Assessment Model of the Soil Fertility Potential of Yatsuda Rice Fields Based on Humus Derived Nitrogen Balance Using UAV Hyperspectral Sensor

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Abstract

In order to maintain environmentally friendly agriculture, it is necessary to apply fertilizers based on an assessment of the potential of agricultural land. However, the effects of soil microorganisms based on bioanalysis have not been fully examined, and because of the unexplored nature of the effects, chemical fertilizers are often applied in excess of what is necessary.
The purpose of this study is to construct a model that enables evaluation of the nitrogen balance in the process from reservoir to paddy field by adding the effect of the amount of humus-derived nitrogen to the model developed by the authors.
For this purpose, the biomass of rice and weeds were detected from hyperspectral images mounted on a UAV, and the growth processes of rice and weeds were grasped with GIS to estimate the amount of nitrogen fixation in rice plants by estimating the biomass of rice and weeds separately.
Furthermore, using soil microbial diversity and activity values (BIOTREX), we qualitatively evaluated the contribution of soil microorganisms to nitrogen fixation in paddy rice, built a model that can evaluate the nitrogen cycle derived from organic nitrogen supplied from reservoirs, and estimated the nitrogen balance. The results showed that this model can be used to evaluate the potential of agricultural land as an indicator of the need for fertilizer application.

1. INTRODUCTION

There are many swamps in the Hiki Hills of Saitama Prefecture, and in the small villages around the swamps, agriculture has been carried on for more than 1,500 years using only rainwater stored in the swamp water, and this culture was selected as an important national agricultural heritage site (J-NIHAS) in March 2023.
This region includes Ogawa-machi, the birthplace of organic farming, the birthplace of organic farming. Focusing on the life knowledge of the organic matter nurtured in the swamps and the soil micro-organisms that feed on it as a factor in the development of environmentally friendly agriculture, including organic agriculture, this project aims to scientifically clarify the natural mechanisms that have supported environmentally friendly agriculture for 1,500 years in the adverse conditions of the mid-mountainous region.
The authors have previously developed a model for evaluating nitrogen balance from reservoirs to valley rice paddies connected to reservoirs by combining spatial information processing, chemical analysis, and bioanalysis, and have constructed a model to estimate nitrogen balance in the process from reservoirs as a water source to rice paddies (Goto Sato et al., 2021, Sato Goto et al., 2024b).
However, it is difficult to quantify the role of soil microorganisms in the inorganization of organic nitrogen and the spatial distribution of humus-derived organic nitrogen, so the impact of bioanalysis on nitrogen balance has not been fully evaluated.
The objective of this study is to build a assessment model of nitrogen balance from reservoir to valley fields linked to reservoirs by combining spatial information processing, chemical analysis and bioanalysis.
To this end, the biomass of rice and weeds was detected from hyperspectral images mounted on UAVs, the growth processes of rice and weeds were understood with GIS, and the biomass of rice and weeds was estimated separately to estimate the amount of nitrogen fixation in rice.
Furthermore, by qualitatively assessing the contribution of soil micro-organisms to nitrogen fixation in rice using soil microbial diversity and activity values (BIOTREX), a model was constructed to enable an assessment of the nitrogen cycle derived from organic nitrogen supplied by the reservoir, and the nitrogen balance was estimated.
It was shown that this could be used as an indicator of the need for fertiliser inputs and as a method for assessing the potential of agricultural land.

2. STUDY AREA AND MATERIAL

2.1 Target Field

The research field for this study is located in the Yatsuda rice field connected to Kozutsumi Swamp, J-NIAHS in Koegawa, Kumagaya City, Saitama Prefecture (Figures 1). The period from rice planting to harvesting was from 6/25/2022 to 11/13/2022. Note that the subject plots have been cultivated with "Kinu Hikari".

