Application of TERRA/MODIS images, TM images and weather data to assess the effect of cold damage on rice yield

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Abstract: Data assimilation is extensively applied in agricultural remote sensing application. However, integration of multi-temporal and high spatial resolution images with crop growth model to evaluate the effect of cold damage on paddy rice was still lacking. In this paper, authors applied data assimilation combining LANDSAT/TM, a series of terra MODIS images with SIMRIW model to detect how cold damage affected paddy rice yield per unit in the Wuchang county, Heilongjiang province for the year 2006. In the study, MODIS images selected corresponding to a series of the key rice growth phases were utilized to retrieve daily LAI values that were needed in the SIMRIW model. Meanwhile, TM was applied to accurately extract paddy rice sown areas. The study results showed that the yield per unit was 10,628.5840 kg/ha under cold damage condition, which was little less than 10,768.3210 kg/ha under optimal condition. Moreover, the ratio of the calculated yield per value under cold damage condition to the actual value of paddy rice yield per unit was 0.56. The result was better than that acquired in USA and Japan. The results of this study expected to provide suggestions to policy-makers and reference to related research.

Keywords: data assimilation, MODIS, TM, cold damage, rice yield per unit, NDVI, LAI

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1 Introduction

Data assimilation is a quantitative, objective method used to infer the state of the dynamic system from heterogeneous, irregularly distributed, and temporally inconsistent observational data with differing accuracies[1]. In last twenty years, this method was extensively utilized in agricultural remote sensing application[2-4]. Mass[5,6] used ground radiometric measurements over maize crops to constrain the simulations of the crop growth model. Carbone et al. [7] utilized remote sensing and geographic information system technologies to drive soybean growth model. Clevers[8] applied data assimilation method to calculate agronomic parameters for sugar beet growth model. Guerif and Duke[9] integrated crop model with canopy reflectance model to estimate sugar beet yield. Weiss et al. [10] combined a crop growth model with the sail model through leaf area index (LAI), relative water content. Although the studies were very significant agricultural remote sensing application, there were still several problems needed to be resolved: (1) Data assimilation of multi-temporal and high spatial resolution images simultaneously with crop growth model had not been attempted; (2) Application of the data assimilation method with model quantified for the effect of cold damage on rice yield per unit was lacking[11,12]

In terms of revelation mentioned above, this paper aims at achieving two objectives: (1) To apply different spatial resolution images to couple crop growth model;

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(2) To detect the effect of cold damage on rice yield per unit by applying the integration method of agronomic mechanism models and remote sensing techniques at local level. This study expected to provide suggestions to policy-makers and reference to related research.

2 Materials and methods

2.1 Study area

Wuchang County is situated in the southernmost part of the Heilongjiang Province; China with the geographic range of 126°32' to 128°15' East and 44°3' to 45°26' North (Figure 1). The study area administrates 24 towns occupying a total area of 512 km^2 with a total population of about 95.9 thousand. The average annual temperature is 3.6℃, and meanwhile the mean annual precipitation is 620.8 mm. Wuchang is characterized with abundant water resources. The two main rivers, the Lalin River and the Mangmiu River, passed through the region, and the longfengshan reservoir is a large catchment for people's daily use and crop irrigation. Based on this advantage, the rice cultivation is extensively spreading, and sown acreage exceeds 70 thousand hactare at present. The study area is distinctive sample for related study.

Figure 1 Sketch map for Wuchang County

2.2 Crop calendar for single cropping paddy rice

There are three kinds of rice varieties in the study area. The variety 'Wuyoudao No.1' occupies approximately 60% of the total rice cultivation area. Moreover, 'Wuyoudao No.1' has very similar pheological, physiological and physical characteristics with the other two varieties. This advantage facilitated a reasonable simplification that 'Wuyoudao No.1' can be seen as unique variety when estimating. In terms of Figure 2, it is important phase from transplanting to maturity for implementing data assimilation.

