IMPROVE TEMPORAL CONSISTENCY OF SATELLITE CONSTELLATION IMAGE TIME-SERIES FOR FARMLAND ABANDONMENT DETECTION

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ABSTRACT: Farmland abandonment causes environmental and socio-economic issues. Satellite remote sensing has been used to map the spatial distribution of abandonment. The satellite constellation is a promising data source for abandonment mapping because of its high temporal and spatial resolution. PlanetScope is one of the nanosatellite constellations with a multispectral sensor (Blue, Green, Red, and NIR). The constellation consists of about 130 satellites and can capture vegetation dynamics with about 4-meter ground sample distance and short revisit time. However, the cross-sensor inconsistency of PlanetScope and differences in atmospheric conditions make reflectance values temporally variable. That causes a problem for time-series data analysis and farmland abandonment detection based on phenology. To cope with the problem, we explored the applicability of the established image normalization technique for satellite constellation image time-series. Satellite images were corrected by Automatic Radiometric Normalization, which automatically selects pixels and calculates an orthogonal regression line expressing the linear relationship between two images. Temporally consistent Normalized Difference Vegetation Index (NDVI) time-series were generated using the method. The NDVI time-series were used as input for the rule-based classification. Considering the main crop in Japan and a degree of abandonment, two types of pixel-wise binary classification were conducted. First is paddy field vs. abandoned farmland with herbaceous vegetation (Paddy vs. Abandoned (herbaceous)). Second is paddy field vs. abandoned farmland with woody vegetation (Paddy vs. Abandoned (woody)). Our approach was tested in Ami-town in Japan. Cloud-free 16 PlanetScope images in 2018 were used for classification after clipped by farmland parcel polygon. Pixels with high NDVI in specific dates were classified as abandoned farmland by a rule-based classifier. Classification results were validated by ground truth collected based on field surveys. Kappa coefficient of Paddy vs. Abandoned (herbaceous) classification improved from 0.255 to 0.786 when image normalization was applied. Kappa coefficient of Paddy vs. Abandoned (woody) classification also improved from 0.560 to 0.887 when image normalization was applied. These results suggest that the image normalization technique improves satellite constellation image time-series consistency and allows abandoned farmland detection based on phenology.

1. INTRODUCTION

Farmland abandonment is defined as "the cessation of agricultural activities on a given surface of land" (Pointereau et al., 2008) and spread over the world. This land-use has important impacts on, for example, food security (Xie et al., 2014). Therefore, an accurate abandonment map and grasping the current situation of abandonment is needed. However, creating a map requires much effort, so it is difficult to generate annual maps of abandonment with high spatial resolution. Satellite remote sensing observation is repetitive and covers a wide area. Therefore, it helps the reduction of the effort to create an abandonment map. Existing research has used various satellite images to detect abandoned farmland (Dara et al., 2018; Estel et al., 2015). MODIS with high temporal resolution and coarser spatial resolution can capture temporal changes in vegetation. Therefore, farmland abandonment can be detected based on seasonal vegetation changes. On the other hand, Landsat can observe smaller land parcels by its middle temporal and spatial resolution. Mapping using Landsat or MODIS was reliable; for example, the average overall accuracy was 90.1% across Europe using MODIS (Estel et al., 2015), and overall accuracy was 89% in northern Kazakhstan using Landsat (Dara et al., 2018). However, the middle or coarser spatial resolution makes it difficult to apply these methods to the region characterized by smaller farmland parcels. In Japan, the average size of operating cultivated land per agricultural management entity is 2.54ha, and the median is less than 1.0ha in 2015 (Cabinet Secretariat Ministry of Economy, Trade and Industry). Abandoned farmland is often smaller, so it is challenging to detect abandonment by middle spatial resolution. In addition, the limitation by the trade-off between temporal and spatial resolution in a single satellite makes it challenging to detect abandonment in small parcels based on the phenological profile of farmland. One of the options available in recent years to achieve both temporal and spatial resolution is satellite constellation using many satellites.

