}} \beta_{i} \] \hspace{1cm} (8)

where \( \alpha \) is a turnover rate of the root exudation (=1.8 \times 10⁻³ day⁻¹), \( vi \) is a specific parameter of methane production defined for each rice variety, \( s_{i} \) is a parameter of soil property, \( \beta_{i} \) is an empirical parameter (=1.25), and \( C_{\text{above}} \) is rice aboveground biomass (gC m⁻²). \( s_{i} \) is given by

\[ s_{i} = \frac{1}{\phi_{i}} \times \frac{1}{\beta_{i}} \times \frac{1}{\alpha_{i}} \]

\[ \phi_{i} = \frac{\text{area}}{\text{depth}} \times \text{density} \times \text{water content} \times \text{~} \]

\[ \beta_{i} = \frac{\text{redox potential}}{\text{temperature}} \times \text{~} \]

\[ \alpha_{i} = \frac{\text{nitrogen content}}{\text{~}} \]
si = 0.325 + 0.0225 × SAND,  

where $SAND$ is a sand percentage in the soil. $C_{\text{CH}_4}$ is the part of soil organic carbon decomposed by soil microbial activity.  

\[
C_{\text{CH}_4} = k \times \Sigma_{a} \times w_{i} \times Q_{10}^{(\text{T} - 25.0)/10.0},
\]

where $k$ is a turnover rate of the soil decomposition (day$^{-1}$), and $w_{i}$ is a parameter depends on soil water content. $Q_{10}$ value for soil decomposition is 3.0 (Huang et al., 2004).

### 2.2. Oxidation

A part of produced methane is oxidized by methanotrophs, and emitted as CO$_2$. $CH_{4,\text{oxir}}$ and $CH_{4,\text{oxis}}$ are calculated by (Walter and Heimann, 2000; Zhang et al., 2002b):

\[
CH_{4,\text{oxir}} = C_{\text{CH}_4\text{atm}} \times (0.5 + 0.5 \times C_{\text{root}} / 1000.0),
\]

\[
CH_{4,\text{oxis}} = (V_{\text{max}} \times C_{\text{CH}_4\text{atm}}) / (K_{m} + C_{\text{CH}_4\text{atm}}) \times Q_{10}^{(\text{T} - 25.0)/10.0},
\]

where $C_{\text{root}}$ is the root biomass (g C m$^{-2}$), $V_{\text{max}}$ is the maximum oxidation rate (=5.76 g C m$^{-2}$ day$^{-1}$), and $K_{m}$ is the Michaelis-Menten coefficient (=0.06 g C m$^{-3}$). $Q_{10}$ value for methane oxidation is 2.0 (Fumoto et al., 2008).

### 2.3. Methane emission

The total methane emission ($E_{\text{CH}_4}$) process consists of three pathways from soil to atmosphere, (1) transport via rice plants ($E_{\text{plant}}$, g C m$^{-2}$ day$^{-1}$); (2) bubble ebullition ($E_{\text{bubble}}$, g C m$^{-2}$ day$^{-1}$); and (3) molecular diffusion through the paddy water ($E_{\text{diffusion}}$, g C m$^{-2}$ day$^{-1}$). Walter and Heimann (2000)'s approach was applied to calculate $E_{\text{CH}_4}$ ($=E_{\text{plant}} + E_{\text{bubble}} + E_{\text{diffusion}}$). At first, $E_{\text{plant}}$ is given by

\[
E_{\text{plant}} = k_{p} \times f_{p} \times f_{\text{root}} \times LAI \times C_{\text{CH}_4\text{atm}},
\]

where $k_{p}$ is the turnover rate of the methane emission via rice plant (=0.03 day$^{-1}$), $f_{p}$ is a factor of methane emission defined for each paddy type (=15.0), $f_{\text{root}}$ is a distribution factor of rice root in the soil, and LAI is the leaf area index (m$^{2}$ m$^{-2}$). $E_{\text{bubble}}$ is given by

\[
E_{\text{bubble}} = k_{b} \times (C_{\text{CH}_4\text{atm}} - C_{\text{chreac}}),
\]

where $k_{b}$ is a turnover rate of the methane emission as bubble (=1.0 g C m$^{-2}$ day$^{-1}$), and $C_{\text{chreac}}$ is the dissolved methane threshold at which methane bubble formation occurs (=6.0 g C m$^{-3}$). $E_{\text{diffusion}}$ is given by

