Understanding temporal and spatial variation of soil available nutrients with satellite remote sensing

Meng Jihua [1] Fang Huiting[1,2] Cheng Zhiqiang [1]

1 Key Laboratory of Digital Earth, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, China

2 College of Resources and Environment, University of Chinese Academy of Sciences, Beijing, China

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Abstract. *Soil available nutrients are the key determinants in crop growth, field stable output and ecological balance. The soil nutrients loss and surplus can strongly influence the stability of field ecological environment and cause unnecessary pollution. Hence, optimizing the status of soil available nutrients status has significant ecological and economic significance. With the advancement of mechanized farming and control technologies, soil available nutrients can be optimize by variable rate fertilization. The effective and stable soil available nutrients variation simulation of the entire region in a large time-span is necessary before the corresponding control measures can be applied. However, the base soil available nutrients are usually variable between and within growth season, making common methods impossible to simulate the temporal and spatial variation with the required precision. Thus in this study, we introduce a new method to map soil available nutrients by integrating the crop model and time series remote sensing data. We select the World Food Studies (WOFOST) and time series HJ-1 CCD data to retrieve the soil available nutrients variation in Shuangshan farm, Northeast China. And the spatial heterogeneity can be effectively estimated within the growth season. Because the farm is implementing uniform fertilization management through last 5 years, the temporal variation can also be simulated using transformation algorithms. The soil available nutrients contents were simulated and analyzed in two ways. Firstly, we applied the simulation method to the study area in recent five years to monitor the inter-annual variation and analyzed the variation inducement. The results indicated that crop growth and precipitation intensity can both bring variations between years and plots. The within-year variation was also analyzed by estimating the soil available nutrients contents of the whole growth season with the step of five days which showed that the nutrients contents presented downtrend basically while the variation can be quite different among plots. In general, the temporal and spatial variation of soil available nutrients under uniform fertilization condition can be simulated with high stability and accuracy. Appropriate fertilization measures can also be developed to protect field ecological environment based on the analysis of simulation results.*

Keywords. *soil available nutrients, spatial and temporal variation, WOFOST, fertilization, HJ-1 CCD.*

I. Introduction

The spatio-temporal variation of soil available nutrients and its influencing factors are benefit to comprehend the dynamic evolution of soil quality and its causes. With the rapid development of precision agriculture, the analysis of temporal and spatial variation of soil available nutrients is attracting more and wide attention. AN, AP and AK are the key factors that determine crop growth, stable farmland output and ecological balance. Because of soil property, landforms, precipitation, fertilization and other reasons, the soil available nutrients show a high degree of spatio-temporal variability(Du et al.2014; Darilek J et al.2009; Cheng et al.2004; Xu et al.2011).Traditional agricultural does not consider this variation normally, and take a unified fertilizer management to each crop plot. Fertilizing in this way not only reduces the utilization of resources but also causes pollution of the water bodies in the area. Therefore, studying the spatio-temporal variation of soil available nutrients has important guiding significance in protecting the soil environment, ensuring grain yield and promoting the sustainable development of agriculture.

There have been many analyzes of soil nutrient variability based on the geostatistics theory created by Matheron (Qui et al.2016; Sun et al.2003; Huang et al.2002), but the time consuming and uncertainties have limited its use. Monitoring soil nutrients with remote sensing technology can well overcome the shortcoming of geostatistical methods that the spatial variability is not evident. Soil nutrient extraction based on remote sensing indices and corresponding statistical analysis methods is currently being used. Remote sensing vegetation index was used to monitor soil organic matter and total nitrogen content(Meng et al 2015;Zhang et al.2010). Soil nutrient prediction model was constructed by using hyperspectral remote sensing data and regression analysis(GOMEZ et al.2008;Casa et al.2013;Hbirkou et al.2012). However, the accuracy and stability of those empirical statistical models are often not guaranteed. Remote sensing data assimilation method, combined with crop model can realize the dynamic monitoring of crop growth(Huang et al.2016;Cheng et al.2016;Cheng et al.2018), which makes the real-time and effective monitoring of soil nutrients in different crop growth stages come true. However, many researches on soil nutrient changes have been conducted on an annual scale, and few on a smaller time scale like during growth season. At present, many studies were for large spatial scales, in which case soil type was considered as the dominant factor of soil nutrients variation(Kang et al.2016;Yang et al.2008). Those researches on the farmland scale were more about single-crop farmland (Sun et al.2014;Xia et al.2005). However, the spatial variability of soil nutrients based on multi-crop under balanced fertilization management is rarely studied.