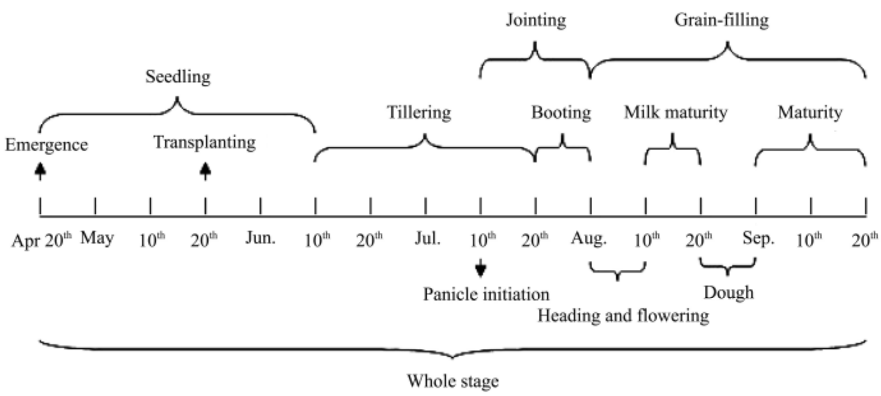

Figure 2 Crop calendar for single-cropping paddy rice

2.3 SIMRIW crop growth model

The SIMRIW model is a simplified process model for simulating growth and yield of irrigated rice in relation to weather. It is excellent in the simulation of paddy rice yield per unit[13,14]. The model was developed by a rational simplification of the underlying physiological and physical processes of the rice growth by incorporating into the effect of low temperature on rice yield. The model is based on the principle that the grain yield forms a specific proportion of the total dry matter production of rice:

$$Y_G = hW_t \tag{1}$$

Where: Y_G is the grain yield, g/m^2; h is harvest index; W_t is the total dry matter production, g/m^2. Dry matter production is proportional to the amount of quanta of photo-synthetically active radiation (PAR) absorbed by the rice canopy. The relationship is described in SIMRIW as follows:

$$\Delta W_t = C_s S_s \tag{2}$$

Where: ΔW_t is the daily increment of the crop dry weight, g/(m^2 • d); C_s is the conversion efficiency of absorbed short-wave radiation to rice crop biomass, g/MJ; S_s is the daily total absorbed radiation, MJ/(m^2 • d), which is a function of leaf area index (*LAI*), and the structure and optical properties of the canopy.

$$S_s = S_0\{1 - r - (1 - r_0)\exp[-(1 - m)k \times LAI]\} \quad (3)$$

Where: S_0 is daily incident solar radiation, MJ/(m^2 • d); r is reflectance of canopy and the bare soil; r_0 is reflectance of bare soil; m refers to the scattering coefficient; k represents the extinction coefficient of the canopy to daily short-wave radiation. C_s is influenced by *DVI* and the CO_2 concentration of the atmosphere and can be expressed in the following format:

$$0 < DVI < 1.0,\ Cs = C_0,\ 1.0 \leqslant DVI \leqslant 2.0$$

$$C_s = C_0(1 + B)/\{1 + B\exp[(DVI - 1)/t]\} \quad (4)$$

Where: C_0 is the radiation conversion efficiency at 330 ppm CO_2, g/MJ, and B, t are empirical constants. The value of *DVI* is calculated by summing the developmental rate (*DVI*) with respect to time:

$$DVI_t = \sum_{i=0}^{t} DVR_i \quad (5)$$

The following equation is used to describe the rate of development from the heading to the maturity ($1 \leqslant DVI \leqslant 2$):

$$DVR = T_m / 1000 \quad (6)$$

In SIMRIW, the harvest index h is represented as a function of the fraction of sterile spikelet and the crop developmental index in order to take into account both types of cooling-summer damage, as follows:

