Integrated Sustainability Evaluation of Field Environment for the Combinations of Tillage and Cover Crop Practices by FAO-SAFA (Sustainability Assessment of Food and Agriculture Systems) Applied with a Modified Rating Method

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The Food and Agriculture Organization of the United Nations’ Sustainability Assessment of Food and Agriculture Systems (SAFA) is a tool covering multiple fields, including the governance, the society, the economy, and the environment to assess the sustainability of agriculture. This system has an important feature, integrated evaluation with many indicators. In the present study, the evaluation of the sustainability of fields, Ibaraki University, with combined 3 types of tillage (plowing, rotary tillage, and no tillage) and 3 types of cover crop (fallow, rye, and hairy vetch) in the environmental dimension was performed using modified SAFA rating method. The objective numerical data in GHG (Greenhouse Gas) absorbance, soil properties and fuel consumption were used. Sustainability ranking was determined with SAFA method through data normalization. On comparison of the nine total combinations, no-tillage with rye as the cover crop had the highest rating and plowing with fallow had the lowest ranking. It revealed that no-tillage with use of cover crops would be the best management method to conserve the field environment.

Key Words: cover crop, sustainability assessment of food and agriculture systems (SAFA), tillage
1. Introduction

Issues related to food security are common and controversial worldwide. "Sustainable agriculture" has been applied to address these issues in the last several decades, but clear standards for its definition remain lacking. The Food and Agriculture Organization of the United Nations’ Sustainability Assessment of Food and Agriculture Systems (SAFA) has been used as an integrated indicator for the assessment of agricultural activities (Food and Agriculture Organization of the United Nations, 2014). The SAFA is mainly used for decision making by agricultural policy makers.

The SAFA framework has been applied in research worldwide. The indicators cover four aspects – 1) the governance, 2) the environment, 3) the economy, and 4) the society – and are expected to provide a holistic definition of sustainable agriculture as agricultural practices that are economically viable, environmentally sound, and socially just (de Olde et al., 2016). The SAFA aims to reflect the approaches to and results of sustainability assessments in the food sector with high degrees of transparency and consistency (Schader et al., 2014).

Gayatri et al. (2016) used the SAFA tool to assess the sustainability of smallholder beef cattle farming in Indonesia. The data in 4 dimensions were collected mainly by interviews from 6 cattle farmers, the sustainability was evaluated from the radar chart obtained by SAFA tool. Soldi et al. (2019) compared the sustainability among 5 farming systems in Paraguay. Data were obtained by interview, direct observation, and scientific literature research from the farms belonging into 5 farming systems, agribusiness, conventional peasant family farming, agroecological peasant family farming, neo-rural farming, and indigenous agriculture. Agribusiness achieved moderate scores in the dimensions of governance and environmental integrity, and was good in the economic and social dimension.

In the dimension of agriculture environment, soil property is a big component. However, the evaluation of soil condition is complex because soil has many functions and such functions are related mutually (Kaneko, 2017). Before the maintenance of soil functional integrity was recognized as soil sustainability, and recently soil resilience, measured by the response diversity of the soil, could therefore be used as a bioindicator for soil management sustainability (Ludwig et al., 2017). Simple and accurate evaluation system will be need for sustainability assessment.

The significant merit of SAFA is the evaluation of sustainability by using integrated data of many indicators. The sustainability of agricultural fields should be also evaluated from multi-sided viewpoints. However, the number of indicators for the evaluation of agricultural field is limited in most of the previous researches (de Olde et al., 2016).

An experimental field at Ibaraki University was selected as the assessment target for the present study, taking the on-going long-term experiments into account in this field, since 2002. Because of the continuous treatment of cover crops and tillage practices in the same field and the data for physics, chemical and biological properties in the cultivated soil, the sustainability focusing on the environmental issues in the field can be evaluated. The present study was performed to apply the SAFA method in the evaluation of field environment and to assess the cropping system with cover cropping and tillage.

2. Materials and methods

1) Study site and field management

This study was conducted at the Center for International Field Agriculture Research & Education of the Ibaraki University, Department of Agriculture, located in Ami, Ibaraki, Japan. The soil in this area (the Kanto region) is humic allophane, a type of Andisols (Zhaorigetu et al., 2008).

