Establishment and application of the modified Chen NDVI model integrated with ground object classification

Haijun Luan1,2,3 and Yunya Wan1

1College of Computer and Information Engineering, Xiamen University of Technology, Xiamen, China;
2Big Data Institute of Digital Natural Disaster Monitoring in Fujian, Xiamen University of Technology, Xiamen, China
3Email: luanhaijun@xmut.edu.cn

Abstract. Heterogeneous land surface causes the scale effect of remotely sensed land surface parameters. Addressing on quantitatively describing the influence of different ground objects on scale effect of the common surface parameter normalized difference vegetation index (NDVI), the paper proposed an improved NDVI scale transformation model. The model integrated accurate classification information from medium- or high- spatial resolution remote sensing images to improve the traditional Chen NDVI scale conversion model, and showed its superiority for NDVI scale effect description. Xiamen was taken as the experimental area for the study and the conclusions could be obtained from the experimental results. Compared with the traditional Chen NDVI model with rough information, the improved Chen NDVI model incorporating fine ground information provides a finer and more quantitative description of the influence of different land types on the NDVI scale effect. Furthermore, it is found that the presence of water is the key factor underlying the NDVI scale effect. The conclusions of this study have important implications for the scale effect research of other NDVI-like surface parameters such as ratio vegetation index (RVI), normalized difference built-up index (NDBI), normalized burn ratio (NBR).

1. Introduction
Scale transformation of remotely sensed land surface parameters is a fundamental issue in quantitative remote sensing. Various land surface parameters have been investigated, including the normalized difference vegetation index (NDVI), which is the optimal indicator for vegetation growth and coverage and has been widely applied in fields such as environmental (climate) change and crop yield estimation. A number of scale transformation methods have been proposed, including statistical methods [1-3], physical model methods [4-8] and analytical methods [9-12]. Statistical methods in particular are easy to apply, but it is difficult to assign a clear physical interpretation to the associated transformation models. Thus, these methods are not suitable for practical application. In contrast, the physical model methods can produce transformation models with clear physical meanings. However, there are only a few such methods, and they usually involve many simplifications and assumptions, with the consequence that their accuracy is limited. The scale transformation model based on Taylor series expansion is an analytical method with high accuracy and practical applicability. In previous studies, however, it has been used for a single land type only. Fractal theory has also been applied to scale transformation of remotely sensed land surface parameters [13-16]. Significant new findings have been reported in the context of the construction of a “continuous” scale transformation model of...
land surface parameters. However, many issues remain regarding “scale-invariant” transformations and the underlying mechanism. At present, scale transformation of remotely sensed land surface parameters on the basis of ground object categories has emerged as a new approach. For example, Chen [17], Zhang et al. [10] and Shi et al. [18] constructed NDVI and leaf area index (LAI) upscaling models by integrating ground object categories. The ground object categories provide an intuitive representation of land surface spatial heterogeneity, which is the fundamental cause of the scale effect on land surface parameters. Therefore, research concepts from these studies have been adopted in the present study. In previous studies on upscaling of land surface parameters integrated with ground object categories, the ground objects have been only crudely categorized and have failed to reflect the spatial heterogeneity of the land surface. Therefore, in this study, to improve the accuracy of the NDVI scale transformation model, fine ground object category information is integrated with the Chen NDVI model [17].

As a representative moderate-resolution satellite sensor, the Landsat 8 Operational Land Imager (OLI) offers numerous advantages in ground object identification and element extraction because of its spectral and radiation features. It has therefore been widely applied in previous studies [19, 20]. Ground object identification was first carried out using 30 m Landsat 8 OLI images. An NDVI upscaling model integrated with ground object categories was constructed. Luan et al. [21] have already experimented with this method. This paper will focus on showing the superiority of the improved Chen NDVI model in characterizing the NDVI scale effect.

2. Study area and data sources
A rectangular area surrounding Xiamen in Fujian Province, China was selected as the study area. The rectangular shape facilitated upscaling of land surface parameters. Xiamen is located in the southeastern part of Fujian Province and west of Taiwan Strait. Because of the social and natural conditions in the study area, the underlying surface exhibits significant spatial heterogeneity, which leads to significant scale effects on remote sensing parameters, including the NDVI. Thus, a great opportunity is presented for the implementation of this study.

The image used in this study was a Landsat 8 OLI image (path number 119, row number 43), collected on January 3, 2017. It was preprocessed as follows.

The OLI-image’s preprocessing (atmospheric correction, geometric correction and clipping) was performed. The OLI image obtained after preprocessing was shown in Figure 1. The NDVI and histogram of the image were then calculated, as shown in Figures 2 and 3. The basic statistics of Figure 2 were also calculated, as shown in Table 1.