In this paper, we applied new methods of mapping soil available nutrients to Shuangshan farm located in Nehe, Heilongjiang Province. Soil AN, AP and AK were retrieved from the WOFOST crop model and the HJ-1 CCD data, which collected from 2012 to 2016. Classical statistics, geostatistics and correlation analysis were used to analyze the variation characteristics of soil available nutrients within year and during the growth season with the step of five days. The main factors of soil available nutrients change were analyzed from the perspective of topographical, meteorological conditions and crop rotation system. Moreover, the rule what we found could be used to provide theoretical basis for ecological balance protection and variable fertilization.

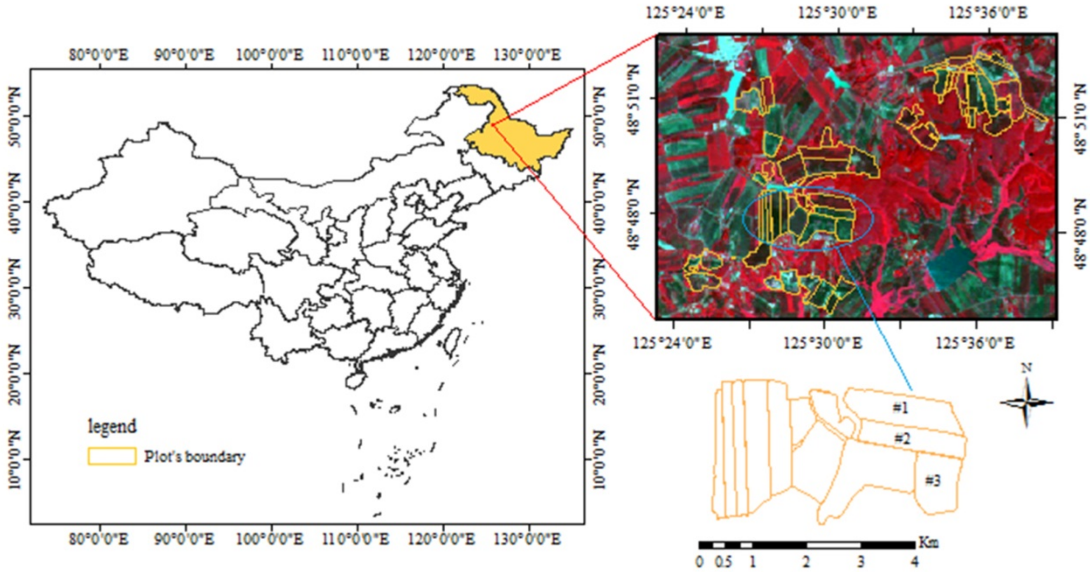

Fig 1. Location of Shuangshan farm and the distribution of research plots, three of which were numbered #1,#2 and #3

II. Materials and Methods

1. Study Area

The study area is located at 48 ° 45'35 "-48 ° 52'36" N, 125 ° 24'22 "-125 ° 38'26" E at Shuangshan farm in Nehe, Heilongjiang(Fig 1). The total area of the farm is 39km^2, and the average plot size is about 850 acres. The overall slope of the farm is mostly in the second grade, which is undulating (2 ° ~ 6 °). The major crops grown on the farm were spring maize, soybeans and wheat, with about 90% of the plantation area, of which more than 50% land was planted with spring maize. Crops were planted by one-harvest-a-year, generally sown in late May and mature in late September to early October. The upper layer of the farm's soil is black soil with the thickness of about 1.2 meters and a lot of humus and nutrients, in which our analyses were conducted. The lower layer is sandy soil with the thickness of more than 10 meters and low fertility. In this study, all the farm crops were under uniform fertilization management during the five-year continuous observation period of 2012-2016 in the experimental farm. In addition, the same fertilization mode was applied to the plots of the same crops.