$$h = h_m(1 - \gamma)\{1 - \exp[-K_h(DVI - 1.22)]\} \quad (7)$$

Where: h_m refers to the maximum harvest under an optimum condition; γ is the fraction of sterile spikelet, and K_{Hz} represents an empirical constant. The harvest index decreases as γ increases due to cool temperature at the booting and flowering stages, or according to the date of cessation of growth before full maturation (*DVI* = 2) due to cool summer temperatures. Using the 'cooling degree-day' concept, the relation between daily mean temperature (T_i, ℃) and the percentage sterility are approximated by the following equation:

$$\gamma = \gamma_0 - K_q Q_t^a \quad (8)$$

Where: γ_0, K_q are empirical constants, and Q_t is the cooling degree-days, given by:

$$Q_t = \sum(22 - T_i) \quad (9)$$

The summation of equation is made for the period of highest sensitivity of the rice panicle to cool temperatures[15-17].

2.4 Data assimilation method

SIMRIW is a farming-level model in which all the agronomic parameters are also acquired by field experiment. Albeit data obtained in this way are accurate enough, efficiency is low with high cost. Moreover, it is very difficult to apply this model to calculate averaged value of rice yield per unit for a large-scale region. Thus, in this paper, MODIS images were applied to retrieve LAI values in the different key growth phases. Furthermore, through the fitting of LAI curve based on these LAI values, daily LAI values for the whole growth period were available. The daily LAI values were input to SIWRIW model to work out rice yield per unit under cold damage condition. The retrieving method for LAI values was realized by calculating NDVI values and identifying correlation between LAI and NDVI. The acquisition of NDVI values were implemented by accomplished bands calculation of MODIS images. Based on NDVI values and LAI values acquired from experimental measure, the correlation was attainable by using statistical method. Authors also applied LANDSAT Thematic Mapping (TM) image to accurately extract rice-sown areas with application of visible interpretation method in order to ensure calculation precision.

2.5 Data collection and processing

2.5.1 Images processing

The TM imagery of May 31, 2006 was selected due to its good quality (cloud free) and suitable timing. It is approximately one month after transplanting. The spectral signature of rice is easily identifiable in comparison with other objects. The reason for selecting TM was its high spatial resolution, abundant band information and low cost. TM image with radiometric calibration and atmospheric correction was acquirable from the China's National Geographic Information Center. The imagery visible interpretation is not an automatic processing technique, but it is often satisfied with relatively accurate outcomes in the features identification and land cover classification. The technique was also applied to draw the sample polygons of rice fields in this paper. In order to realize the objective mentioned above, the 4-3-2 false color composite of the TM imagery was implemented. The red regions showed mountainous forest areas since rice vegetative spectral feature could not be that strong in their seedling phase. The light blue areas were naturally eliminated in terms of their intense reflect as water in the rice fields should have an absorption spectrum. Combined with the experience of field survey, the grey-dark areas were identified as rice-sown regions and the green sample polygon was manually drawn.

The 23 TERRA/MODIS imageries (cloud free) were downloaded from the website of the National Aeronautics and Space Administration (NASA) also with radiometric calibration and atmospheric correction. The dates of these 23 modis images were respectively corresponding to key rice growth phases (Table 1).