Nine field management systems, as combinations of three tillage methods (plowing, rotary tillage, and no tillage) and three cover crops [fallow, rye (Secale cereale L.), and hairy vetch (Vicia villosa R.)], have been applied in the field (Figure 1). The field management systems were compared in non-fertilizer condition. Rye and hairy vetch were planted the previous fall, and their grown plants were mechanically incorporated. For the leveling
of the plot fields, drive harrow was worked after plowing in plow plot. The field was rotary-tilled twice in rotary plot. Upland rice was sown by drill seeder in plow and rotary plot. In the no-till plot, a subsoiler formed planting furrows, onto which the upland rice seeds were sown.

2) Data collection

In the present study, fourteen indicators belonging to five categories were selected based on the findings of a previous experiment conducted at the same study site (Table 1). The measured indicators were the greenhouse gas (GHG) absorption from the atmosphere in the soil (GHG Category); the soil inorganic nitrogen content (water Category); the soil hardness, soil moisture, available phosphorus, cation exchange capacity (CEC), electrical conductivity (EC), soil organic carbon (SOC) content, soil respiration, and soil organic matter (SOM) content (land Category); the maturity and structure indices, calculated using the nematode dynamics in soil (biodiversity Category); and fuel consumption (materials and energy Category).

3) Measurement of field environment

Measured methods were shown simply in Table 1. Greenhouse gases (GHG; Carbon dioxide (CO₂) and nitrous oxide (N₂O)) were obtained by chamber method and analyzed by gas-chromatography system (Komatsuzaki and Ohta, 2007; Zhaorigetu et al., 2008).

Soil properties were measured after crop harvest in fall as follows. Nitrate and ammonia nitrogen concentrations in 1 M KCl extracts (10 g of soil in

![Figure 1](sample_of_plot_arrangement_with_different_tillage_and_cover_crop_application_in_the_study_field.png)

Figure 1 Sample of plot arrangement with different tillage and cover crop application in the study field. PL: plowing, NT: no tillage, RO: rotary tillage, RY: rye, HV: hairy vetch, FA: fallow.

| SAFA indicator category | Environmental indicators | Measured year (Season) & methods | Data source |
|-------------------------|--------------------------|----------------------------------|-------------|
| Atmosphere              | GHG absorption in soil   | 2003-2007 (Fall), CO₂ and N₂O, gas-chromatography | Komatsuzaki, 2007; Zhaorigetu, 2008 |
| Water                   | Soil inorganic nitrogen content | 2003-2007 (Fall), NO₃⁻ + NH₄⁺, MgO–Devarda alloy distillation method | Mu, 2008 |
| Land                    | Soil hardness 0-15cm depth | 2003-2007 (Fall), cone penetration meter. | Mu, 2008 |
|                        | Soil hardness 15-45cm depth | 2003-2007 (Fall), cone penetration meter. | Mu, 2008 |
|                        | Soil moisture            | 2003-2007 (Fall), drying at 105°C | Mu, 2008 |
|                        | Available phosphorus     | 2003-2007 (Fall), Truong method | Mu, 2008 |
|                        | CEC                      | 2003-2007 (Fall), Schollen berger method | Mu, 2008 |
|                        | EC                       | 2003-2007 (Fall), 1:5 solution (soil: water) | Mu, 2008 |
|                        | Soil organic carbon      | 2003-2007 (Fall), CN coder | Mu, 2008 |
|                        | Soil respiration         | 2003-2007 (Fall), gas detector tube | Mu, 2008 |
|                        | Soil organic matter      | 2003-2007 (Fall), Tyurin method | Mu, 2008 |
| Biodiversity            | Maturity index           | 2005-2011 (Spring and Fall), Baermann Funnel Method | Ito, 2015 |
|                        | Structure index          | 2005-2011 (Spring and Fall), Baermann Funnel Method | Ito, 2015 |
| Materials and Energy    | Fuel consumption         | 2003-2007 (Spring), Basal data from the book 'Hokkaido Agricultural Production Technology System' | Hokkaido Agricultural Administration Department, 2019 |
100 mL) were determined by the MgO–Devarda alloy distillation method (Keeney and Nelson 1982). Soil hardness was evaluated by cone penetration meter (FieldScout SC 900). CECs were determined by Schollenberger method (Schollenberger and Simon, 1945). Soil organic carbon was measured by CN coder. Soil respirations were measured by chamber methods and CO₂ concentration was evaluated by gas detector tube (Gastech 2EL). Soil organic matters were determined by ignition loss methods. The details were described in Mu’s report (2008).