Table 1. Basic statistics of Xiamen OLI NDVI image.

| Time     | NDVI image       | Maximum | Minimum | Mean               | Standard deviation |
|----------|------------------|---------|---------|--------------------|--------------------|
| 2018.7.15| 30 m Landsat8 OLI| 1       | −1      | 0.71221976         | 0.20802305         |

Figure 1. Post-preprocessed OLI image of Xiamen (R: 4, G: 3, B: 2).
Figure 2. The 30 m OLI NDVI image of Xiamen.
Figure 3. Histogram of the 30 m OLI NDVI image of Xiamen.
Luan et al. [21] verified the difference between the traditional and improved Chen NDVI models by taking as an example the case of two land types. Here, a variety of ground-mixed experimental studies were carried out. This experiment classified the land into the seven categories listed in Table 2. And according to the post-preprocessed OLI image in Figure 1, the land surface reflectance of the ground objects in the red and near-infrared bands was approximately taken values and listed in Table 2.

Table 2. Approximate values of land surface reflectance of different ground objects in the red and near-infrared bands.

| Ground object | Land surface reflectance in the red band | Land surface reflectance in the near-infrared band |
|---------------|----------------------------------------|-----------------------------------------------|
| Construction land | 0.16 | 0.23 |
| Water | 0.03 | 0.03 |
| Farmland | 0.04 | 0.40 |
| Tidal flat | 0.10 | 0.13 |
| Sand | 0.30 | 0.39 |
| Bare land | 0.11 | 0.22 |
| Forest | 0.03 | 0.26 |

3. Methods

One previous work [21] experimented with this method based on the Xiamen research area at an early stage and found that there was no significant difference between the upscale conversion results from the improved Chen NDVI model incorporating fine ground information and those from the traditional Chen NDVI model with rough information, but that the improved method gave a finer and more quantitative description of the influence of different land types on the NDVI scale effect. Therefore, this paper will further investigate both the traditional and improved Chen NDVI models, focusing on the superiority of the improved model for NDVI scale effect characterization.

The traditional and modified Chen NDVI models [21] are expressed as

\[
\rho_r = \frac{1}{N} \sum_{i=1}^{N} R_{i, \text{class}} \rho_{r,i},
\]

\[
\rho_{\text{nir}} = \frac{1}{N} \sum_{i=1}^{N} R_{i, \text{class}} \rho_{\text{nir},i},
\]

\[
\text{NDVI} = \frac{\rho_{\text{nir}} - \rho_r}{\rho_{\text{nir}} + \rho_r},
\]

where \( \rho_r \), \( \rho_{\text{nir}} \), and NDVI represent, respectively, the surface reflectance of the red band, the near-infrared band, and the corresponding NDVI values in the up-scaled image obtained after the medium and high spatial resolution NDVI image is up-scaled at a specific conversion multiple; \( N \) represents the number of the types of ground objects recognition in the medium and high spatial resolution image; \( i \) represents the serial number of the category, and the value ranges from 1 to \( N \); \( R_{i, \text{class}} \) represents the proportion of the number of \( i \)-th category within the model calculation window (such as the 8 pixels \( \times \) 8 pixels window of the OLI NDVI image up-scaled to 240m spatial resolution of MOD13 Q1 image); and \( \rho_{r,i} \) and \( \rho_{\text{nir},i} \) are, respectively, the average values of surface reflectance in the red band and near-infrared band of the number of \( i \)-th category in the calculation window. When the value of \( N \) is 2, one case is to divide the medium and high spatial resolution images into land and water bodies, and at this time Equations 1-3 is the traditional Chen NDVI model [17]; when the value of \( N \) is larger, it indicates that the images will be finely classified, and Equations 1-3 is the improved Chen NDVI model [21].
The improved NDVI model could be considered as an expanded Geometrical Optical (GO) model and applied into the up-scaling of NDVI image, but without consideration of the influence of shadows, which could be approximately accurate for medium resolution images such as OLI ones. It was expanded from original single-pixel field to full image field, and expanded from original two categories (vegetation and soil) to several ones in practical surface. Therefore, the improved NDVI model is creditable, and ref. [21] proved its accurate up-scaled results. Besides the NDVI, the improved model could be applied into other vegetation index such as ratio vegetation index (RVI), and other NDVI-like surface parameters such as normalized difference built-up index (NDBI), normalized burn ratio (NBR).