2.2 Analysis Procedure

The analysis procedure was as follows. In the material cycle of the reservoir-valley paddy field system, the natural supply of phosphorus and potassium (excluding nitrogen) to the study site is low, and the amounts detected in the reservoirs are extremely small.
Furthermore, since there are no urban areas upstream of the study site, water originating from the reservoir is dominant, and nitrogen uptake by rice cultivation is clearly evident. Phosphate

is strongly adsorbed to the soil, making it unlikely to increase or decrease rapidly as it moves from the reservoir to the valley paddy fields, resulting in little change on an annual scale. Potassium is highly dependent on soil and geology, making it difficult to discern its role in the material cycle of the reservoir-paddy field system.
In light of the above, this study used the nitrogen cycle—which is directly linked to both crop production and water quality regulation—as the primary indicator. We believe that this evaluation framework allows us to clearly demonstrate the functional characteristics of the agricultural system in question without becoming overly element-reductionist.
Environmental conditions and paddy rice growth were measured in each plot, and nitrogen fixation was estimated using spatial information processing technology and chemical and biological analysis according to the flow chart as Figure 2.

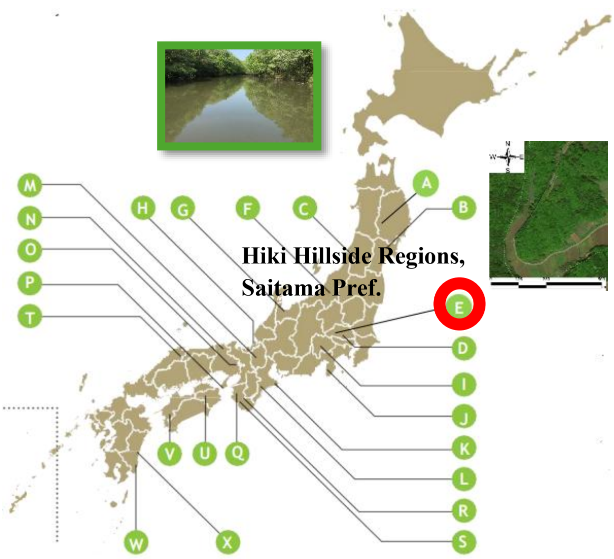

Figure1 Definition of plots in the target field and J-NIAHS site

2.3 UAV image acquisition and processing

In acquiring the UAV images, GCPs were shot into the four corners of the paddy field to be photographed, and an anti-aircraft sign 30 cm in length and width was placed so that the GCPs were centered. Image acquisition was conducted using a UAV (DJI MavicPro) equipped with a 4-band multispectral camera Parrot Sequoia (Sequoia). The center wavelengths of each band were set to green, blue, red, blue-green, and blue-green. The center wavelengths of each band are Green: 550 nm, Red: 660 nm, Red-edg: 735 nm, and Near Infrared: 790 nm. The ground altitude was set to 30 m, the flight speed to 1 m/s, the overlap rate on the flight path to 80%, and the sidelap rate between flight paths to 60%.
In addition, using a dedicated program in sequoia, a 1-second time-lapse setting was used, and after the images were taken, the images capturing the same point as the main body visible light camera were selected for analysis. We acquired a total of about 80 images, including long-range brightness value images and RGB images from the camera that is standard equipment on UAVs, for a total of five types of images.
The 3D modeling software Agisoft Metashape Professional Ver. 1.7.5 (Agisoft LCC, Russia) was used for SfM (Structure from Motion) processing, reflectance transformation, and orthorectification.
RGB images, Digital Surface Model (DSM) images, and Normalized Difference Vegetation Index (NDVI) images were produced from the above process. The projection method was Japan Geodetic System JGD2000/Japan Plane Rectangular CS IX (EPSG:2451).
The NDVI is given by the following equation

$$NDVI=(NIR-Red)/(NIR+Red) \quad (1)$$

where Red: spectral reflectance of Sequoia in the visible red region, NIR: spectral reflectance of Sequoia in the near-infrared region and NIR: Spectral reflectance of Sequoia in the near-infrared region.