2. Data sources

The data used in this paper was divided into remote sensing data and basic data, which contained meteorological data, topographic data and crop distribution map. The local meteorological history data provided precipitation, temperature and other climate information. The digital elevation(DEM) data of 30m resolution was obtained from the computer network information of Chinese Academy of Sciences. The crop distribution was mapped basing on farming plan and remote sensing image classification results, which were the spatial distribution of the three crops: maize, soybean and wheat between 2012 and 2016. The remote sensing data used in this study was time-series HJ-1CCD data collected from the Environment and Disaster Monitoring and Forecasting Small Satellite Constellation A and B Small Satellites(HJ-1A/1B Satellites). A total of 55 images were taken during 2012-2016. The time series HJ-1CCD data used in 2014 are shown in Tab 1. The remote sensing image preprocessing included radiation calibration, atmospheric correction, geometric refinement. The distribution of soil available nutrients were retrieved by the WOFOST crop model with the results of remote sensing data assimilation within year and during the growth season with the step of five days(Cheng et al.2016).

Table 1. Time-series HJ-1 CCD data of Shuangshan Farm used to retrieve soil available nutrients

sensor	acquisition time	orbit number

HJ-1A CCD1	2014-5-03	451-52
HJ-1A CCD2	2014-6-06	448-56
HJ-1A CCD1	2014-6-23	453-53
HJ-1A CCD1	2014-8-06	451-56
HJ-1B CCD2	2014-9-06	448-56
HJ-1A CCD1	2014-9-18	454-53
HJ-1A CCD2	2014-9-24	452-56
HJ-1B CCD2	2014-10-04	452-56

3. Map of soil available nutrients

In this paper, the WOFOST crop model and remote sensing data assimilation were used to obtain soil available nutrients stably and accurately. The parameters of WOFOST model were calibrated using the sampling data of soil, which generated two data sets used for calibration and accuracy evaluation, respectively. Retrieving the leaf-area-index (LAI) data by remote sensing data, and producing assimilation data sets. The nutrients simulation was extrapolated from the point to the region by using Ensemble Kalman Filter(EnKF), which included the time-series remote sensing data into the simulation model. The crop growth stages simulated by the model were the initial stage of growth simulation (stage 1), the stage of growth simulation under stage of moisture stress (stage 2) and the stage of growth simulation under stage of nutrient stress (stage 3). Using LAI at critical points of each stage under different moisture and nutrient stress to reverse the content of available nutrients in the soil.

4. Analysis of the variation of available nutrients

For the retrieved nutrients data, the method of comparing adjacent point was used to identify the outlier, firstly. Then the estimated value of the suspect value (Estimate Neighborhood Method, ENM) was used for further judgment to determine whether to replace the suspect value *G* with the threshold *GL* or not. The statistic *I* and the threshold *GL* in the ENM method are shown in formula (1) and (2). Where *I* obeys the F distribution with degrees of freedom of 1 and ∞, and when $I > 3.84$, *G* is determined as a outlier with 0.95 confidence interval.

$$I = \frac{n\left(G - m\right)^2}{\left(n+1\right)\sigma^2} \tag{1}$$

$$GL = \sqrt{\frac{3.84\sigma^2\left(n+1\right)}{n}} + m \tag{2}$$

The *n* is the number of samples that do not contain a neighborhood of *G*, *m* is the arithmetic mean of other samples that do not contain a neighborhood of *G*, and σ^2 is the mean variance of samples in the neighborhood of *G*.

