

# SPATIAL ANALYSIS ON SURFACE DEFORMATION BY SOIL EROSION IN THE CHINESE LOESS PLATEAU USING INSAR TECHNIQUES

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**ABSTRACT:** Monitoring the surface deformation over the loess hills could help us understand the dynamics of soil erosion, the extent of anthropogenic impacts, and the mitigation methods for the potential damage to local ecosystems, agricultural production, socioeconomic infrastructure, water quality, and air quality in the Loess Plateau and the surrounding areas. The objectives of this study were to comprehend the spatial soil erosion dynamics over wide areas by using remote sensing and other related techniques, and also to confirm the validity of the techniques and the involved challenges. Wuqi County of Shaanxi Province in which soil and water have been intensively conserved at the national level was chosen as a study area. A Differential Interferometric Synthetic-Aperture Radar (D-InSAR) was applied using L-band ALOS-1/PALSAR-1 images to measure the surface deformation at several loess hills between 2008 and 2010. In the results, the surface deformation data, inclusive of the spatial effects of soil erosion across a wide area, was collected. By investigating these surface deformations, we observed that the degree of soil erosion depended on the slope direction and slope angle. In addition, the intensity of soil erosion vary by the features of hilly terrains, so that it can be considered that the location of the loess hills could be a factor. These findings provided us with important information that could help for the development of effective spatial land-use plans, which would aid current efforts in soil and water conservation.

## 1. INTRODUCTION

Soil erosion is one of the serious global environmental problems. It causes not only soil nutrient loss and land degradation, but also many secondary environmental problems such as flooding, river siltation, food security problems, impacts for infrastructures and water pollution (Wang et al., 2016). With increasing population pressure and consequent problems of deforestation and land management issues, it is also expected to increase in many areas of the world in the 21st century (Ryken et al., 2016). Considering that it would be threat to the sustainable development, monitoring and evaluation of the soil erosion and the effectiveness of counter measures are vital to support the sustainable land use management, especially collecting the reliable quantitative data on the extent of soil erosion (Ryken et al., 2016; Wang et al., 2016; Yang et al., 2013).

In China, soil erosion is one of the serious environmental problems. The total water and wind eroded areas are approximately 3 million km<sup>2</sup>, which is equal to 32 % of the territory of the country (Wang et al., 2016). In many regions of China, a combination of both wind and water erosion is cause of land degradation. It is also known as the Wind Water Erosion Crisscross Region which is located in the Loess Plateau of China. The study region is the one of such area experiencing severe land degradation (Yang et al., 2013), as shown that the Yellow River is the largest sediment discharge river in plain rivers, and most of these sediment are derived from the Loess Plateau (Matsunaga, 2011).

Research undertaken in many different target regions and the various disciplines in the world has resulted in the development of techniques and approaches and contributing to predict the soil loss by wind and water erosion (Yang et al., 2013). These are demarcated three contrasting approaches to documenting erosion that are field monitoring, a lot of experiments and numerical models (Yang et al., 2013). The first approach involves measuring the amount of soil or dust transported by the wind and water, using traps or wind tunnel experiments, both in the laboratory and in the field. The resulting data are employed to infer the amount of soil lost from the land surface (Xin et al., 2009; Yang et al., 2013; Yellow River Conservation of MWR, 2001). The second approach attempts to measure the surface lowering caused by the erosion using soil sampling, gamma-ray measurements and the calculation models of the fallout radionuclides (FRNs) such as <sup>137</sup>Cs, <sup>7</sup>Be, <sup>210</sup>Pb<sub>ex</sub> (Mabit et al., 2008; Yang et al., 2006, 2013). In this case, the reduction in the fallout radionuclide inventory caused by erosion is established by comparing an eroding site with a reference site. The degree of reduction is in turn used to estimate the amount of soil lost (Yang et al. 2013). The third approach is the empirical modelling such as the Universal Soil Loss Equation (USLE) and its derivatives (e.g. RUSLE: Revised Universal Soil Loss Equation) are easily applied in the world (Martinez et al., 2009). These models are formulated using 6 or 7 factors such as rainfall, soil erodibility, landform, cover-management, and support practice.