Soil nematode community was measured as biological indicator. Maturity Index (MI) and Structure Index (SI) show the disturbance of soil environment and the development of soil food web, respectively (Ito et al., 2015). High score in MI shows small disturbance of soil environment. In SI, high score also does the establishment of soil food web. That is, high scores of MI and SI mean stable condition in soil.

Fuel consumption of tractor was calculated from standard consumption table (Hokkaido Agricultural Administration Department, 2019) by the data of mechanical specification in plow, harrow, rotary and subsoiler used in the present study. The impact on field environment was different by measured indicators, and the positive and negative impacts were decided in each indicator (Table 2, Table 3).

4) Normalization and SAFA rating

All data were collected during the study period shown in Table 1 and averaged. Since measured data were not always the same in types nor expressed in the same units (Table 1), normalization was performed using the following equation in each indicator:

\[
\text{Normalized Value} = \frac{\text{Value} - \text{MEAN}}{\text{STD}}
\]

Table 2  Mean and variation of environmental indicators during measured years in 9 field managements with tillage and cover crops.

| Environmental indicators                  | Impact* | Unit | Field management (tillage and cover crop) | Mean  | SD** | CV** |
|-------------------------------------------|---------|------|-------------------------------------------|-------|------|------|
| GHG absorption in soil                    | +       | (CO₂ t/year) | Plow Fallow Rye HV | -0.26 | -0.21 | -0.2 |
|                                           |         |                               | Plow Rye HV | -0.11 | 0.567 | 0.255 |
|                                           |         |                               | No Tillage Rye HV | -0.15 | 0.468 | 0.046 |
| Soil Inorganic Nitrogen Content            | -       | (mgN/kg) | Plow Fallow Rye HV | 44    | 44   | 63   |
|                                           |         |                               | Plow Rye HV | 38    | 25   | 50   |
|                                           |         |                               | No Tillage Rye HV | 37    | 25   | 75   |
| Soil hardness, 0-15cm                      | -       | (Mpa) | Plow Fallow Rye HV | 0     | 0.1  | 0    |
|                                           |         |                               | Plow Rye HV | 1.1   | 1.3  | 1.1  |
|                                           |         |                               | No Tillage Rye HV | 1.3   | 0.8  | 0.9  |
| Soil moisture                              | +       | (%) | Plow Fallow Rye HV | 64.6  | 65.9 | 63.6 |
|                                           |         |                               | Plow Rye HV | 63.1  | 66.0 | 65.7 |
|                                           |         |                               | No Tillage Rye HV | 63.4  | 68.2 | 66.4 |
| Available phosphorus                       | +       | (mg/100g) | Plow Fallow Rye HV | 29.0  | 35.5 | 18.5 |
|                                           |         |                               | Plow Rye HV | 36.0  | 41.5 | 37.5 |
|                                           |         |                               | No Tillage Rye HV | 22.0  | 22.5 | 27.0 |
| CEC                                       | +       | (meq/100g) | Plow Fallow Rye HV | 210   | 204 | 211 |
|                                           |         |                               | Plow Rye HV | 231   | 231 | 227 |
|                                           |         |                               | No Tillage Rye HV | 235   | 234 | 232 |
| EC                                        | -       | (mS/cm) | Plow Fallow Rye HV | 90.5  | 65.5 | 74.8 |
|                                           |         |                               | Plow Rye HV | 89.5  | 80.3 | 73.8 |
|                                           |         |                               | No Tillage Rye HV | 69.8  | 74.5 | 62.8 |
| Soil organic carbon                        | +       | (g/cm³) | Plow Fallow Rye HV | 3.5   | 3.7  | 3.8 |
|                                           |         |                               | Plow Rye HV | 3.6   | 3.9  | 3.8 |
|                                           |         |                               | No Tillage Rye HV | 3.8   | 4.0  | 4.0 |
| Soil respiration                           | +       | (kg CO₂/ha/day) | Plow Fallow Rye HV | 30.6 | 28.8 | 549 |
|                                           |         |                               | Plow Rye HV | 28.8  | 30.1 | 39.6 |
|                                           |         |                               | No Tillage Rye HV | 17.0  | 57.4 | 77.7 |
| Soil organic matter                        | +       | (%) | Plow Fallow Rye HV | 117   | 118  | 118 |
|                                           |         |                               | Plow Rye HV | 113   | 116 | 115 |
|                                           |         |                               | No Tillage Rye HV | 11.6  | 12.0 | 11.8 |
| Maturity Index                             | +       | (MI) | Plow Fallow Rye HV | 1.52  | 1.67 | 1.37 |
|                                           |         |                               | Plow Rye HV | 1.55  | 1.70 | 1.51 |
|                                           |         |                               | No Tillage Rye HV | 1.77  | 1.82 | 1.70 |
| Structure Index                            | +       | (SI) | Plow Fallow Rye HV | 45.4  | 51.4 | 39.3 |
|                                           |         |                               | Plow Rye HV | 34.4  | 36.8 | 35.3 |
|                                           |         |                               | No Tillage Rye HV | 55.8  | 62.9 | 52.9 |
| Fuel Consumption                           | -       | (litter/10a) | Plow Fallow Rye HV | 631   | 631 | 631 |
|                                           |         |                               | Plow Rye HV | 328   | 328 | 328 |
|                                           |         |                               | No Tillage Rye HV | 386   | 386 | 386 |