Classical statistics indicators, including average, standard deviation (S.D.), coefficient of variation (C.V.), maximum and minimum values were selected for global analysis of available nutrients. C.V. presents the degree of variation of the soil available nutrients. And the value of C.V. is divided into three classes, weak variation(C.V.<0.1),medium variation(0.1≤C.V.≤1.0), strong variation(C.V.>1.0)(Nielsen).

The graded color maps of soil attributes were produced with the ArcMap/Spatial Analyst module of ArcGIS (10.2) using the original soil available nutrients retrieved before.

1) Temporal variability analysis

For the inter-annual variability of soil available nutrients from 2012 to 2016, it was firstly qualitatively demonstrated by graded color maps of nutrients and then quantitatively expressed by statistical parameters such as mean value and coefficient of variation. For the variation of available nutrients in growth season, analyzing the change of mean value in each growth season. Moreover, taking into consideration of the available nutrients change every five days.

2) Spatial variability analysis

The distribution and the change of available nutrients in the whole farm were demonstrated by graded color maps of nutrients. Three adjacent plots selected were labeled as plot # 1, # 2 and # 3, respectively(Fig. 1). Crop rotation system of these three plots for five years were bean, maize, bean. maize, bean; maize, bean, maize, bean, maize; maize, maize, maize, maize, maize. And the changes of available nutrients in two different spatial scales were analyzed, respectively.

3) Analysis of the causes of nutrients variations

The impact of topography on the availability of available nutrients was analyzed based on DEM data. Regression analysis showed the relationship between the variation of available nutrients (from 2012 to 2016) and the initial value (in 2012). Comparing the nutrients changes of those three plots to analyze the effects of crop rotation system on nutrients changes. Using the data of temperature and precipitation within five years to analyze the relationship between the changes of soil available nutrients and climatic conditions.

III. Results and discussion

1. The variation of soil available nutrients between years

Fig. 2 shows the distribution of AN in farm scale from 2012 to 2016. There was a uniform change tendency that the content of AN in soil moved closer to the middle value year by year. The value of nutrients content was divided into seven levels, which were extremely low, low, lower, medium, higher, high and extremely high. The area ratio of the 1st, 2nd, 5th, 6th and 7th level showed a wavy decline trend year by year, and all of which reached the highest value in 2014; the 3rd and 4th level showed a wavy increase trend year by year, and both of which reached the lowest value in 2014. By 2016, the range of soil AN, AP and AK content were 280-360 mg / kg, 38-42 mg / kg and 160-200 mg / kg, respectively. And the available nutrients content was more concentrated compared with 2012.

Fig. 3 shows the spatial distribution of soil AN, AP and AK in plot # 1, # 2 and # 3 from 2012 to 2016. The uniform change tendency of available nutrients could also be seen in plot scale. For plot # 2, the lowest content of available nutrients was in the year of 2013. This suggested that precipitation greatly influence the available nutrient content. Although only one crop was planted on an plot and the fertilizers were applied uniformly, we found that there was also a significant variation in available nutrients content on the plot scale. In this case, topography and climatic conditions were the dominant factors in nutrients changes, and precipitation may enhance the impact of topography on nutrients distribution.

Fig 2. The spatial distribution maps of soil AN under farm scale from 2012 to 2016