A satellite constellation is described as "a number of similar satellites, of a similar type and function, designed to be in similar, complementary, orbits for a shared purpose, under shared control" (Wood, 2003). PlanetScope is one of the nanosat constellations operated by Planet. PlanetScope consists of more than 130 satellites and acquires images of the entire earth every day at a 3.7 m Ground Sample Distance (GSD) (Planet, 2019). In a satellite constellation, multiple satellites observe the land surface. Therefore, it is possible to observe the same place with short time intervals. Frequent observation makes it possible to obtain detailed information about land cover changes. Since the trade-off between temporal resolution and spatial resolution is eliminated, each satellite can be equipped with a sensor with a higher spatial resolution. These features serve to detect abandoned farmland.

However, Houborg pointed out that "the relatively low radiometric quality and cross-sensor inconsistencies" (Houborg and McCabe, 2018) is a crucial problem in observation by PlanetScope. In addition to the problem, there is also another problem with farmland abandonment detection using PlanetScope time-series. In other words, the atmospheric conditions vary depending on the observation date and orbit, so the consistency of time series data is not guaranteed. These cause a problem for time-series data analysis and farmland abandonment detection based on phenology. Phenology is vegetation dynamics such as greenup or senescence (Zhang et al., 2003). Therefore, image correction is necessary to ensure data consistency between the sensor and the observation date. We applied the established image correction method, Automatic radiometric normalization (Canty et al., 2004). This method has been established for Landsat, but its application in a satellite constellation has not been investigated. Moreover, there are few studies to use satellite constellation image time-series for the detection of abandoned farmland. The satellite constellation is a new data source for detecting abandoned farmland, and it is crucial to consider the correction method for this time series image. Therefore, in this study, we examine the effect of the image correction method for detecting abandoned farmland.

2. METHOD

2.1 Study area

The study area is Ami-town, Ibaraki Prefecture, Japan. In Ami, the abandoned land rate in 2015 was 36.84% (Cabinet Secretariat Ministry of Economy, Trade and Industry), which is about three times the average abandoned land rate in Japan (12.14%) (Cabinet Secretariat Ministry of Economy, Trade and Industry). Figure 1 shows the study area. Satellite images used in this study cover about 12 km^2. The reflectance product of the satellite constellation PlanetScope (Planet Team, 2017) was used. PlanetScope has four spectral bands; Blue: 455 - 515 nm, Green: 500 - 590 nm, Red: 590 - 670 nm, and Near-infrared: 780 - 860 nm (Planet, 2019). Revisit time is nearly daily, and ground sample distance at nadir is 3.7 meters (Planet, 2019). We used only PS2 images even though PlanetScope has some instrument types of satellites (PS2, PS2.SD, PSB.SD) (Planet, 2019). That is because the number of available PS2 images is larger than that of other instrument types.

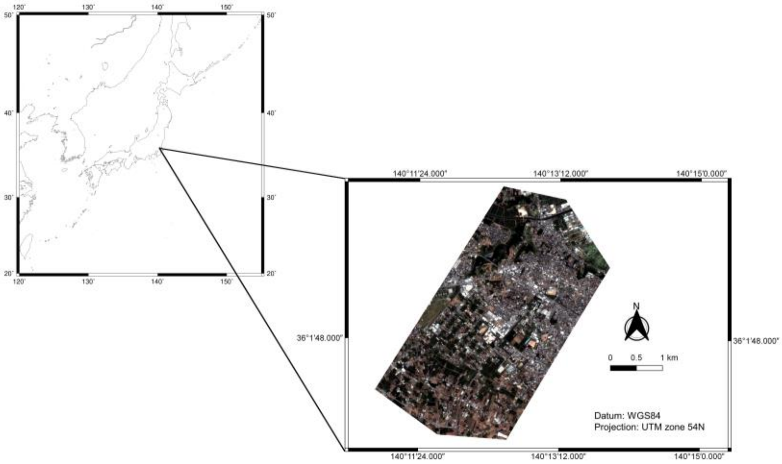

Figure 1 A location of the study area in the Ami-town, Ibaraki, Japan. PlanetScope image was acquired on July 2nd, 2018, and displayed in false-color, RGB=Band4, Band3, Band2.