*Impact; Positive (+) and negative (-) effect to field environment. Evaluation after crop harvest.
Abbreviation; GHG; Greenhouse gas, HV; Hairy vetch, SD; Standard deviation, CV; Coefficient of variance
were particularly high, indicating that these values tended to fluctuate depending on the type of field management. On the other hand, the CVs for the CEC, SOC content, and SOM content were relatively small. These characteristics are governed mainly by soil properties, and their rates of change are thought to be slow even if the annual application of cover crops and tillage practices.

Positive and negative impact was recognized in the measured indicators (Table 2). Soil moisture measured after crop harvest indicated the water retention value in soil and was judged as a positive parameter to the field environment. The indicators of GHG absorption, available phosphate acid, CEC, soil organic carbon, soil respiration, soil organic matter, Maturity Index (MI) and Structure Index (SI) were also classified into positive parameters. On the other hand, the soil inorganic nitrogen content and each indicator for the objective division, normalized values were given evaluations written above, from 1 to 5 scores. For SAFA rating, large normalized value in each indicator provided high rating score (4 or 5) that showed positive impact on field environment (Table 4). Whereas, small normalized value did low score (1 or 2) that were meant as relatively negative impact. The final SAFA rankings were calculated by averaging of rating scores in 9 treatments.

### Table 3  Normalized values of mean data from measured years and impact on the field environment in each environmental indicator.