\[
E_{\text{diffusion}} = (C_{\text{CH}_4\text{atm}} - C_{\text{CH}_4\text{soil}}) \times f_{\text{diff}} \times f_{\text{root}} \times P_{\text{soil}},
\]

where $C_{\text{CH}_4\text{atm}}$ is the atmospheric methane concentration (=1.0 $\times$ 10$^{-3}$ g C m$^{-3}$), $f_{\text{diff}}$ is a diffusion coefficient of methane (=1.73 $\times$ 10$^{-4}$ m$^{2}$ day$^{-1}$), $f_{\text{root}}$ is a tortuosity coefficient of the soil (=0.66), and $P_{\text{soil}}$ is the soil porosity defined for each soil type (mm mm$^{-3}$).

### 3. Model Validation

We validated the model estimation at the Mase (MSE) site, a AsiaFlux flux station (36°03′14.3″N, 140°01′36.9″E, 15 m a.s.l.). The paddy field of MSE is managed as a single cropping of rice (Oryza Sativa, cv Koshihikari); the mean flood water depth is around 30 mm; rice straw is sprayed over the field at harvest and then incorporated therein; rice cultivar is Koshihikari; the crop calendar was accurately recorded (Table 1) (Miyata et al., 2005; Saito et al., 2005). Methane and CO$_2$ fluxes were measured by flux gradient and eddy covariance techniques, respectively (Han et al., 2005, 2007). Atmospheric methane concentration was measured at 2.5-min intervals using a flame ionization detector gas analyzer (FIA-510/APHA-360, Horiba, Kyoto, Japan), and aggregated to 10-min mean profiles. The periods of methane and CO$_2$ validation are from January 2002 to December 2005 and January 2001 to December 2005, respectively. The model inputs are meteorological and phenological parameters that we observed with carbon and water fluxes at MSE. All flux and meteorological observations were converted to monthly interval data to validate the monthly-step BEAMS-C model.

The crop calendar-induced seasonal change in the methane emission, Gross Primary Production (GPP), and Net Ecosystem Production (NEP) had good agreements with the measurements (Fig. 2). GPP was zero after the stubble plowing, and started to increase from following year's transplant, because no rice plants existed in the field during the fallow period. NEP at harvest month was very low because all leaf biomass and the part of stem biomass fell as litter and soil organic carbon increased. Therefore, soil decomposition increased drastically and NEP decreased. The improved model accurately demonstrated the effect of agricultural practices on seasonal and annual patterns of each carbon fluxes; the methane emission in 2002 was lower than that in 2003, while GPP was higher. The model analysis indicates that the reason was the shorter irrigation period of 2002 than that of 2003 (87 days and 100 days, respectively). Methane is produced only during the irrigation period because methanogens are the obligatory anaerobic bacteria. Although much carbon substrates existed due to active photosynthesis, the methane production was restricted in 2002.

### 4. Regional analyses

By using satellite dataset (e.g., MODIS, ASTER, SRTM products) (Table 2) and simulating the 1-km-grid carbon cycle with monthly step, we estimated the spatial and temporal patterns

![Fig. 2. Comparisons of methane emission (a), GPP (b), and NEP (c) between the measurement and estimations of BEAMS-C.](image-url)
in methane and CO₂ fluxes in Japan (Fig. 3). We assumed that every paddy field among the same prefecture has the same rice plant type. For the timing of transplanting and harvest, and irrigation periods, the dataset summarized by Hayano et al. (2013) was used, which was based on the statistics of the Ministry of 199 Agriculture, Forestry and Fisheries of Japan (MAFF) and the agricultural experiment station of each prefecture. The timing of transplanting and harvest, and irrigation periods were defined based on the statistics of Ministry of Agriculture, Forestry, and Fisheries of Japan (MAFF) and the agricultural experiment station of each prefecture (Hayano et al., 2013). The plowing event was performed in the next month of harvest. The paddy fields were derived from the ALOS/AVNIR-2 50-m-grid land cover map (Hashimotò et al., 2014). Tier-1 was calculated based on Yan et al. (2009)’s method and the database in Hayano et al. (2013). Tier-2 was literature data in the GIO (2009) reports.