2.2 Satellite data

The image acquisition period is from April 13th, 2018, to November 2nd, 2018, which corresponds to DOY 103-306. We used 16 cloud-free images during the period. When one scene did not cover the entire area of the survey area, adjacent images were used together. The data were retrieved on May 28th, 2019. Table 1 shows the list of used images.

Table 1 Sixteen PlanetScope scenes were used for abandonment detection in 2018.

No.	ID	Acquisition date	DOY	Cloud cover	Same date
1	20180413_004938_0f17	2018/04/13	103	0-1%	
2	20180420_004949_101d	2018/04/20	110	0-1%	
3	20180429_010338_0f46	2018/04/29	119	0-1%	
4	20180505_005112_0f15	2018/05/05	125	0-1%	
5	20180511_005039_1005	2018/05/11	131	0-1%	
6	20180516_010130_0f4d 20180516_010131_0f4d	2018/05/16	136	0-1%	○
7	20180522_005019_1033	2018/05/22	142	0-1%	
8	20180603_005124_0f25 20180603_005125_0f25	2018/06/03	154	0-1%	○
9	20180702_005457_0f3c	2018/07/02	183	0-1%	
10	20180801_005316_1034	2018/08/01	213	0-1%	
11	20181002_005438_1029	2018/10/02	275	0-1%	
12	20181007_005609_0f4e	2018/10/07	280	0-1%	
13	20181022_005540_1014	2018/10/22	295	0-1%	
14	20181025_003709_1051	2018/10/25	298	0-1%	
15	20181030_005105_0e2f	2018/10/30	303	0-1%	
16	20181102_005601_1022 20181102_005603_1022	2018/11/02	306	0-1%	○

2.3 Class setting

Three classes have been set up for classification (Table 2). Abandoned farmland with herbaceous plants, abandoned farmland with herbaceous and woody plants, and paddy file for rice. These classes are called Abandoned (herbaceous), Abandoned (woody), Paddy, respectively. Urban areas and forests, which are areas other than agricultural land, were excluded in advance based on the Agricultural Land Information System (National Chamber of Agriculture) and field survey. The exclusion is conducted by clipping satellite images using farmland parcel polygon. The class-wise images produced by the parcel polygons were converted to ASCII data using ENVI Classic 5.4 (ESRI) for data processing.

Table 2 Class and definition.

No.	Class	Definition
1	Abandoned (herbaceous)	Abandoned farmland where herbaceous plants grow.
2	Abandoned (woody)	Abandoned farmland where herbaceous plants and woody plants grow.
3	Paddy	Paddy fields for rice.

2.4 Reference data

In this study, the binary classification was performed. Satellite images were clipped using parcel polygons for each class to perform a class-wise analysis. Parcel polygons mean the boundaries of the farmland created as shapefile. Parcel polygons were created based on field observations conducted in November, December, and March 2019. Using false-colored PlanetScope satellite images and high-resolution aerial photographs from Google Earth^{TM}, polygons inconsistent with the field survey and polygons with undefined classes were removed. For example, polygons of farmlands classified as abandoned farmlands in the field survey but had no vegetation in the summer, or farmlands with a mixed land cover were deleted. Figure 2 shows the PlanetScope image of Ami Town and parcel polygons.