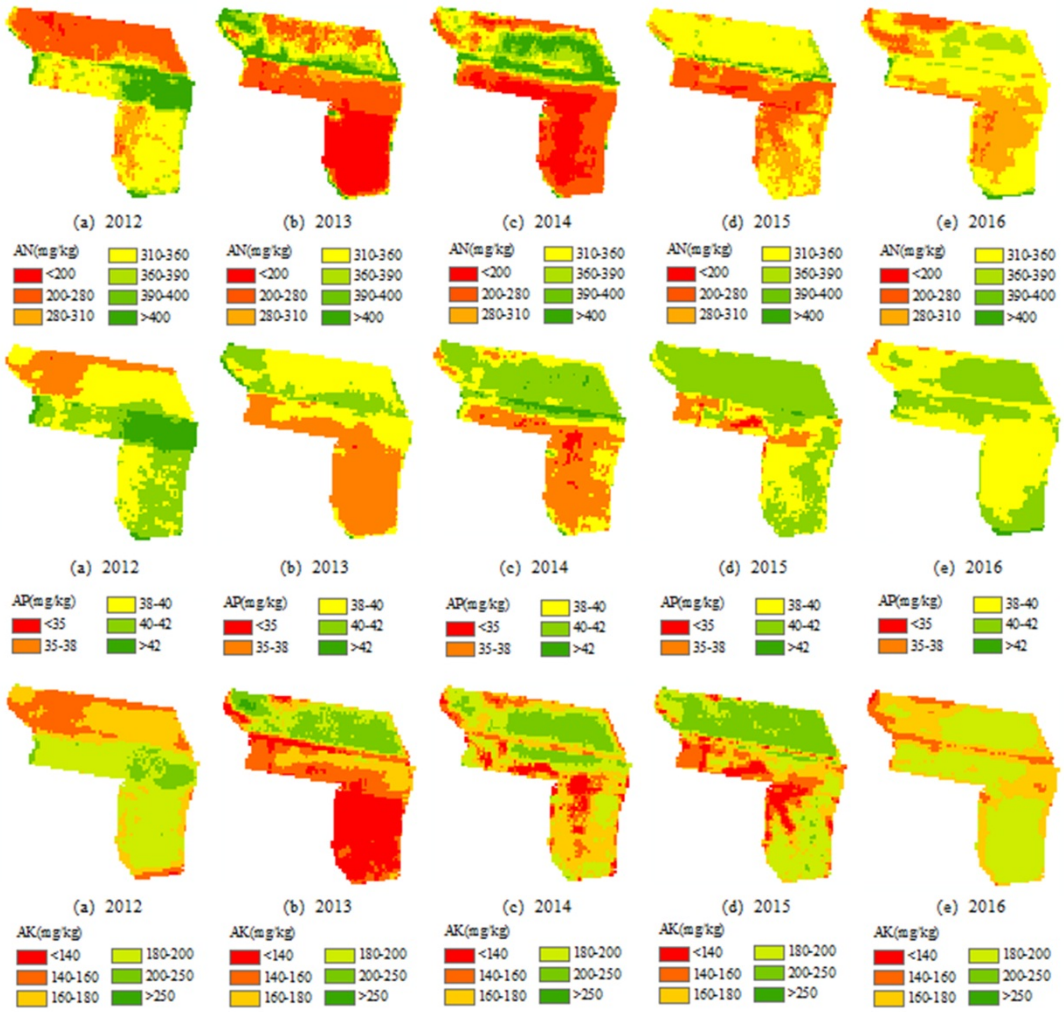

Fig 3. The spatial distribution maps of soil available nutrients under plot scale from 2012 to 2016

Tab 2 shows the statistical parameters of soil AN content from 2012 to 2016. There was a slight change on the average of AN content for five consecutive years on the farm scale. Compared with 2012, the minimum of AN content increased by 72.9% and the maximum reduced by 20.1% in 2016. Standard deviation (S.D.) measure soil nutrients content dispersion degree. The content of soil AN showed a medium variation, and the coefficient of variation (C.V.) for all years have been declining except 2014. It provided strong evidence that the diversity of soil AN distribution was decreasing during five years. Meteorological data showed that the year of 2013 was a waterlogging year, and it implied that the rainwater leaching can be accounted for the increase of soil AN variability. The C.V. for AP and AK also showed similar variety characteristics with AN during 2012 to 2016, decreased by 0.074 and 0.159, respectively. Compared with soil AN and AP, AK showed a higher stability in waterlogging year, because the C.V. of AK did not peak in 2014, but have been decreasing from 2012 to 2016.

Table 2. The summary statistics for soil AN(Mean, Min, S.D., C.V.)

year	Mean (mg/kg)	Min (mg/kg)	Max (mg/kg)	S.D.	C.V.