We estimated total carbon exchange (= NEP – Ecosystem methane emission, NEP, and grain biomass in harvesting from 2001 to 2010 (Fig. 4). The total carbon exchange showed carbon sink over the whole of Japan (5.1 Tg C year\(^{-1}\)) because of the removal of harvested biomass. The methane emission showed different spatial patterns from CO₂ fluxes, and it is mainly determined by the irrigation period. A longer irrigation period increases the methane emission by anaerobic conditions (Cui et al., 2005); for southern Kyusyu and north Shikoku regions, the methane emission was lower because of the shorter irrigation period: central part of the main island (e.g., Tokai, eastern Kansai, northern Kanto regions) has higher methane emission by the longer irrigation period. Whereas, northern region (Tohoku region and Hokkaido) had different patterns, and the heterogeneous spatial pattern in the methane emission was rather similar to the harvest biomass. In higher latitudinal area, the slowing carbon circulation decreases the plant biomass and soil organic matter, leading a lower exudation and decomposition rates intercept the methane production. They suggested that both an artificial event like irrigation and a turnover rate in the natural carbon cycle are important for understanding spatial properties of the methane emission.

Based on Fig. 4b, a region-averaged value of the methane emission was compared to the existing observation- and inventory-based results. The methane emission averaged from 2001 to 2010 was 15.0 Gg C m\(^{-2}\) year\(^{-1}\), which was similar to observations (12.4 Gg C m\(^{-2}\) year\(^{-1}\) at MSE; 10.9 Gg C m\(^{-2}\) year\(^{-1}\) by Matsumoto et al. (2002)). The total amount of methane emission over Japan was 256.6 Gg C year\(^{-1}\) averaged from 2001 to 2010 (approximately 5% of NEP), and within the range of the previous inventory-based studies averaged from 2001 to 2010 (Tier-1 estimated at 285.0 Gg C year\(^{-1}\); Tier-2 estimated 202.1 Gg C year\(^{-1}\)). A recent report revised the estimate much upward (GIO, 2016): the value was 501.4 Gg C year\(^{-1}\) in 2001. The rise could partly be attributed to the following parameter and methodological modifications: the area of paddies under continuous flooding was revised upward and the information on paddy drainage rate was included. Both did not take into account for our preset estimate. This is a further challenge of our approach.

The comparison with inventory-based approach showed that BEAMS-C and Tier-1 had major changes and Tier-2 had little year by year (Fig. 5). BEAMS-C showed the largest variation range. The effect of climate change and rice plant dynamics essentially generates larger variation in biomass and carbon fluxes, and for just that reason, BEAMS-C has an advantage over the others. Moreover, as Katayamugi et al. (2016) suggested, the IPCC inventory approaches possibly underestimated the inter-annual variation ranges of the methane emission, and our comparison results also agreed. At least, we need to rethink the effect of agrometeorological event on rice growth to enhance the existing inventory-based approach. Because the diagnostic approach incorporates the actual crop growth pattern as an input, it is potentially more efficient for estimating the spatial methane emission under the climate change. For example, BEAMS-C showed the lower methane emission in 2003. The reason is that satellite observation can detect lower solar radiation due to longer hovering of the Baiu front during growing season (e.g., Saigusa et al., 2008; Sasai et al., 2011, 2012). Since the photosynthesis and biomass production of rice plants are inhibited under the lower radiation (Resurrección et al., 2001; Sasai et al., 2012; Ono et al., 2013), the carbon substrates of the methane production were decreased by lower litter and root exudation (Sass et al., 1991; Lu et al., 2002). The year’s event of 2003 ensures a consistent understanding to the methane estimation over Japan.

Table 2. Input data for BEAMS-C.

| Parameter                          | Dataset                                      |
|------------------------------------|----------------------------------------------|
| LST                                | MOD11A2\(^a\), MYD11A2\(^a\)                 |
| ipAR, LAI                          | MOD15A2\(^a\), MYD15A2\(^b\)                 |
| Albedo                             | MCD43B3\(^a\)                                |
| Incoming solar radiation           | JAXA/EORC Radiation product\(^c\)            |
| Precipitation                      | GPCP version 2.2\(^e\)                       |
| Air temperature                    | NCEP/NCAR\(^f\)                              |
| Wind speed                         | NCEP/NCAR\(^f\)                              |
| Relative humidity                  | NCEP/NCAR\(^f\)                              |
| Atmospheric CO₂ concentration      | Observation in Mauna Loa\(^g\)              |
| Soil texture                       | SRTM 30\(^h\)                                |
| Land cover map                     | FAO soil texture group\(^i\)                 |
| Crop calendar                      | ALOS/AVNIR-2\(^2\)                           |
| Crop calendar                      | MAFF Crop Statistics: General Crop, Feed Crop, Horticulture Crop (in Japanese) (Hayano et al., 2013) |