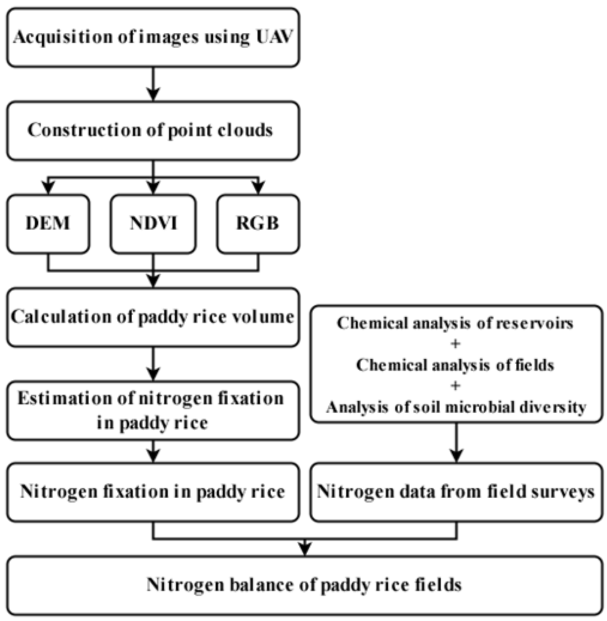

Figure 2 Estimation flow of nitrogen fixation in paddy rice

3. METHODOLOGY

3.1 Estimation of rice stump area using DSM and NDVI images

To calculate the area of paddy rice stump, the location, bottom, top, and height of the paddy rice stump were calculated. From the post-harvest (11/13/2022) field survey, it was confirmed that the only conditions in the field were the remaining rice stump and the field surface, so RGB images were acquired using a UAV and converted to DSM images(Sato Goto et al., 2024a).
A post-harvest DSM image clipped inside the foot of the paddy field was created, and after two iterations of weighted kernel neighborhood analysis using a 3*3 low-pass filter and a high-pass filter, Otsu’s binarization fomula was used to classify the image into two categories: uncut rice plants and field surfaces.
In addition, a 3*3 tilt angle calculation was performed based on the first low-pass filtered DSM image to create a tilt angle image. The number of times filtered was compared between the first, second, and third filtering patterns, and results that were close to the plant area and number of plants obtained during the field survey were used.
The image of the plant position obtained from the tilt image and the image of the plant position obtained from the DSM image were intersect processed, and the range included in both two images was extracted as the plant position. The raster images of the extracted plant positions were vector processed to create polygons of rice plants. This was used as the positional

reference point for each paddy plant. The reference point was assumed to remain unchanged in position throughout the growing season and was used in subsequent image processing. The NDVI images clipped in the field were binarized using the Otsu's formula, and the RGB images and NDVI were used to visually decipher the rice plants and extract the high NDVI range on each paddy plant. The extracted high NDVI range diameters were measured and averaged.
When determining the relationship between rice yield and soil composition and other factors, it is necessary to consider the amount of biomass growth combined with the accumulated amount of weeds weeded out other than rice. A raster image of the average leaf area centered on the reference point was created, and high NDVI pixels that did not overlap this raster range were used as weed pixels, and each pixel was divided after clip extraction.
The above process was applied to the NDVI image for each observation to create a time series of rice and weed raster data.
Since the paddy rice plants were harvested, leaving at least 5 cm of stump from the field surface, the area of the rice stubble was defined as the pixel range 10 cm or higher above the field surface based on the in-field DSM image after harvest.

3.2 Estimation of paddy rice plant volume

For volume estimation, the paddy plant was assumed to be a conical trapezoid. The conical trapezoid was calculated by the following equation.

$$(a+b+\sqrt{ab})*h/3 \qquad (2)$$

where, a: plant area, b: leaf area, h: grass height.

The plant area a was defined as the area of paddy rice plants left over after harvesting. A smoothing filter layer was created by applying a 10*10 smoothing filter process that fits the paddy rice plants in the DSM used in Section 3 and removing noise. Next, a 10*10 maximum value filter was applied to the smoothing filter to create a maximum value filter layer. Using the smoothing filter layer and the maximum value filter layer, a binarization process was performed to obtain the center-of-gravity pixel. Binarization was set to 1 if the smoothing filter layer and the maximum filter layer had the same value, and to 0 if they had different values. The center of gravity of each rice plant was obtained by the binarization process. The obtained center-of-gravity pixels were converted to points and a buffer was created. The buffer area was set so that the rice plants measured during the field observations would fit in it, and the inclination angle was calculated from the DSM.
Leaf area b was defined as the leaf area of paddy rice before rice harvest. Based on the position of the center of gravity of each polygon extracted when calculating the plant area, pixels with an NDVI value of 0.5 or higher that overlapped the center of gravity were merged as paddy rice to obtain the area. The height h was obtained from the DSM difference before and after rice harvest by clipping the DSM in the overlapping range of plant area and leaf area.