2012	315.967	52.976	1680.971	149.433	0.473
2013	315.943	71.401	1222.755	93.209	0.295
2014	316.056	70.604	1564.507	155.307	0.491
2015	316.056	70.604	1510.432	75.295	0.238
2016	315.998	91.630	1343.076	81.268	0.257

2. The variation of soil available nutrients during the growth season

The average of available nutrients content of during the growth season showed a uniform change tendency over time (Fig. 4). This variation characteristic was the same as the available nutrients change of the whole farm. The available nutrients content of plot # 2 and # 3 all decreased in 2013, and soil AN and AK content in plot #3 decreased 15.6% and 9.8% more than plot #2, respectively. Affected by the floods, rainwater leaching was the main reason for nutrients loss. The difference between plot #2 and plot #3 may be due to the crop rotation system. The change trend of available nutrients in plot # 1 and # 2 was almost the opposite, which provided strong evidence that the crop rotation system affected the variation characteristic of nutrients. Because the rotation system of plot # 1 and # 2 was the exactly opposite.

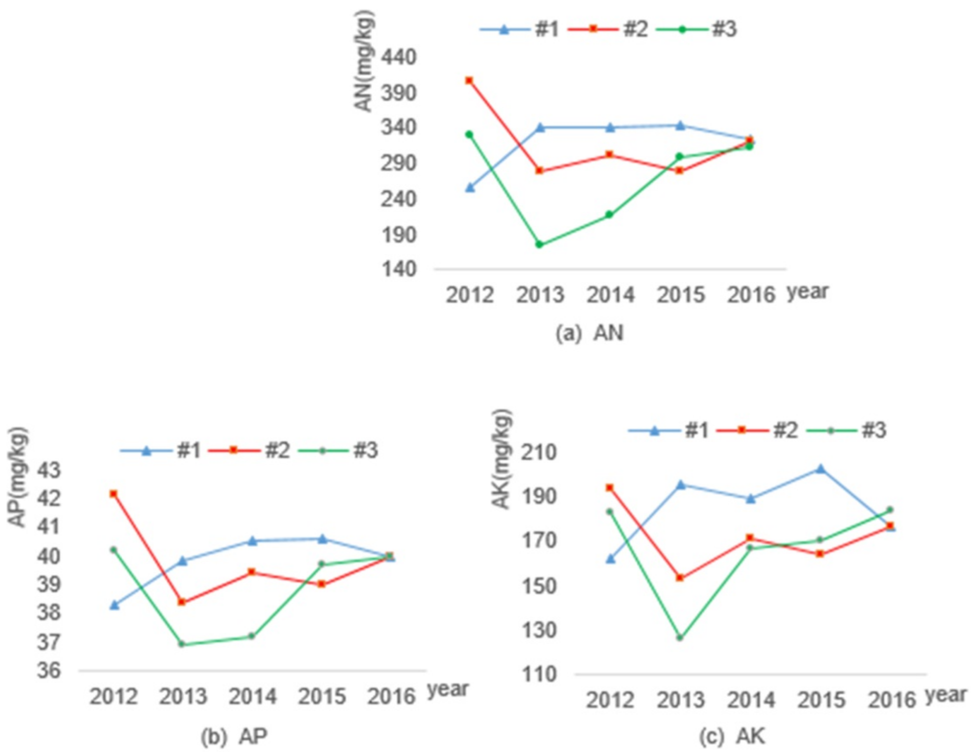

Fig 4. The average of soil AN, AP and AK during the growth season from 2012 to 2016 for plot #1, #2 and #3

The plot # 1 and # 3 were selected to analyze the changes of soil AN during the growth season in the recent five years, and the growth season was simulated from May 19 to September 11 with the step of five days (Fig. 5). Fig. 5(a) shows the decline rate of soil AN during the growth season of maize could be divided into three stages, which were corresponding to three stages of the growth of maize: the seedling stage, the ear stage and the reproductive stage. In addition, decline rate of soil AN in the third stage of maize growth was the fastest. It could be found that the reduced content of soil AN were largest in 2014, which could be attributed to the good harvest in the year. Comparing the soil AN uptake in plot # 1 and # 3 in 2015, it was found that maize in plot # 3 absorbed 2.6% more AN than plot # 1. It implied that it was more conducive to the absorption of soil available nutrients in the plot where different crop rotated.