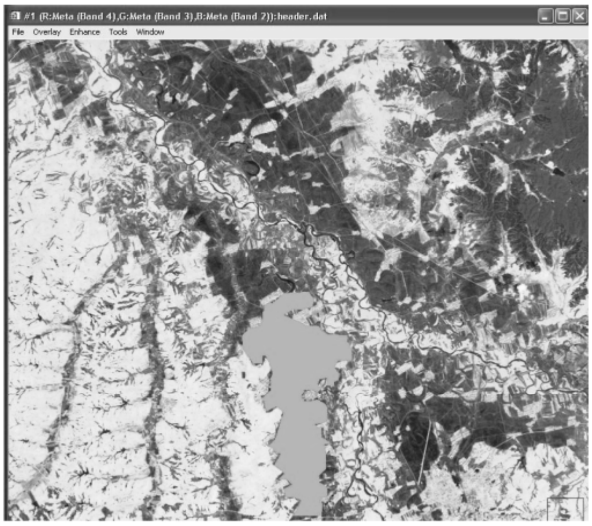

Figure 3 Extraction of the sample areas

Table 1 Dates of selected modis imageries

Date					
May 20th,2006	Jun 12th, 2006	Jul 1st, 2006	Jul 26th, 2006	Aug 21st, 2006	Sep 12th, 2006
May 30th,2006	Jun 21st, 2006	Jul 6th, 2006	Aug 4th, 2006	Aug 25th, 2006	Sep 16th, 2006
Jun 1st, 2006	Jun 24th, 2006	Jul 14th, 2006	Aug 7th, 2006	Aug 30th, 2006	Sep 23rd, 2006
Jun 5th, 2006	Jun 28th, 2006	Jul 19th, 2006	Aug 15th, 2006	Sep 5th, 2006	

Although these images data have been pre-georeferenced, authors unified them to identical coordinates reference system that is UTM system with zone 52.

The equation of NDVI values was as follows:

$$NDVI= (B2-B1)/(B2+B1) \qquad (10)$$

Where: $B2$ represents near infrared reflectance and $B1$ refers to the red band reflectance.

2.5.2 Experimental data

The experimentally measured data were from the Heilongjiang Academy of Agricultural Sciences. The data-makers selected 100 spots in the study area by using spatial sampling method for the two years 2002 and 2005. The NDVI and LAI values were measured in pair in the selected eleven dates, which correspond to key rice growth phases. The NDVI and LAI values in the Table 2 were averaged one for each spot for certain year. Based on these data, correlation between LAI and NDVI was calculated.

Table 2 NDVI and LAI values acquired from experimental measurement

Year	Date	NDVI_value	LAI_value
2005	May 30th	0.0340	0.2800
	Jun 10th	0.0390	0.5700
	Jun 20th	0.1570	1.7400
	Jun 30th	0.2470	3.4900
	Jul 10th	0.3060	5.2300
	Jul 20th	0.3670	5.8200
	Jul 30th	0.4900	6.4100
	Aug 10th	0.4690	5.0100
	Aug 20th	0.4870	4.9800
	Aug 30th	0.3270	4.3900
	Sep 10th	0.2940	3.8000
2002	May 30th	0.0390	0.3200
	Jun 10th	0.0850	0.6200
	Jun 20th	0.1310	1.7100
	Jun 30th	0.2220	3.4700
	Jul 10th	0.4330	5.8500
	Jul 20th	0.4880	6.4300
	Jul 30th	0.4910	6.7100
	Aug 10th	0.5480	7.0500
	Aug 20th	0.4290	5.1000
	Aug 30th	0.4090	4.3200
	Sep 10th	0.3920	4.2000

3 Results

3.1 Calculation of daily LAI values for the whole rice growth period

The calculated NDVI values were shown in Table 3. And correlation between NDVI and LAI data was expressed as $y = 12.462x + 0.0778$, R^2 = 09179. The correlation passed F-test. Based on correlation and NDVI values, the LAI values were calculated (Table 3).

Authors applied cubic curve to fit daily LAI values. The abscissa was the revised Julian date, which equation was as follows:

$$x=(date-140)/50 \qquad (12)$$

Where, date was Julian date from 1 to 365 for a normal year. The equation was proved optimal when fitting LAI values in the study area[18]. The expression of cubic curve was $y= -1.018x_3+0.1408x_2+6.7769x+1.4794$, R^2= 09027. The fitting curve passed F-test. The daily LAI was shown in Table 4.