3.3 Estimation of the biomass of paddy rice plants across the field

To estimate the biomass of a paddy rice plant, a correction factor was first calculated from the volume calculated using the conical trapezoidal model for each plant and the actual volume of paddy rice per plant that was measured. The volume of paddy rice plants in the entire field was further estimated by using UAV imagery and correcting the volume calculated using the conical trapezoidal model with the correction coefficients.
The representative stock sample was defined as follows. The number of ears, weight of brown rice per ear, weight of rice straw per ear, number of offshoots per ear, grass length, weight of brown rice, and cross-sectional area of stem were measured and averaged.
The average of the circumference of one ear was measured from a representative sample of plants, and from the average of the circumference of one ear, the radius of one ear and the cross-sectional area of one ear were obtained. The volume per plant was obtained by multiplying the obtained cross sectional area of one ear by the average of grass height and the average of the number of ears.

4. RESULTS AND DISCUSSION

4.1 Estimation of nitrogen supply from soil

4.1.1 Estimation Method

In this study, the target field was a paddy field where environmentally friendly agriculture is practiced, located in the Oegawa district of Kumagaya City, Saitama Prefecture, where continuous observation is conducted by Rissho University. To obtain the nitrogen content of the soil corresponding to the reflectance of the hyperspectra, topsoil was sampled at 25 points in the center and four corners of the target field after plowing. The five sampled soil samples were analyzed for nitrogen content using an organic element analyzer (NCH coder, Jay Science Labs, Inc.) as Figure3 after drying.