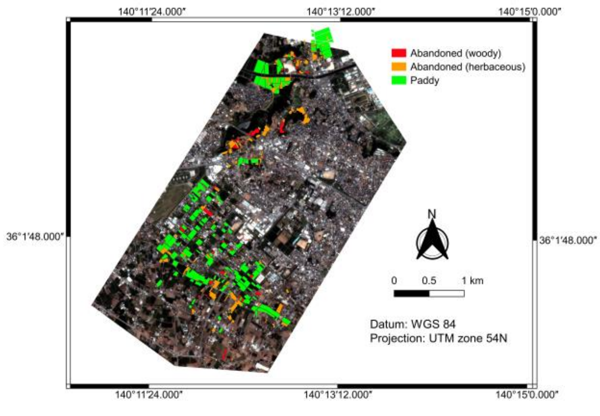

Figure 2 The spatial distribution of parcel polygons. These objects are overlaid on a PlanetScope image (acquired on July 2nd, 2018, and displayed in false-color, RGB=Band4, Band3, Band2). The colors of the polygons are separated based on agricultural land-use types that we sampled by field surveys in the study area.

2.5 Image correction and NDVI time-series generation

Reflectance for each band was normalized by Automatic radiometric normalization (Canty et al., 2004). This method uses Multivariate Alteration Detection (MAD). MAD is a method that selects pixels that change little between two images based on canonical correlation analysis. Pixels that change little with time are called invariant pixels. From the selected pixels, an orthogonal regression equation for the band value at each time is calculated. Images with different shooting conditions are normalized to be consistent with the reference image by applying this formula to images. The normalization was performed based on the image on July 2nd, 2018. The reference image of normalization was selected because the image on July 2nd, 2018, was judged as the clearest scene in all images by visual interpretation. In MAD, the change index between pixels in two periods follows the χ^2 distribution (Canty et al., 2004). Therefore, we used the pixels whose change index for the two periods corresponds to a lower cumulative probability of 0.01 or less in the χ^2 distribution suggested by Canty (Canty et al., 2004). Note that the linear function for normalization was generated based on the full scene over the study area once, and the single function was applied to all three classes (Abandoned (herbaceous), Abandoned (woody), Paddy).

Abandoned farmland was identified based on the Normalized Difference Vegetation Index (NDVI), widely used for farmland abandonment detection (Alcantara et al., 2012; Estel et al., 2015). The NDVI was calculated for each pixel from the following equation using the reflectance normalized for each band.

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}}, \tag{1}$$

where NIR and RED are the red spectral reflectance and the near-infrared spectral reflectance, respectively. NDVI was calculated for each scene, and NDVI time-series was generated for each pixel.

2.6 Classification and accuracy assessment

Considering the main crop in Japan and a degree of abandonment, two types of pixel-wise binary classification were conducted. First is paddy field vs. abandoned farmland with herbaceous vegetation (Paddy vs. Abandoned (herbaceous)). Second is paddy field vs. abandoned farmland with woody vegetation (Paddy vs. Abandoned (woody)).

A rule-based classifier using NDVI thresholds (Fukumoto and Yoshisako, 2014; Yusoff and Muharam, 2015; Zukemura et al., 2011) was used for the classifications. This classifier uses NDVI thresholds based on empirical knowledge of phenology in farmland; abandoned farmland has high NDVI over a year, while NDVI in active farmland varies according to season. The increase of NDVI is caused by crop growing, and the decrease of NDVI is caused by plowing or harvesting. Each pixel was classified as abandoned farmland when it exceeded the NDVI threshold set on a specific date and classified as active farmland when it fell below the NDVI threshold. The threshold was selected based on visual interpretation of the NDVI time series obtained from the training data. The validation data were classified based on a predefined threshold. The number of all pixels in each class is 12381 (Abandoned (herbaceous)), 3784 (Abandoned (woody)), 40845 (Paddy), respectively and training data and validation data were equally divided by simple random sampling.

For accuracy assessment, four accuracy indices were used: kappa coefficient, Overall accuracy, Producer's accuracy, and User's accuracy. These indices were calculated based on the confusion matrix of validation data.

Figure 3 describes the process of preprocessing and classification.