Table 3 NDVI values of 23 MODIS imageries

Date	LAI_value	NDVI value	Date	LAI_value	NDVI value
May 20th,2006	2.2906	0.1776	Jul 26th, 2006	9.1711	0.7297
May 30th,2006	2.4795	0.1927	Aug 4th, 2006	8.5737	0.6817
Jun 1st, 2006	2.2522	0.1745	Aug 7th, 2006	9.3584	0.7447
Jun 5th, 2006	2.0453	0.1579	Aug 15th, 2006	9.3557	0.7445
Jun 12th, 2006	3.6257	0.2847	Aug 21st, 2006	9.5469	0.7598
Jun 21st, 2006	4.5987	0.3628	Aug 25th, 2006	8.0539	0.6400
Jun 24th, 2006	5.3297	0.4214	Aug 30th, 2006	7.8274	0.6219
Jun 28th, 2006	6.9769	0.5536	Sep 5th, 2006	7.9548	0.6321
Jul 1st, 2006	7.3527	0.5838	Sep 12th, 2006	7.3292	0.5819
Jul 6th, 2006	8.4726	0.6736	Sep 16th, 2006	5.5990	0.4430
Jul 14th, 2000	8.5132	0.6769	Sep 23rd, 2006	5.4252	0.4291
Jul 19th, 2006	9.2331	0.7347			

Table 4 Daily LAI values

Date	LAI_value	Date	LAI_value	Date	LAI_value	Date	LAI_value	Date	LAI_value
April 20th	0	21	2.31	21	5.72	22	8.63	23	8.86
21	0.08	22	2.33	22	5.84	23	8.69	24	8.80
22	0.16	23	2.35	23	5.96	24	8.75	25	8.74
23	0.23	24	2.37	24	6.08	25	8.80	26	8.68
24	0.31	25	2.39	25	6.19	26	8.85	27	8.61
25	0.39	26	2.40	26	6.31	27	8.90	28	8.53
26	0.46	27	2.42	27	6.42	28	8.94	29	8.45
27	0.54	28	2.44	28	6.53	29	8.98	30	8.37
28	0.62	29	2.46	29	6.64	30	9.02	31	8.28
29	0.69	30	2.48	30	6.75	31	9.05	Sep 1st	8.19
30	0.77	31	2.98	Jul 1st	6.86	Aug 1st	9.08	2	8.09
May 1st	0.85	Jun 1st	3.12	2	6.96	2	9.11	3	7.99
2	0.92	2	3.25	3	7.07	3	9.13	4	7.89
3	1.00	3	3.39	4	7.17	4	9.15	5	7.78
4	1.07	4	3.52	5	7.27	5	9.17	6	7.66
5	1.15	5	3.66	6	7.37	6	9.19	7	7.54
6	1.23	6	3.79	7	7.46	7	9.20	8	7.41
7	1.30	7	3.92	8	7.56	8	9.20	9	7.28
8	1.38	8	4.06	9	7.65	9	9.21	10	7.14
9	1.46	9	4.19	10	7.74	10	9.21	11	7.00
10	1.53	10	4.32	11	7.83	11	9.20	12	6.85
11	1.61	11	4.45	12	7.91	12	9.20	13	6.70
12	1.69	12	4.58	13	8.00	13	9.19	14	6.54
13	1.76	13	4.71	14	8.08	14	9.17	15	6.38
14	1.84	14	4.84	15	8.15	15	9.15	16	6.21
15	1.92	15	4.97	16	8.23	16	9.13	17	6.04
16	1.99	16	5.10	17	8.30	17	9.10	18	5.86
17	2.07	17	5.22	18	8.38	18	9.07	19	5.67
18	2.14	18	5.35	19	8.44	19	9.04	20	5.48
19	2.22	19	5.47	20	8.51	20	9.00	21	5.29
20	2.29	20	5.60	21	8.57	21	8.95	22	5.08
						22	8.91	23	4.87

3.2 Calculation of rice yield per unit under cold damage condition

The average temperature data in the study area for 2006 were downloaded from the website of the National Oceanic and Atmospheric Administration (NOAA). T_m less than 22℃ in the dates when paddy rice growth is subject to cold temperature was shown in Table 6, and Q_t value was worked out to be 17.1177 in terms of Equation 9 and Figure 4.