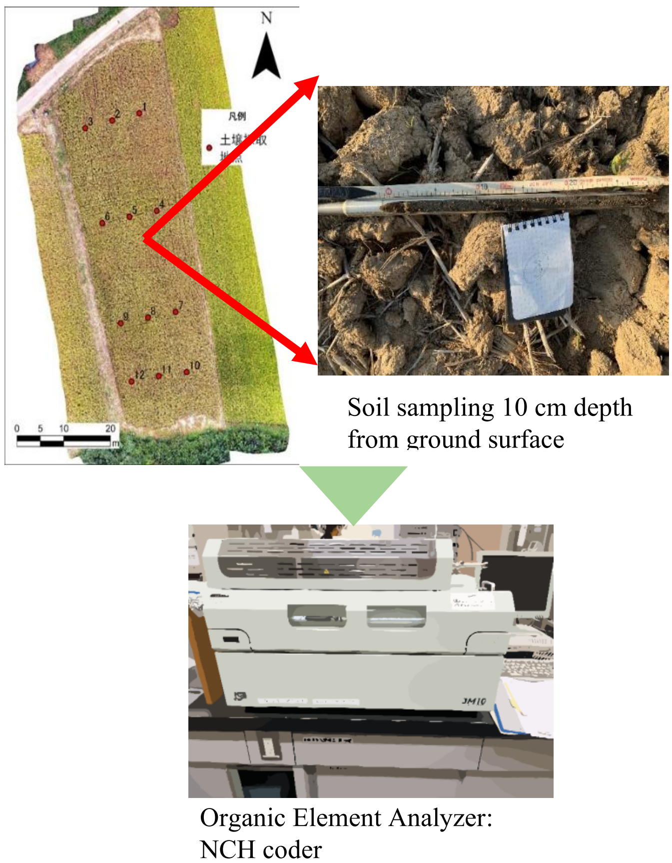

Figure3 Estimation of nitrogen supply from soil by NCH corder

4.1.2 Estimation of nitrogen content by soil analysis

In order to determine the amount of nitrogen in the soil, soil was sampled in the target field using the diagonal soil sampling method, and the collected samples were analyzed using the soil analyzer (ZA-II, Fujihira Industries Co). Sampling was conducted twice, once before and once after rice planting, and the difference was used as the amount of soil nitrogen consumed during the observation period. NO_2- was not detected by soil analysis either before or after rice planting.
Table 1 shows the nitrogen balance in the paddy field during the observation period as 1.3 kg of nitrogen from the reservoir and 4.5 kg of nitrogen fixed in the paddy rice as the supply source.
The humus percentage after rice planting and before cultivation was measured by the SPAD method (extraction: Kumada variant method Measurement: colorimetric method (Kumada variant method)) using an absorbance spectrophotometer (530 nm).
The humus percentage decreased from 2.0% before rice planting to 1.7% after cultivation, indicating that humus is decomposed by soil microorganisms.
The area of the field: 1,680 m2, the depth of the crop soil layer: 10 cm, and the provisional weight of 1.0 were used to determine the amount of humus from the soil weight of the field, and the amount of available nitrogen in the soil that plants can use through the action of microbes.
Furthermore, the amount of available nitrogen (the amount of organic nitrogen in the soil that is converted into a form that can be used by plants through the action of microorganisms, i.e., the amount of available nitrogen) was determined by Eq.(3) for black loam soil in the estimation model (Miyagi Prefectural Agricultural Center, 1993).
As a result, the amount of available nitrogen in the soil was estimated to be 6.7 kg and 5.9 kg of available nitrogen before rice planting and after, cultivation respectively, and the reduction in available nitrogen was estimated to have contributed to 4.5 kg of fixed nitrogen in the paddy rice.

$$Y=2.32X^{0.79} \tag{3}$$

where X: soil humus content.(%),Y: amount of available nitrogen(Air-dry soil 30°C, 4 weeks incubated in water; NH4-Nmg/100g dry soil).

Table1 Nitrogen balance in the process from reservoir to farm field

	Nitrogen supplied from reservoirs (kg*)	Nitrogen supplied to paddy soil (kg*)	Fixed nitrogen in paddy rice (kg*)	Available nitrogen in humus of paddy soil before rice planting (kg*)	Available nitrogen in humus of paddy soil after rice cultivation (kg*)
Nitro-gen (kg*)	1.3	n.a.	4.5	6.7	5.9

*Nitrogen Equivalent

4.2 Estimation of nitrogen from humus using UAV hyperspectral sensor

4.2.1 Measurement Method

Hyperspectral data of the field prior to rice planting was generated by aerial photography of the entire field using a UAV (Matrice600 DJI) equipped with a hyperspectral sensor (Nano-Hyper Headwall) and automated operation as Figure 4. The hyperspectral sensor used in this study stores 270 wavelengths in the range of 400 nm to 1000 nm in a single image. The UAV hyperspectral sensor was used to capture images of the field before rice planting, and the obtained data was stored as a data cube containing 270 bands and used for data analysis.

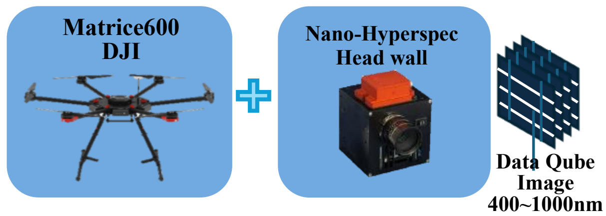

Figure 4 Measurement method by UAV hyperspectral sensor

4.2.2 Estimation of nitrogen from humus using UAV hyperspectral sensor

Since the 270 wavelengths captured are a mixture of wavelengths that respond highly to soil nitrogen and wavelengths that respond less to nitrogen, a random forest was used to select variables for the wavelengths to be used.
Next, the objective variable was the nitrogen content of the sample soil, and the explanatory variable was the reflectance of the wavelengths that reacted highly to nitrogen, and the Akaike Information Criterion (AIC) was used to find the best combination of wavelengths. In this study, wavelengths were combined in three patterns of 2, 5, and 10 wavelengths, and multiple regression analysis was conducted using the selected wavelengths. Among the regression models obtained from the multiple regression analysis, the regression model with the highest coefficient of determination and the lowest AIC was used as the estimated model for nitrogen content.
Finally, the soil weight of the field was determined by assuming the area of the field to be 1680 m^2, the crop depth to be 10 cm, and the soil density coefficient to be 1.0, and the nitrogen content of the field was estimated by multiplying the soil weight of the field by the nitrogen content of the soil determined from the estimated model of nitrogen content.Estimation flow is shown as Figure5.