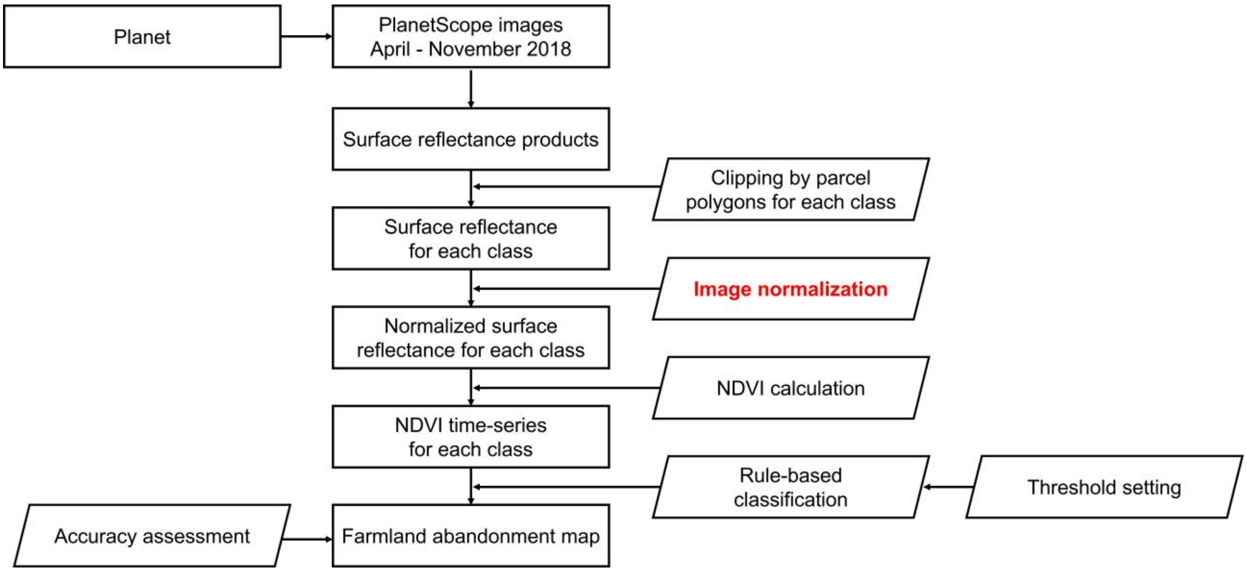

Figure 3 Flowchart representing the major steps of image preprocessing and abandoned farmland classification.

3. RESULTS

3.1 NDVI time-series and threshold setting

Figure 4 shows the results of comparing the NDVI time-series calculated using normalized reflectance and NDVI time-series calculated using not normalized reflectance. Firstly, NDVI in July does not change by normalization because this image is the reference of normalization. Secondly, NDVI in April increase and become close to NDVI in July because NDVI in July is high. Finally, even though NDVI in April and November become higher than the original images, the seasonal change of NDVI remains.