The Chen NDVI scale conversion model can also be called the “first average post-inversion method”. To reflect the effect of the method on characterization of the NDVI scale effect, the following “first inversion after averaging” method [21] is introduced and compared:

\[
\text{NDVI} = \frac{\rho_{\text{nir}i} - \rho_{\text{r}i}}{\rho_{\text{nir}i} + \rho_{\text{r}i}}, \quad (4)
\]

\[
\text{NDVI}_2 = \sum_{i=1}^{N} R_{\text{class}_i} \text{NDVI}_i, \quad (5)
\]

where, \(i\), \(\rho_{\text{r}i}\), \(\rho_{\text{nir}i}\), and \(R_{\text{class}_i}\) has the same meanings as them in formulas 1-3; NDVI\(_i\) represents the \(i\)-th category’s NDVI value corresponding to \(\rho_{\text{r}i}\), \(\rho_{\text{nir}i}\); NDVI\(_2\) represents the NDVI value of the big pixel in the up-scaled image.

4. Experimental procedures

4.1. Analysis of the influence of mixed land types on the NDVI scale effect

The results are calculated based on formulas (1)-(5) and then plotted. For convenience of presentation, the “first average after inversion” (the improved Chen NDVI model) is termed Method 1 and the “first inversion after averaging” as Method 2.

On the above basis, the experimental results for different mixtures of land types are as follows.

4.1.1. Mixed construction land, water and farmland and mixed construction land, sand and bare land.

First, experiments are carried out on three land types. Three of the seven types of land are selected and a total of 35 combinations are used. The calculations are performed by both Methods 1 and 2, 35 sets of results are obtained and the results are plotted. Two sets of results are selected for analysis: those for mixed construction land, water and farmland and those for mixed building land, sand and bare land. In Figures 4 and 5, the x-axis represents the area ratio of the first land type, the y-axis represents the area ratio of the second land type and the z-axis represents the calculated NDVI value of all three land types.

**Figure 4.** NDVI results obtained by the two methods for mixed construction land, water and farmland: (a) Method 1; (b) Method 2.
Figure 5. NDVI results obtained by the two methods for mixed construction land, sand and bare land: (a) Method 1; (b) Method 2.

The difference between the NDVI values obtained by the two methods (Method 1 NDVI − Method 2 NDVI) is also calculated and the results are shown in Figure 6.

Figure 6. Difference in the NDVI values obtained by the two methods: (a) for mixed construction land, water and farmland; (b) for mixed construction land, sand and bare land.

Table 3. Analysis of the results shown in Figure 7.

| Area ratio | Fixed land type                          | Construction land          | Water                              | Farmland                             |
|------------|------------------------------------------|----------------------------|------------------------------------|--------------------------------------|
| 0          | Mixed water and farmland.                | Mixed construction land and farmland. The difference between the results of the two methods is smaller. | Mixed construction land and water. The results of the two methods are very different, but they show similar trends. | Mixed construction land and farmland. The difference between the results of the two methods is smaller. |
| 0.2        | Construction land is present.            | Water is present. The difference between the results of the two methods increases. | Farmland is present. The two methods show opposite trends. | Farmland is present. The two methods show opposite trends. |
| 0.4        | The difference between the results of the two methods continues to decrease. | The difference between the results of the two methods continues to increase. | The results of the two methods change in opposite directions and the difference between them decreases. | The results of the two methods change in opposite directions and the difference between them continues to decrease. |
| 0.6        | The difference between the results of the two methods continues to decrease. | The difference between the results of the two methods continues to increase. | The results of the two methods change in opposite directions and the difference between them continues to decrease. | The results of the two methods change in opposite directions and the difference between them continues to decrease. |
| 0.8        | The difference between the results of the two methods continues to decrease and tends toward zero. | The difference between the results of the two methods continues to increase. | The results of the two methods change in opposite directions and the difference between them continues to decrease. | The results of the two methods change in opposite directions and the difference between them continues to decrease. |

Analysis of Figures 4-6 shows the following. (1) There are significant differences in the NDVI obtained by the two methods, indicating that NDVI is subject to a significant scale effect. (2) When the mixtures of different types of features are different, the results obtained by the two methods are different, indicating that the NDVI scale effect is affected by different types of ground objects. (3)
When the types of ground objects remain unchanged, but the area ratios of different ground objects change, then the results obtained by the two methods are different, which implies that the significance of the NDVI scale effect changes accordingly and further proves that different land types have different influences on the NDVI scale effect. These conclusions agree with those in [10] and [21].

To further analyze the difference between Methods 1 and 2, the proportion of one land type is fixed by considering mixed use of construction land, water and farmland and the difference between the NDVI results calculated by the two methods is examined. The area ratio of fixed land types is varied, taking values of 0, 0.2, 0.4, 0.6 and 0.8. The results obtained by the two methods are shown in Figure 7.

The analysis of the results is presented in Table 3.