Although these studies were able to quantitatively estimate soil erosion in accordance with the terrain conditions and the land-use situation at the target slope, they have several weaknesses. Firstly, a major disadvantage of some

classical field methods such as the erosion pins is its low spatial resolution, as it is not possible to install enough pins to identify processes such as rotational and translational slides. Quantify gully erosion have involved labor-intensive field measurements, such as field tapes, theodolite or total station, the Global Navigation Satellite System (GNSS) methods (e.g. Differential-GNSS or RTK: Real Time Kinematic). In addition to being spatially limited in scope, they have several weaknesses that include being expensive, labor intensive, and requiring long-term observation (Neugirg et al., 2016). Furthermore, in these approaches, slopes are affected directly by the person measuring erosion depth (Neugirg et al., 2016). Then, the empirical models such as USLE and RUSLE require quantitative data from long-term field experiments and onsite monitoring, which are difficult to be obtained in China and many developing countries, because the datasets are usually incomplete and not well developed at official observing stations (Wang et al., 2016). In addition, the model the most widely used erosion model for estimating soil loss in China is the USLE originally developed in the United States for large fields with relatively gentle slopes (Lu and Higgitt, 2000). This situation is contrasting characteristic that Europe has another empirical models such as the Pan-European Soil Erosion Risk Assessment (PESERA) (Kirkby, et al., 2003). Many researchers are prepared to defend its simplicity and elegance as a means of identifying erosion hazard, however previous researches used the limited data, which covered small area, to clarify the complex erosion and processes in different regional scales. As a result, there are concerns that erosion estimates are unreliable beyond the geographical and parameter limits of the original model. Problems in applying the USLE, specific to the Loess Plateau, involve the nature of terrain (Lu and Higgitt, 2000). Therefore, the knowledges of soil erosion in China are still in the initial stage for erosion assessment (Huang et al., 2016).

As explained above, previous approaches can only be applied to certain areas. Analyzing a small area can deliver some concrete knowledge of soil erosion dynamics, but it might be difficult to develop a solution to the issues because soil erosion usually occur and is observed over wide areas. By contrast, remote sensing (RS) has some advantages such as the evenly accurate of surface in a certain area, and high spatial temporal resolution insofar as correcting images over the long term. In addition, satellite-RS, especially Differential interferometric synthetic aperture radar technique (D-InSAR) has higher likelihood that discover unknown displacement than aircraft-RS and field methods by the wide spatial coverage and regular measurement. D-InSAR is applied to monitor the surface deformations caused by earthquakes, landslides, underground mining, groundwater withdrawal, ice motion, volcanic activity, etc (Bateson et al., 2015; Kiseleva et al., 2014; Samsonov et al., 2014; Tizzani et al., 2007; Zhao et al., 2016). The objectives of this study are to comprehend the spatial soil erosion dynamics over wide areas by using InSAR and through related techniques, and to confirm the validity of the techniques.

## **2. STUDY AREA**

### **2.1 Overview of the study area**

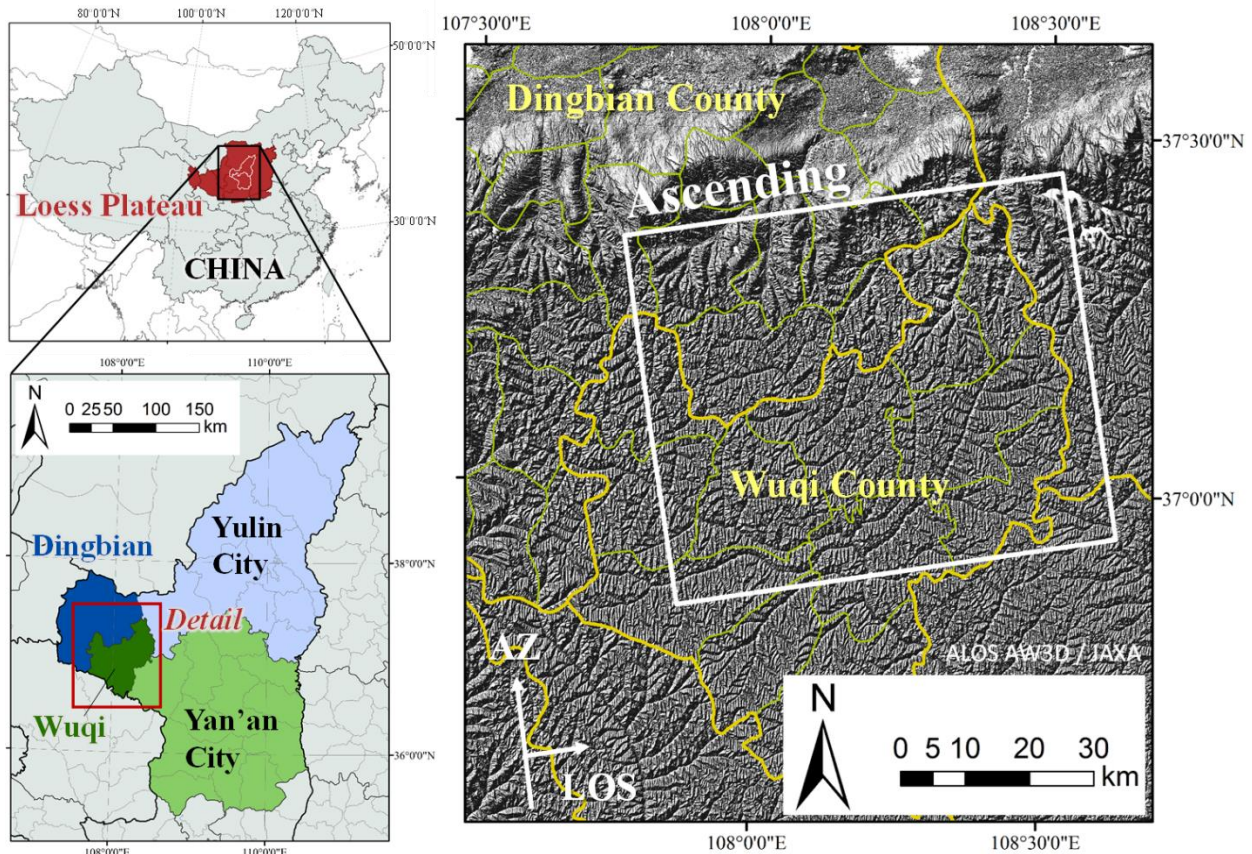
We chose the study area which is drawn by the white rectangle in Fig. 1. The area includes some townships of Wuqi and Dingbian Counties and has confronted with severe soil erosion in the Loess Plateau.