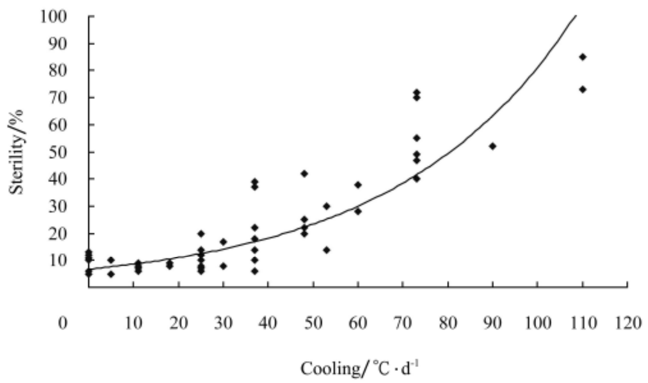

Figure 4 Relationship illustration between cooling degree-days and percentage spikelet sterility at the booting and the flowering stage

Table 5 T_m and its derivation at the booting and the flowering stage

Date	T_m/℃	22 - T_m/℃
Jul 21	21.1024	0.8976
22	16.2819	5.7181
23	16.8604	5.1396
24	18.2101	3.7899
25	20.4275	1.5725

Ultimately, rice yield per unit under optimal and cold damage conditions were shown in Table 6 based on calculation by using Equations (1)-(10).

Table 6 Yields per unit under actual, optimal and cold damage conditions and their ratios

	kg ha^{-1}	Y_a /Y_o
Y_a	10,628.5840	0.9870
Y_o	10,768.3210	
Y_r	5,940.0000	Y_r /Y_a 0.5600

Note: Y_a is the calculated yield per unit under cold damage condition; Y_o is the calculated yield per unit under optimal condition; Y_r is the actual yield per unit from local statistical bureau

4 Conclusions and discussion

In order to take advantage of multi-temporal and high spatial resolution images to evaluate the effect of cold damage on paddy rice yield per unit, the data assimilation method was applied to combine the TM image and a series of modis images with crop growth model, SIMRIW. For the first time, the integration of multi-temporal image and high spatial resolution image was realized. Moreover, with incorporating SIMRIW model with coefficients retrieved by remote sensing technology, the paddy rice yield per unit representing farm-level advanced to the one indicating regional level.

In terms of Table 6, the value difference between Y_a and Y_o was very little. Meanwhile, Q_t, spikelet sterility equal to 17.1177, was closely near zero in terms of the curve in Figure 4. This result proved that low temperature taking place in 2006 did not greatly damage paddy rice production. However, the calculated yield per unit was nearly one time more than the actual value, which was similar to result obtained in USA and Japan. The ratios for the two countries were 0.38 and 0.49, respectively. There should be some reasons for the error between Y_r and Y_a. Firstly, a series of errors for method could possibly be conveyed to the study output. For instance, errors of visible interpretation and NDVI could be avoidable. Secondly, the consequence indicated SIMRIW model still needed to be greatly improved, even though it was excellent for predicting rice yield per unit in a number of crop growth models. Thirdly, the comparison between the actual yield per unit and the calculated one was only implemented in one year. If the work was done in a period (for instance 10 years), comparison result may be different.

In this paper, NDVI was applied to retrieve LAI. The method was no doubt extensively acceptable in agricultural remote sensing application[19,20]. However, some other vegetative indexes such as EVI, PVI, which could be more suitable in the retrieving of LAI in the different rice growth stages. In addition, cubic curve was excellent in the fitting process of daily LAI values. However, the curve for crop growth turned to be more irregular in some growth stages. Hence, deeper exploration of mathematical relationship between vegetative index and LAI will be better detected in the future study.

MODIS and TM have their own advantages in agricultural remote sensing application[21]. However, MODIS often suffers cloud cover, which makes MODIS images incapable. In the key rice growth stage, risk of unavailable to capture good quality MODIS image does exist, either does in TM. Unavailability of good quality images will be a large hurdle for study. Thus, improvement of the methodology is subject to progress of remote sensing technology to a large extent.

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