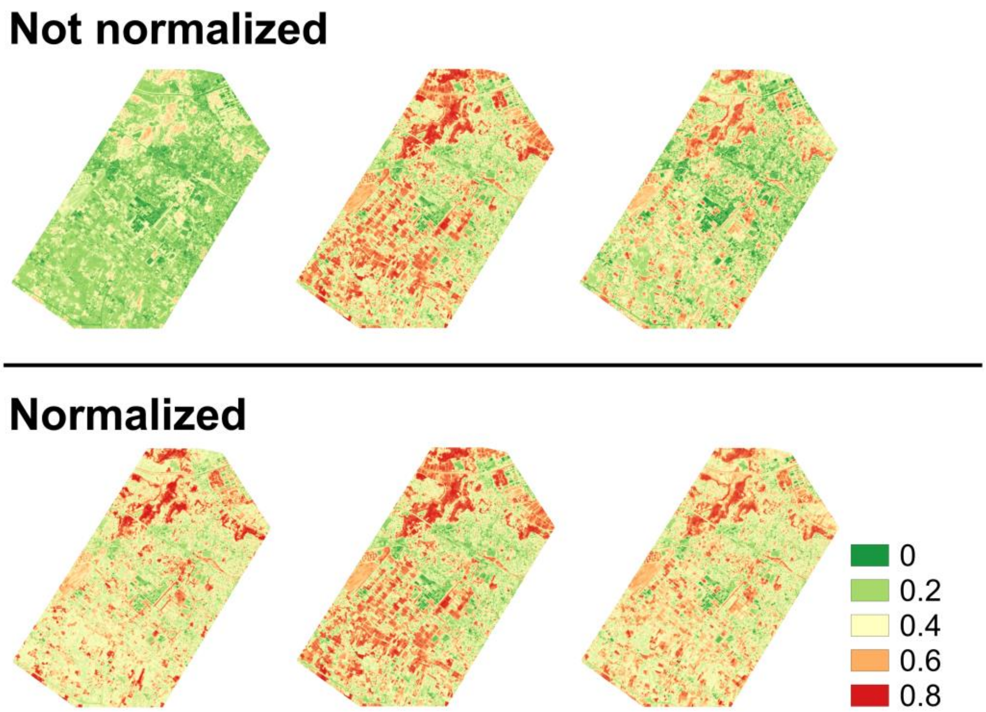

Figure 4 NDVI time-series of April 13th (left), June 2nd (center), and November 2nd (right).

Figure 5 shows the NDVI time-series calculated using normalized reflectance and NDVI time-series calculated using not normalized reflectance. Each line shows the NDVI time-series of each pixel in each class.