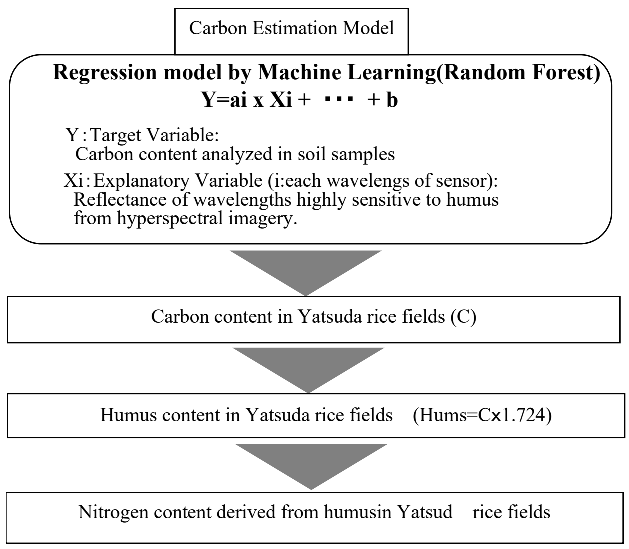

Figure 5 Estimation flow of nitrogen from humus using UAV hyperspectral sensor

The carbon content measured by the NCH coder was used as the objective variable and the reflectance of the spectrum at each frequency emitted from the hyperspectral center at the measured value point as the explanatory variable, with wavelength selection selected using a random forest. Among the combinations, the combinations with P-values less than 0.5 and the lowest AIC were the 16 wavelength combinations for which Equation (4) was used to estimate the carbon content of the field. Figure6 shows the correlation of regression.

Among the wavelengths selected in this study, many wavelengths near 400 nm were extracted; the wavelength near 440 nm is the peak of fulvic acid, which may indicate that the wavelengths reacting to humic substances that are highly correlated with nitrogen were extracted. The wavelength at 948 nm is in the near-infrared region, which may indicate the extraction of wavelengths that react with plant residues in the soil.

Namely the area of the field: 1,680 m2, the depth of the crop soil layer: 10 cm, and the provisional weight of 1.0 were used to determine the amount of humus from the soil weight of the field, and the amount of available nitrogen in the soil that plants by Hyperspectal sensor is estimated as 7.3kg.

$$y = 3.43 - 4.57x_{404.808} - 3.70x_{407.046} - 0.79x_{413.76} + 3.58x_{415.998} - 3.97x_{424.95} - 7.84x_{431.664} + 19.64x_{436.141} - 7.56x_{442.855} + 0.07x_{507.758} + 2.50x_{724.85} - 0.22x_{838.991} + 5.72x_{932.99} - 2.84x_{937.466} - 5.19x_{948.656} - 1.18x_{966.56} - 0.31x_{971.037} \quad (4)$$

Where xi:: reflectance and i:wavelength of hyperspectral sensor,

Figure 6 Correlation between carbon content (objective variable) vs. hyperspectral sensor reflectance by frequency (explanatory variable) estimated by regression equation

The humus content of each cell is estimated by multiplying the carbon content estimated by equation (4) by 1.742. Figure 7 shows the spatial distribution of carbon content and humus in the field. This shows the distribution of humus and provides information on the distribution of humus-derived nitrogen, which can provide information to correct the distribution of organic compost. Furthermore, the amount of humus in each cell can be summed to obtain the amount of available nitrogen using equation (3).

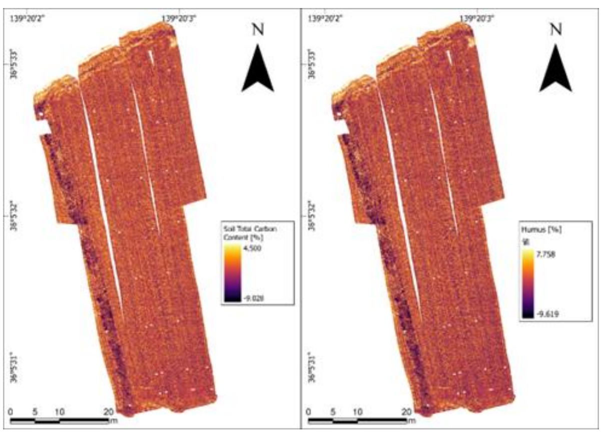

Figure 7 Spatial distribution of carbon and hums by UAV Hyperspectral sensor

4.3 Assessment of biogenic nitrogen supply potential by soil microorganisms

In addition to the nitrogen supply sources we have studied so far, it has been reported that humus generated from rice straw and organic matter from reservoirs is converted to available nitrogen by soil microorganisms and supplied to rice paddies, but the amount of humus is still unknown because many soil microorganisms have not been identified and their amounts cannot be determined using environmental DNA(eDNA) or other methods (Hosoya, 2017). The amount of paddy rice has not been clarified yet. In this study, BIOTREX by Yokoyama were used as a scientific and objective method to evaluate soil biological properties, and the diversity of organic matter decomposition ability of microbial communities in soil was examined by quantifying the diversity (Yokoyama,1996).