| Environmental indicator                  | Impact<sup>a</sup> | Field management (tille and cover crop) |
|-----------------------------------------|---------------------|----------------------------------------|
|                                         | Plow                | Rotary                                 |
|                                         | Fallow | Rye | HV<sup>b</sup> | Fallow | Rye | HV<sup>b</sup> | Fallow | Rye | HV<sup>b</sup> |
| GHG absorption in soil<sup>y</sup>      | +      | -1.02 | -0.85 | -0.82 | -0.52 | 1.79 | 0.73 | -0.64 | 1.46 | -0.14 |
| Soil inorganic nitrogen                 | -      | -0.04 | -0.04 | 1.19 | -0.42 | -1.26 | 0.35 | -0.49 | -1.26 | 1.96 |
| Soil hardness, 0-15cm                   | -      | -0.89 | -0.67 | -0.89 | -0.67 | -0.22 | -0.67 | 2.00 | 0.89 | 1.11 |
| Soil hardness, 15-45cm                  | -      | -1.26 | -0.83 | -1.26 | 0.26 | -0.17 | 0.26 | 0.91 | 0.26 | 1.78 |
| Soil moisture                           | +      | -0.37 | 0.41 | -0.96 | -1.26 | 0.47 | 0.29 | -1.08 | 1.79 | 0.71 |
| Available phosphorus                    | +      | -1.14 | -1.65 | 1.09 | 0.61 | 0.55 | 0.26 | 0.92 | 0.86 | 0.69 |
| CEC                                     | +      | 1.53 | -1.06 | -0.10 | 1.43 | 0.48 | -0.20 | -0.61 | -0.13 | -1.34 |
| EC                                      | -      | -1.71 | -0.53 | -0.06 | -1.12 | -0.65 | 0.06 | 0.06 | 1.24 | 1.24 |
| Soil organic carbon                     | +      | 0.52 | -0.62 | 0.75 | -0.62 | -0.55 | -0.05 | -1.23 | 0.88 | 1.95 |
| Soil respiration                         | +      | 0.10 | 0.60 | 0.60 | -1.90 | -0.40 | -0.90 | -0.40 | 1.69 | 0.60 |
| Soil organic matter                     | +      | 0.71 | 0.36 | -1.79 | 0.50 | 0.57 | -0.79 | 1.07 | 1.43 | 0.57 |
| Maturity Index                           | +      | -0.06 | 0.53 | -0.66 | -1.14 | -0.90 | -1.05 | 0.96 | 1.65 | 0.67 |
| Structure Index                          | +      | 0.10 | 0.60 | 0.60 | -1.25 | -1.25 | -1.25 | 0.21 | 0.21 | 0.21 |
| Fuel consumption                        | -      | 1.03 | 1.03 | 1.03 | -1.25 | -1.25 | -1.25 | 0.21 | 0.21 | 0.21 |

<sup>a</sup>Impact; Positive (+) and negative (-) effect to field environment. Evaluation after crop harvest.
Impact becomes strong in positive and negative so that normalized value is large.

Abbreviation, <sup>y</sup>GHG; Greenhouse gas, <sup>b</sup>HV; Hairy vetch.

3. Result and Discussion

1) Variability of measured data and impact on the field environment

Table 2 showed the mean values of data obtained during the study period and the variation in the indicators. The coefficients of variation (CVs) for GHG absorption, soil inorganic nitrogen content, soil hardness (0–15-cm depth), and soil respiration were particularly high, indicating that these values tended to fluctuate depending on the type of field management. On the other hand, the CVs for the CEC, SOC content, and SOM content were relatively small. These characteristics are governed mainly by soil properties, and their rates of change are thought to be slow even if the annual application of cover crops and tillage practices.

Positive and negative impact was recognized in the measured indicators (Table 2). Soil moisture measured after crop harvest indicated the water retention value in soil and was judged as a positive parameter to the field environment. The indicators of GHG absorption, available phosphate acid, CEC, soil organic carbon, soil respiration, soil organic matter, Maturity Index (MI) and Structure Index (SI) were also classified into positive parameters. On the other hand, the soil inorganic nitrogen content and
EC were evaluated as negative parameters because of nitrogen leaching potential causing underground water pollution (Gu et al., 2004; Komatsuzaki and Wagger, 2015). Soil hardness and Fuel consumption were also recognized as negative effective parameters.

The normalized values in each indicator were shown in Table 3. Some characteristics of the treatment were recognized by the comparison of normalized value. Large values were calculated in no tillage with cover crops. For example, as a rule, HV showed large values in the indicators of soil inorganic nitrogen and soil respiration. HV provided much nitrogen into soil and increased biological activity in soil. On the other hand, Rye showed the large value in soil moisture, soil organic matter, Maturity Index and Structure Index. Rye is concerned to play a role in physics and biological change in soil. In addition, small values were shown in the indicators of soil moisture, soil organic carbon, soil organic matter, Structure Index in fallow combined with plow and rotary tillage, as a rule. Fallow treatment is not necessary to have positive effect in the field management and cover cropping will show positive effect into field environment from the long-term trial.

2) SAFA rating and ranking

The score of GHG absorption in soil comparably tended to rate high in Rye except for the plow (Table 4). The soil inorganic nitrogen content after the upland rice production remarkably found out the difference in hairy vetch which rated worst.

The tillage systems were clearly contributed to the soil characteristics. For example, plow and rotary treatments obviously reduced the score in soil hardness in both 0-15 cm and 15-45 cm depth. Whereas, rating scores in MI (Maturity index) and SI (Structure index) were high for no-tilled fields.