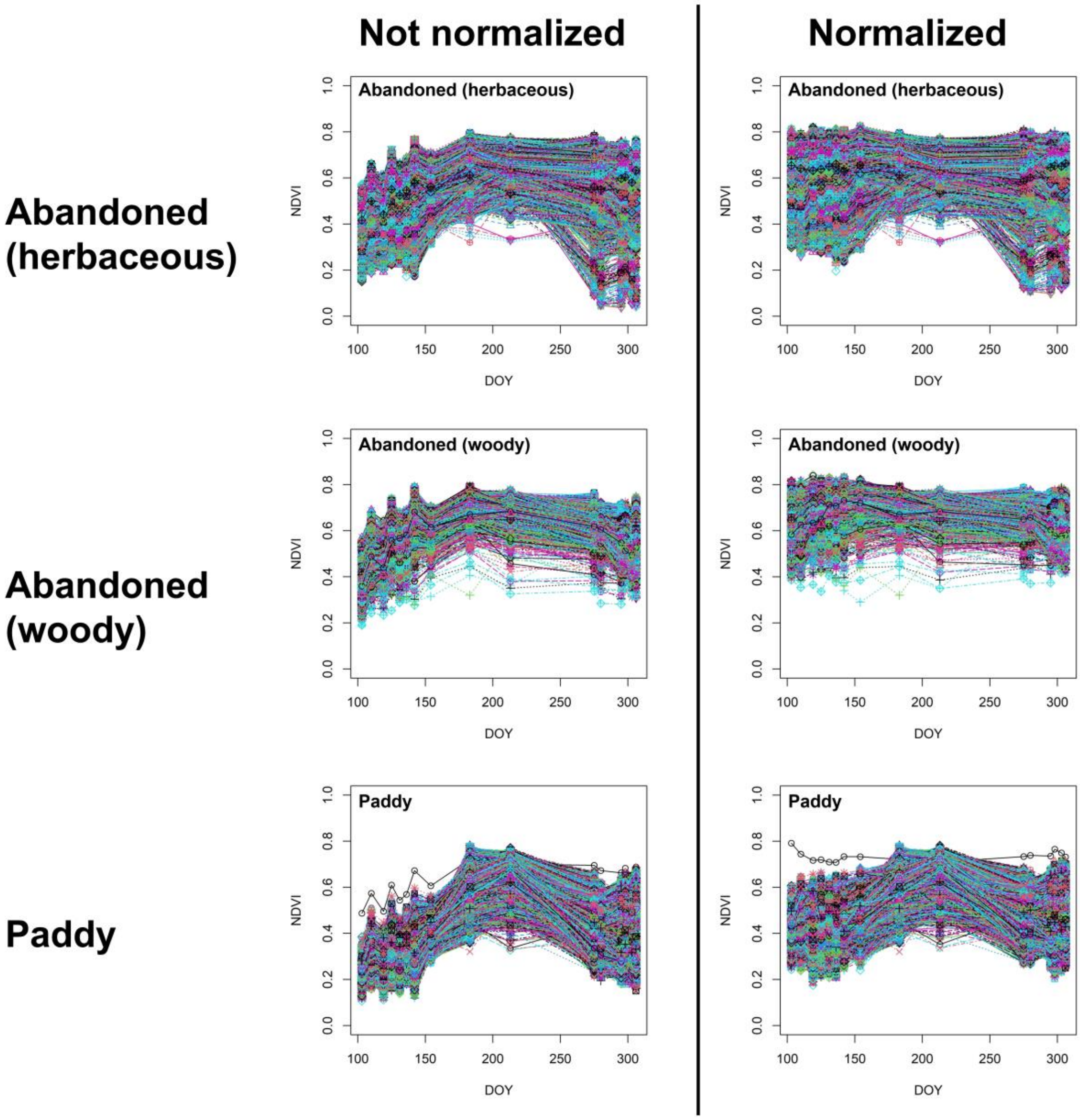

Figure 5 Comparison of NDVI time-series. Left: NDVI was calculated using original reflectance, right: NDVI was calculated using normalized reflectance.

Usually, NDVI does not increase or decrease in the short term, but such short-term fluctuations are not normalized in the image and can be seen at Day of Year (DOY) = 100 to 150. This variation is reduced in the normalized image.

3.2 Threshold setting

As the threshold value used for rule-based classification, the same value was used regardless of whether the normalization was applied. One is NDVI = 0.4 at DOY = 103 and the other is NDVI = 0.6 at DOY = 280. Pixels with NDVI higher than the threshold in these two periods were classified as abandoned farmland. The former threshold is set in early April, and this time is before transplanting rice. The latter threshold is set in early October, which is after the rice harvest season.

3.3 Classification results and accuracy

Figure 6 and 7 show the farmland abandonment map for Abandoned (herbaceous) vs. Paddy, and Abandoned (woody) vs. Paddy.