Wuqi County is located in the central Loess Plateau and one of the loess-hilly region, belonging to the northwest of Yan'an City, Shaanxi Province, China (Fig. 1), and constitute the upstream of Luo River and Wuding River that is one of the major tributary of the Yellow River. The county is with an elevation of more than 1,233 to 1,809 m above sea level, and the annual mean precipitation is approximately 440 mm at the county seat. The climate is the semi-arid temperate continental, heavily influenced by the Indian monsoons, so more than 60 % of the precipitation arrives during the months of July to September. Soil and water have been intensively conserved in the county by the national level (Forestry Department of Shaanxi Province and Shaanxi Provincial Forestry Survey and Design Institute, 2009). In addition, the county adopted the reforestation policy "the Grain for Green" to conserve the soil and water for the first time in China (Yao and Zhang, 2008), and be designated as the national model district (Li et al., 2006).

Dingbian County is located in north of Wuqi County, and south of Inner-Mongolia Autonomous Region and Ningxia Hui Autonomous Region, belonging to the southwest of Yulin City, Shaanxi Province (Fig. 1). In the county, the north area is grouped into blown-sand region, whereas the south area is grouped into loess-hilly region, and the loessial hills spread in my main target towns of this county such as Xin'anbian Town. In this town, the annual mean precipitation is approximately 300 to 400 mm, climate is not much different from Wuqi County, and the cultivated fields spread around the town because "the Grain for Green" area is smaller than towns of Wuqi County (Compilation Committee of Dingbian County Annals, 2003).

### **2.2 Previous estimation of the soil erosion in the loess plateau**

Average annual speed of soil losses in the Yellow River basin is estimated to reach into 4,600 t/km<sup>2</sup>. This value tells us that the average erosion rate is estimated to reach into the order of millimeters in the Loess Plateau (Matsunaga, 2011). However, it is assumed that the erosion rate has large value range depending on the characteristics of land situations and conditions.



**Fig. 1** Study area

Matsunaga (2006) clarified the characteristics of the geomorphic change by districts divided based on the geomorphic features theoretically, by considering the relationship between confluence and starting-point of talweg based on topographic maps. Tang (1993) conducted the field monitoring at a few sites in Ziwu Mountains as the forest region of the Loess Plateau and found that it had been experiencing soil erosion mere 0.01mm/yr. On the other hand, a specific slope site of deforestation area in the mountain has been experiencing soil erosion from tens to hundreds of times as large as that of forest cover, such as the valley wall slope and a ridge gentle slope (Tang et al., 1993). Yang et al. (2006) applied FRNs to analyze the soil erosion and found that the soil erosion speed at the gully slops and bottoms are approximately six times larger than that at the top of ridge in a gully of An'sai County, Shaanxi Province. The soil erosion speed at the sloop croplands is approximately two times larger than that at the terrace in a gully of Suide County, Shaanxi Province (Huo and Zhu, 2013). In reforestation area, the intensity of the soil erosion can be different depending on the slope angle as shown in Fig. 2 (Liu et al., 2014). These results are estimated as weight per unit area (e.g. ton per ha), from radioactivity per unit area (e.g. Becquerel per m<sup>2</sup>). In consequence we can estimate the amount of soil lost, and compare the each studies using specific gravity. Bell (1992) indicated that the specific gravity of sandy loess in the northern part of Shaanxi Province was 1.59 to 1.85 t/m<sup>3</sup>. Depending on this data, the range of displacement is estimated from 1 to 9 mm/yr in the areas (Fig. 2). Then interestingly, the soil lost amount of terrace in Suide County is minor than the amount of a few reforestation sites in Jingbian County (Huo and Zhu, 2013; Liu et al., 2014), despite the fact that the potential of soil erosion in Suide County is more severe than in Jingbian County (Huang, 1955).