\(^a\)Terra and Aqua/MODIS Land Surface Temperature/Emissivity 8-Day L3 Global 1 km (Wan et al., 2002); \(^b\)Terra and Aqua/MODIS Leaf Area Index/IPAR 8-Day L4 Global 1km (Myneni et al., 1997, 2002); \(^c\)Terra/ MODIS Albedo 16-Day L3 Global 1 km (Lucht and Lewis, 2000; Liang et al., 2002); \(^d\)JAXA EORC PAR product provided by JAXA Satellite Monitoring for Environmental Studies (http://kuroshio.eorc.jaxa.jp/JASMES/index.html) (Frouin and Murakami, 2007); \(^e\)Global Precipitation Climatology Project (GPCP) version 2.2 dataset (Huffman et al., 2009); \(^f\)National Center for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) re-analysis dataset; \(^g\)Atmospheric CO₂ values (ppmv) derived from in situ air samples collected at Mauna Loa, Hawaii, USA provided by the CDiac Web Site (Keeling et al., 1995; Keeling et al., 2009); \(^h\)Shuttle Radar Topography Mission (SRTM) 30 arc- seconds Digital Elevation Model (DEM) dataset (Farr et al., 2007), Global Distribution of FAO Soil Units (Types) at 1 degree × 1 degree Resolution (Zobler, 1999); \(^i\)JAXA ALOS-2 project (Hashimoto et al., 2014); \(^j\)Ministry of Agriculture, Forestry, and Fishery (MAFF) Crop Statistics: General Crop, Feed Crop, Horticulture Crop (in Japanese) (Hayano et al., 2013)
estimate the methane emission from paddy fields by using the diagnostic approach, because we used the satellite-driven information only about rice growth (LAI, fPAR, and paddy fields area). If more time-series satellite products for agricultural properties (e.g., irrigation period, paddy water level, surface carbon subtracts after harvesting) were involved deeply in the diagnostic model, we could simulate more realistic carbon cycle including artificial operation in paddy fields, leading more accurate evaluation of the methane emission at national scales. To contribute to the global warming prediction and policy against global warming, we strongly expect a development of the diagnostic model and remote sensing products relevant to paddy fields.

5. Conclusion

We improved the diagnostic ecosystem model BEAMS-C to estimate the methane emission from paddy fields. The major improvement points are (1) methane production in the anaerobic soil by methanogens, (2) methane oxidation by the methanotrophs, and (3) the three pathways for methane emission. The validations of the carbon fluxes at MSE showed good agreements between the estimation and observation, leading that the model improvement has BEAMS-C certainly enhanced. However, our validation for paddy field is just one site, so we need to have a continuing development with more observations. For regional analyses, the estimates of methane and carbon dioxide represented reasonable spatial and temporal patterns.

Fig. 3. Fractions of paddy field area in Japan derived from the ALOS/AVNIR-2 product.

Fig. 4. Spatial patterns of annual mean carbon exchange (a), methane emission (b), NEP (c), Harvest (d) estimated by BEAMS-C, and irrigation period (e) derived from Hayano et al. (2013).
Comparing the spatial estimates with the existing inventory-based approach, we concluded that the diagnostic model has enough advantages such as the effect of meteorological change and providing realistic surface data from spatial observations. In the future, we will obtain more accurate and kinds of satellite products relevant to paddy fields. To more accurately estimate the methane emission from paddy fields, we need to develop the diagnostic ecosystem model with more efforts that the satellite observations are used as a realistic paddy information.

Acknowledgments

The corresponding author is deeply grateful to Tamon Fumoto, Michiko Hayano, Gwang-Hyun Han and Leslie J. Cobar. We are grateful to the MODIS Fumoto, Michiko Hayano, Gwang-Hyun Han and Leslie J. Cobar, K, Papen H, Rennenberg H, 1997: Impact of Cao MK, Dent JB, Heal OW, 1995: Modeling methane emissions from rice paddies. Global Biogeochemical Cycles 9, 183–195. 

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Fig. 5. Comparisons of annual change in the methane emission estimated by BEAMS-C, Tier-1 and -2 from 2001 to 2010.
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