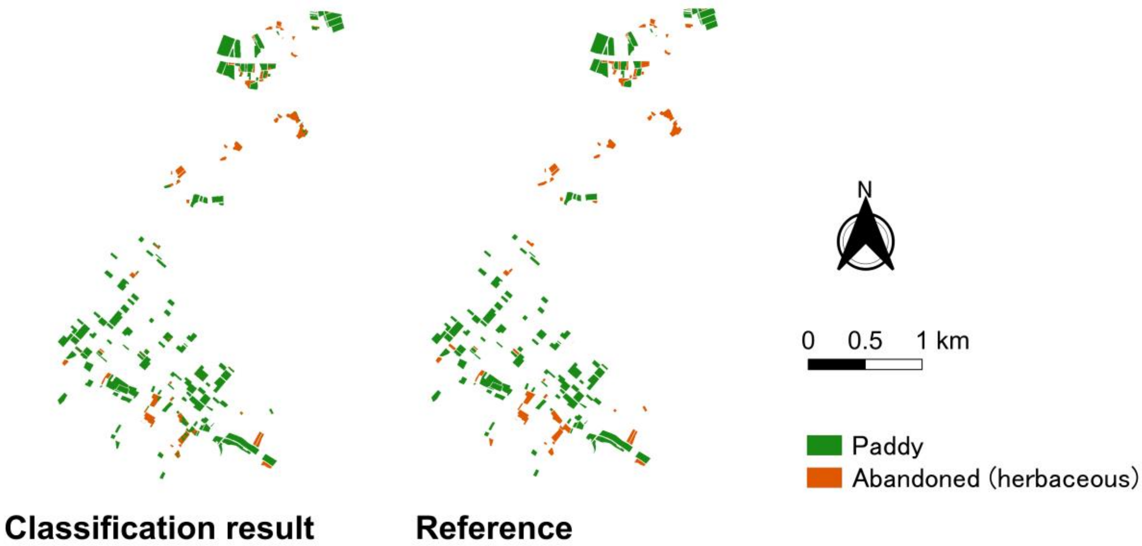

Figure 6 Farmland abandonment map for Abandoned (herbaceous) vs. Paddy. Left: classification result, right: reference data.

Figure 7 Farmland abandonment map for Abandoned (woody) vs. Paddy. Left: classification result, right: reference data.

The classification accuracies of paddy fields and abandoned farmland based on normalized reflectance were different from the classification accuracies based on not normalized reflectance (Table 3). Kappa coefficient of Paddy vs. Abandoned (herbaceous) classification improved from 0.255 to 0.786 when image normalization was applied. Kappa coefficient of Paddy vs. Abandoned (woody) classification also improved from 0.560 to 0.887 when image normalization was applied.

Table 3 Accuracy of two binary classifications; Abandoned (herbaceous) vs. Paddy and Abandoned (woody) vs. Paddy. The classification results based on normalized reflectance and not normalized reflectance are contrasted.

	Abandoned (herbaceous) vs. Paddy		Abandoned (woody) vs. Paddy	
	Not normalized	Normalized	Not normalized	Normalized
Kappa coefficient	0.255	0.786	0.560	0.887
OA (%)	81.0	93.0	95.0	98.3
PA [Abandoned] (%)	18.2	73.1	41.0	89.7
PA [Paddy] (%)	100.0	99.0	100.0	99.0
UA [Abandoned] (%)	100.0	95.8	100.0	89.6
UA [Paddy] (%)	80.1	92.4	94.8	99.0

4. DISCUSSION

This study aims to investigate the applicability of the established image normalization technique for satellite constellation image time-series. That is important because PlanetScope image time-series has problems in the cross-sensor inconsistency and differences in atmospheric conditions. These cause a problem for time-series data analysis and farmland abandonment detection based on phenology.

The improvements of accuracies indicate that image normalization is effective for identifying abandoned farmland based on phenology. Automatic radiometric normalization using MAD is a relative correction that assumes a linear relationship between two images. It can correct not only the inconsistency between sensors but also the difference in atmospheric conditions depending on the observation date. Eliminating such fluctuations is essential for observing the phenology of vegetation. Therefore, it is considered useful in classification based on phenology using a satellite constellation that uses multiple sensors.

There are some uncertainties and limitations in this study. Firstly, the field survey was conducted from November 2018 to March 2019 from autumn to spring. Therefore, class label judgment may be wrong because weeds on abandoned farmland die in winter, making it difficult to judge. Secondly, the NDVI thresholds for rule-based classification is empirically determined and is not always the optimum one. Thirdly, only binary classifications between paddy field and abandoned farmland were conducted. Therefore, discrimination between the vegetable fields and abandoned farmlands should be considered in the future. Also, further research is needed for the multi-class classification. Fourthly, we used only cloud-free images. The number of available images is small so that we can not capture phenology fully. Therefore, we should increase the number of images used. If we use cloud-contaminated images, the effect of clouds, such as a decrease of NDVI, should be reduced.

5. CONCLUSION

We applied an established image normalization method to the satellite constellation PlanetScope images with high spatial resolution and high temporal resolution. The method ensured image consistency and corrected for increases and decreases of NDVI happened in the short-term. Based on the NDVI time series obtained from the corrected images, abandoned farmland was detected. Accuracy of the abandoned farmland classification improved by the image normalization. That suggests that this method is useful for the abandoned farmland detection based on phenology. This study also highlights the potential of satellite constellation to map farmland abandonment with high spatial and temporal resolution.

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