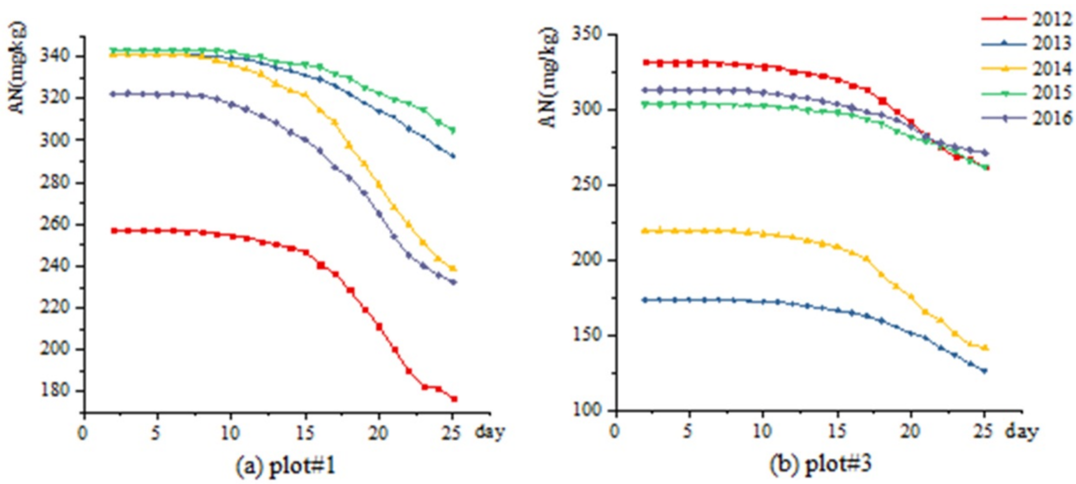

Fig 5. The changes of soil AN during the growth season with the step of five days from 2012 to 2016 for plot #1 and #3

3. Factors affecting spatio-temporal variation of soil available nutrients

1) Topography and climate factors

According to the analysis of available nutrients contents in the plots with large difference in topography, the available nutrients in the plots with high topography were generally low. Topographic factor had a greater impact on available nutrients change in years with heavy rainfall.

In other words, the effect of rainwater leaching on nutrients was more obvious in the areas with more difference in terrain.

Tab 3 shows the monthly average temperature and monthly precipitation in the study area from 2012 to 2016. The average annual temperature has risen from 0℃ to 2.3℃ during the first four years, but has reduced to 0.6 ℃ in 2016. The increase of temperature would promote the absorption of nutrients in crop soils, which contributed to the decline of soil nutrients. The change trend of annual total precipitation showed an opposite with the variation of available nutrients content (Tab 3). The time of rain was the maximum in the year of 2013 (Tab 4), which contributed to the lowest of the available nutrients content average. The number of precipitation in 2016 was the same as in 2015, but the number of torrential rain was higher. That was one of the important influence factors for the decrease of nutrients content average in 2016.

We found that the effect of temperature on soil available nutrients was subtle compared to precipitation according to the analysis above.

Table 3. The statistics of monthly average temperature and total precipitation from 2012 to 2016

Year	Item	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Mean	Sum
2012	Average temperature(℃)	-28.8	-21.1	-8.9	4.5	13.8	20	22.3	19.1	12.9	2.7	-11.2	-24.5	0	/
	Total precipitation(mm)	0.9	1.5	1.5	12.9	25.3	140.1	88.6	26.3	175.2	36.3	14.7	10.2	/	533.5
2013	Average temperature(℃)	-27.6	-22	-12.3	2	14.9	19.4	21.4	19.1	12.3	3	-5.6	-17.8	0.6	/
	Total precipitation(mm)	6	9.8	12.4	13.9	93.8	109.8	228.1	104.8	51.5	39.1	12.4	5.4	/	687
2014	Average temperature(℃)	-24.6	-23.7	-7.1	8.2	12.5	21.5	20.5	19.6	12.1	2.2	-8.8	-20.9	1	/
	Total precipitation(mm)	7.6	12.5	0	0.6	87.5	45.3	133.8	135.8	92.4	18.5	16.5	6.8	/	557.3
2015	Average temperature(	-19.8	-14.4	-6.9	4.7	11.4	20	22.5	20.8	12.7	3.7	-9.6	-17.2	2.3	/