As explained above, we can estimate that the soil erosion level has the large value range depending on the landform units, direction of dip, slope angles, and land-use/land-cover. These knowledges are the tidemark of soil erosion studies in the Loess Plateau.

### 3. DATA PROCESSING

#### 3.1 Data set

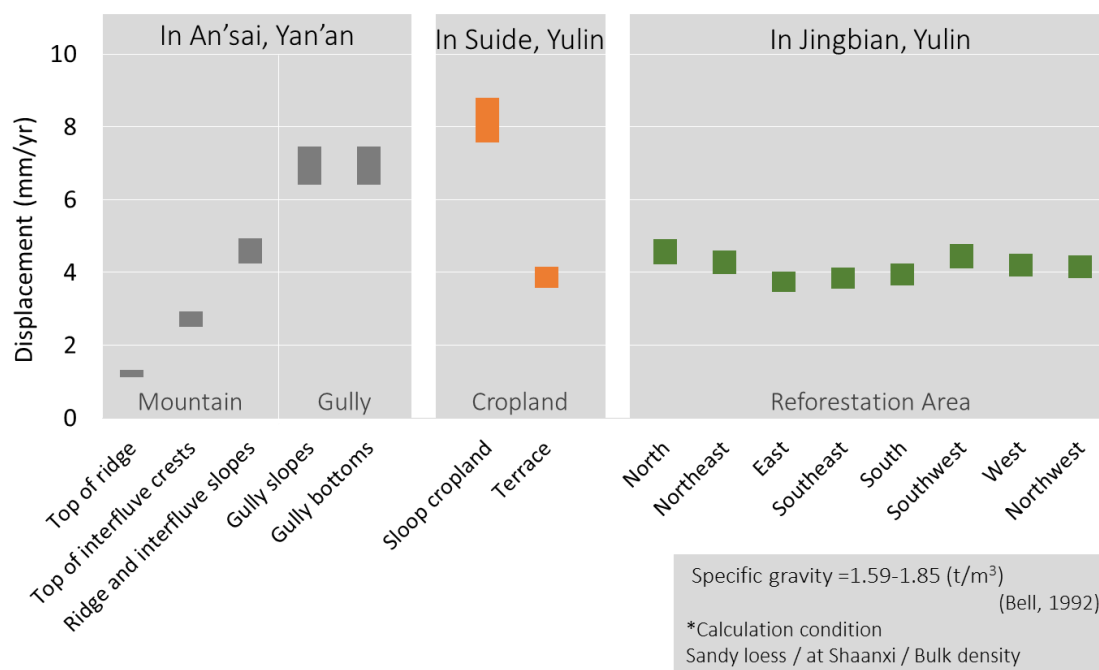
Totally two ALOS-1 L-band (wavelength: 23.6 cm) PALSAR ascending images have been collected in this study (Table 1). Their acquisition time spans from February 2, 2008 to March 25, 2010 (Table 2). Normal baseline value is -607.247 m. The spatial coverage of these images is approximately 70 × 70 km (marked by the white rectangle in Fig.

1). Besides the PALSAR images, direction and angle of inclination data are also needed in this study. As the surface deformation by soil erosion generally is affected the topographic factors, cropping management factors. In a limited site of the loessial hills, soil erosion dynamics are known to be affected the form of cropland, landform units, and the direction of inclination. In consideration of the spatial resolution and vertical accuracy, we use ALOS World 3D 30 by JAXA, and Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global from USGS that is one of the global surface data.

### 3.2 Method and data processing

The workflow with D-InSAR data analysis is shown in Fig.3. The D-InSAR processes were processed using the SARscape 5.2 of ENVI software from EXELIS VIS Information Solutions (Abir et al., 2015). The first step is creation of SLC images from observed raw data of master and slave. Second is slave image resampling to superimpose master images, and creation of first interferogram. After that, we clean up the flat earth phase and the topographic phase, and calculate the deformation phase. And then through phase unwrapping, geometric correction, final displacement map is created that represents the spatial surface displacement.