The effective maintenance of soil moisture was observed in no-tilled fields with cover crops.
The ratings of soil organic carbon and soil organic matter were higher in fields with cover crops than in fallow fields. Fuel consumption rated the highest, small consumption, in rotary on the whole. Though the variation (CV) in CEC was small among the treatments (Table 2), the SAFA rating became relatively high in rotary and no-till treatment, compared to plow treatment. EC and available phosphorus were the elements that could not figure out a definite tendency.

The positive and negative tendencies to the field environment were roughly understood by SAFA rating. Among all field management systems examined in the present study, average ratings were highest for no-tilled fields with rye as a cover crop, followed by rotary-tilled field with rye, no-tilled field with hairy vetch, and rotary-tilled field with hairy vetch. Average Ratings were lowest for plowed and fallow fields. Thus, ratings tended to be higher for the six fields with cover crops than for those left fallow.

SAFA rankings were highest for non-tillage, followed by rotary tillage and plowing. In addition, ratings were higher for rye and hairy vetch use than for fallowing. Hence, compared with fallowing, treatment with cover crops imposes a lesser environmental burden. Rotary tillage and non-tillage contributed more significantly to environmental conservation than did the management of fields by plowing.

3) Progress in assessment method

Considering the SAFA original purpose, decision making for future agriculture system, used data in the present research were limited, only in field environment that was a part of environmental dimension. In the present study, rating scores in measured indicators were obtained through the normalization of numerical data. This process was different from that in SAFA. However, by using rating and ranking method in SAFA, integrated evaluation of field environmental sustainability in the long term field examination with cover crops and tillage practices was carried out accurately. From the ranking result in Table 4, the importance of no tillage and cover cropping was realized. Though most of the previous assessments of sustainability have focused on one or a few data types (de Olde et al., 2016), the present process took accurate assessment one step further.

The SAFA indicators provided a progressive assessment framework for the integrated examination of agricultural sustainability. For example, the case of "The New Zealand Sustainability Dashboard" showed the importance of accurate data for sustainable practice (Manhire et al., 2012). The dashboard, which originated the characteristics of SAFA, was well managed by the independent scientist team. They enhance and confirm data input accuracy to the dashboard database to avoid mistrust among regulators. By their work, the farmers can also use a transdisciplinary combination of classic qualitative and quantitative methodologies to rationally manage massive amounts of information for decision-making.

The present study described the significance of the numerical data source and the variation among cultivation methods for comparative research as a discussion. The idea similar to “The New Zealand Sustainability Dashboard” is also required to build up an assessment method nowadays. Therefore, the numerical data and the normalization method as modified method in SAFA were effectiveness in the present study.

A Simple evaluation system of sustainability of field environment is provided in the present research. Meanwhile, the verification will be necessary for expanding this evaluation system and a detail investigation on the interaction among soil functions is expected.

4. Conclusion

The integrated evaluation of environmental sustainability in agricultural field was performed by using SAFA method with 14 indicators in the present research. Overall, no-tillage with cover crops was evaluated as a progressive system for reduction of the environmental impact to the field from a long-term research. Such evaluation will provide a useful information to establish a sustainable farming system.
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要旨

FAO が提示している SAFA（Sustainability assessment of food and agriculture system）は政策、社会、経済、環境の 4 分野から農業の持続性評価を行うツールである。この手法は多方面的データを統合的に評価できる特徴がある。本研究では、3 種の耕起方法（ブラウン・ロータリ・不耕起）および 3 種の緑肥（裸地・ライムギ・ヘアリーベッチ）を組み合わせた管理を施している茨城大学の試験園場において、環境面からの持続性評価を試みた。温暖化効果ガス、土壌特性および燃料消費に関して客観的な数値データを活用した。データの標準化を行い、SAFA 手法によるランキング付けを行った。9 種の管理方法を比較すると、ランキングはライムギを施した不耕起圃場が最大で、裸地でのブラウン耕起で最小になった。緑肥を導入した不耕起栽培が圃場環境を保全することが明らかになった。

キーワード

カバークロップ、耕起、SAFA（Sustainability assessment of food and agriculture system）