	℃)														
	Total precipitation(mm)	0.1	22.6	7.3	16.1	37.4	60.3	14	106.1	72.4	25	1.3	6.9	/	369.5
2016	Average temperature(℃)	-22.1	-18.3	-3.8	4.6	13.8	17.1	21.35	18.91	14.09	0.103	-16.8	-21.46	0.6	/
	Total precipitation(mm)	1.2	0.2	4	12	54.7	111.5	58.2	57.6	158.1	17.8	26.8	3.4	/	505.5

Table 4. The precipitation frequency of moderate, heavy and torrential rain from 2012 to 2016

Year	10mm-25mm) moderate rain	(25mm-50mm) heavy rain	(50mm-100mm) torrential rain	Total
2012	9	3	1	13
2013	20	5	0	25
2014	13	2	1	16
2015	10	2	0	12
2016	9	2	1	12

2) The relationship between nutrients change and initial value

The variation of soil AN from 2012 to 2016 showed a very significant negative correlation (p <0.01) with the initial value of soil AN in 2012(coefficient=0.839)(Fig. 6). And for soil AP and AK, the correlation coefficients between variation and initial value were 0.882 and 0.569, respectively. It is conceivable that the AK is more stable than AN and AP in soil.

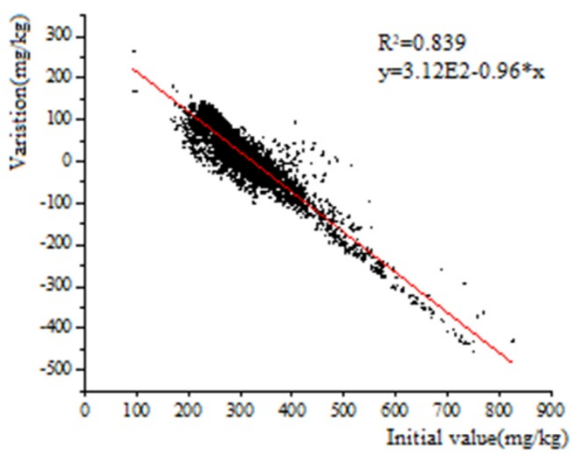

Fig 6. Relationships between contents of soil AN in 2012 and variation of the contents during the 5 years (2012-2016)

IV. Conclusions

The soil available nutrients in farmland was mapped based on the WOFOST crop model and time series satellite HJ-1 CCD data. Temporal and spatial variability of soil available nutrients in Shuangshan farm from 2012 to 2016 was studied. The results showed that the soil available nutrients content showed a uniform change tendency and the variation of nutrients distribution was weakened in the last five years. Rotation of different crops could be conducive to crop absorption of available nutrients in the soil. The effect of rainwater on the variation of soil available nutrients was increased in the area with larger topography changes. There was a significant negative correlation between the nutrients variation and the initial value of soil AN, AP. Fertilization management and crops rotation system were the dominant factors that affecting the spatio-temporal variation of available nutrients.

Taking into considering that there was diversity upon spatial distribution of available nutrients, the fertilization management based on experience alone could not achieve the goal of efficient use of resources and environmental protection. It is suggested that long-term monitoring of available nutrients should be implemented on farmland plots, which can be useful for variable-rate fertilization. The influence weight of each factor can be calculated according to the historical observation data of available nutrients and the specific value of each impact factor. These factors can be used to establish the prediction model of soil available nutrients, which can be used to provide the theory basis for guiding variable fertilization

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