The measured BIOTREX value before rice planting was 903,209, indicating that rich soil components derived from the reservoir flowed into the field.

The reduction of 0.8 kg of avalable nitrogen before rice planting and after cultivation (Decrease of available nitrogen in humus of paddy soil 6.7-5.9kg in Table1 may have contributed to 0.8kg of nitrogen fixed in the paddy rice. This indicates that if the BIOTREX value is high and the amount of soil microorganisms is high, the potential amount of nitrogen that can be fixed in paddy rice as inorganic nitrogen could be an indicator of whether or not more fertilizer should be added than necessary(Figure8).

5. CONCLUSIONS

This study showed the possibility of determining the distribution of humus from the distribution of carbon and nitrogen in a paddy field by using a UAV hyperspectral sensor, a random forest, and AIC.

We showed that the nitrogen balance can be evaluated from the balance of soil-derived nitrogen and humus-derived available nitrogen in reservoirs, rainfall, and rice paddies by chemical analysis.

By combining this with BIOTREX, it was shown that when humus-derived available nitrogen is high and BIOTREX values are high, the change of organic nitrogen in humus to inorganic nitrogen is promoted. However, when chemical fertilizers were abundant, even with high BIOTREX values, the amount of change to inorganic nitrogen was suppressed, indicating that soils with high organic matter and high BIOTREX values do not require chemical fertilizers.

This suggests that BIOTREX can be used as an indicator of the necessity for chemical fertilizers. In the future, we would like to conduct similar measurements in many fields and increase the number of measurements made with BIOTREX to examine its applicability as an indicator of the need for chemical fertilizer application in the field and its validity as a tool for soil quality assurance in organic farming.

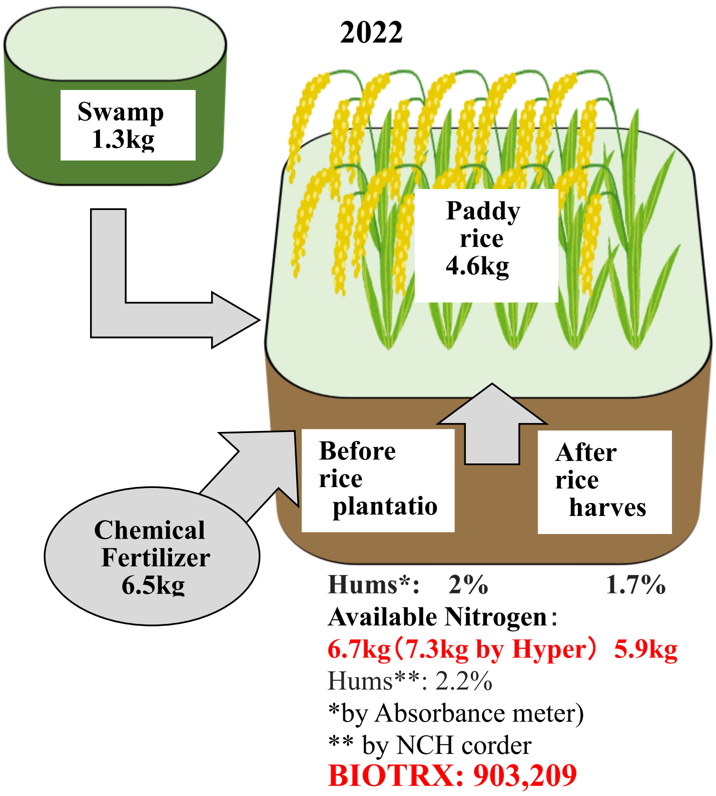

Figure8 Nitrogen balance from Swamp-to "Yatsuda" rice field

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