As shown in Figure 7 and Table 3, first, when the area ratio of a fixed land area is 0, this represents the case where there is a mixture of just two types of ground objects (Figure 7a1-c1). It is found that when there is no water (Figure 7b1), the difference between the two methods is small, but as the area proportion of water increases (Figure 7b1-b5), this difference becomes larger and larger, indicating that water has a greater impact on the NDVI scale effect. Second, when construction land and farmland are present, Method 1 can quantitatively describe the effect of their area ratio on the NDVI (Figure 7a1-a5, c1-c5), which gives a more accurate reflection of the NDVI scale effect.

| Fixed land type | Construction land | Water | Farmland |
|-----------------|-------------------|-------|----------|
| 0               | ![Diagram](a1)    | ![Diagram](b1) | ![Diagram](c1) |
| 0.2             | ![Diagram](a2)    | ![Diagram](b2) | ![Diagram](c2) |
| 0.4             | ![Diagram](a3)    | ![Diagram](b3) | ![Diagram](c3) |
| 0.6             | ![Diagram](a4)    | ![Diagram](b4) | ![Diagram](c4) |
| 0.8             | ![Diagram](a5)    | ![Diagram](b5) | ![Diagram](c5) |

Figure 7. NDVI results for mixed construction land, water and farmland.
4.1.2. Mixed tidal flat, sand and another land type. An analysis of the other three land types is carried out in a similar manner to that adopted above, and it is found that mixtures of two land types that include tidal flat or sand represent a special case. Figure 8 shows the results for tidal flat and sand types only, with the third land area being 0. In this case, the NDVI obtained by the two methods is the same, and a fixed (approximate) value of 0.130434783 is taken.

Figure 8. Calculation results for mixed tidal flat and sand.

For mixed tidal flat, sand and another land type (construction land, water, farmland, bare land or forest), the area ratio of the other land type is fixed and taken as 0.2, 0.4, and 0.6 in turn. The calculation results for all five other land types are shown in Figure 9.

| Fixed land type | Area ratio |
|-----------------|------------|
|                 | 0.2        |
|                 | 0.4        |
|                 | 0.8        |
| Construction land | (a1) |
| Water           | (b1)       |
| Farmland        | (c1)       |
| Bare land       | (d1)       |
| Forest          | (e1)       |

Figure 9. Calculation results for mixed tidal flat, sand and another land type.

An analysis of Figures 8 and 9 reveals the following. (1) When the area proportion of the third ground type is 0, that is, when only tidal flat and sand are present (Figure 8), no matter how the area ratio of these two land types changes, both Methods 1 and 2 give the same NDVI value, and it can be
considered that a scale effect does not occur in this case. This is due to the spectral characteristics of tidal flat and sand: since the approximate values of the surface reflectance of the two land types are specified, and the surface reflectance of the two ground objects is proportional (see Table 2), so the NDVI values of the two types of features are the same: approximately 0.130434783. In reality, the surface reflectivity of the two land types will fluctuate to some extent and the approximate equivalence will not be completely preserved, but the overall trend of the results will remain the same.

(2) When a third land type is present, if its area ratio remains unchanged, then no matter how the area ratio of tidal flat and sand varies, the NDVI calculated by Method 2 remains unchanged (the red line in Figure 9), indicating that the relationship between the NDVI of mixed ground objects and the area ratio of the third ground object is linear. (3) When the third land type is water, the calculation results in Figure 9b1-b3 show that the results obtained by Methods 1 and 2 are significantly different. Thus, it is clear that the presence of water has a great influence on the NDVI scale effect. (4) The behavior of mixtures of tidal flat and sand with land types other than water is similar to that of mixtures with water. That is to say, from 0.2 to 0.8 of another land type’s area ratio (construction land, water, farmland, bare land or forest), the difference between the results of the two methods first increases and then decreases with the increasing area ratio of tidal flat, and at a certain value of this ratio the NDVI results of the two methods are equal, thus proving that the NDVI scale effect is significant and cannot be ignored.

4.2. Analysis of results
The experimental results reveal the following. (1) For different mixtures of land types, there are differences (sometimes large) between the results from the “first average after inversion” method (based on the improved Chen NDVI model) and those from the “first inversion after average” method, which indicates that the NDVI is subject to a significant spatial scale effect. (2) Different land types have different influences on the NDVI scale effect. In particular, the presence of water has an important role in determining the significance of this effect, which is consistent with the results of previous studies [10, 17, 21]. The experimental results show that the improved Chen NDVI scale conversion model is able to finely detect the effects of different land types on the NDVI scale effect.

5. Conclusions
Land type classification of OLI images has been carried out in the Xiamen research area and the modified Chen NDVI model integrating classification information has been used to characterize the NDVI scale effect. The results indicate that the NDVI is subject to a significant spatial scale effect and that the improved Chen NDVI scale conversion model is able to finely detect the effects of different land types on this effect.

Furthermore, the improved NDVI model could be referred by other NDVI-like surface parameters such as RVI, NDBI, NBR, and quantitatively described their scale effect in various surface conditions.

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Conflicts of interest
The authors declare that they have no conflicts of interest.

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