After D-InSAR processing, we executed the overlay between the displacement map and direction of dip or slope angle, to elucidate the geographical characteristics of soil erosion under the GIS application. The overlays were processed using the ArcGIS 10.3.1 from ESRI. In this study, we make 50 thousand random points on around each Town or Township domains, and derive each overlay input data. Finally, we calculate the displacement and compare it with the results in Fig. 2.



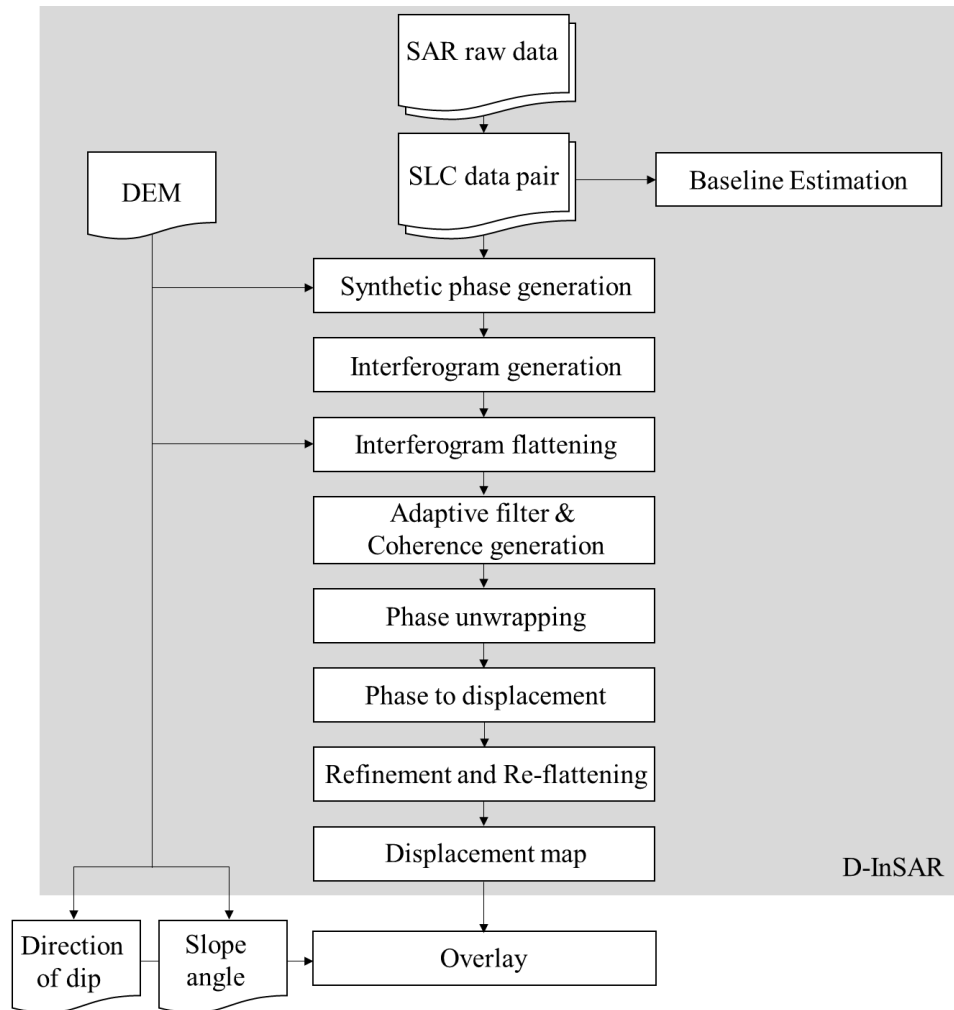
**Fig. 2** Examples of the estimation of the soil erosion rate by FRNs approach in the less-hilly region, the northern part of Shaanxi Province (Bell, 1992; Huo and Zhu, 2013; Liu et al., 2014; Yang et al., 2006)

**Table 1** Summary of ALOS-1/PALSAR-1 for the analysis

Orbit	Path	Frame	Polarization	Off-nadir angle
Ascending	464	730	HH	34.3 deg.

**Table 2** Used scene data for the analysis

No.	Scene ID	Date
1	ALPSRP107880730	Feb. 02, 2008
2	ALPSRP221950730	Mar. 25, 2010



**Fig. 3** Workflow of this study

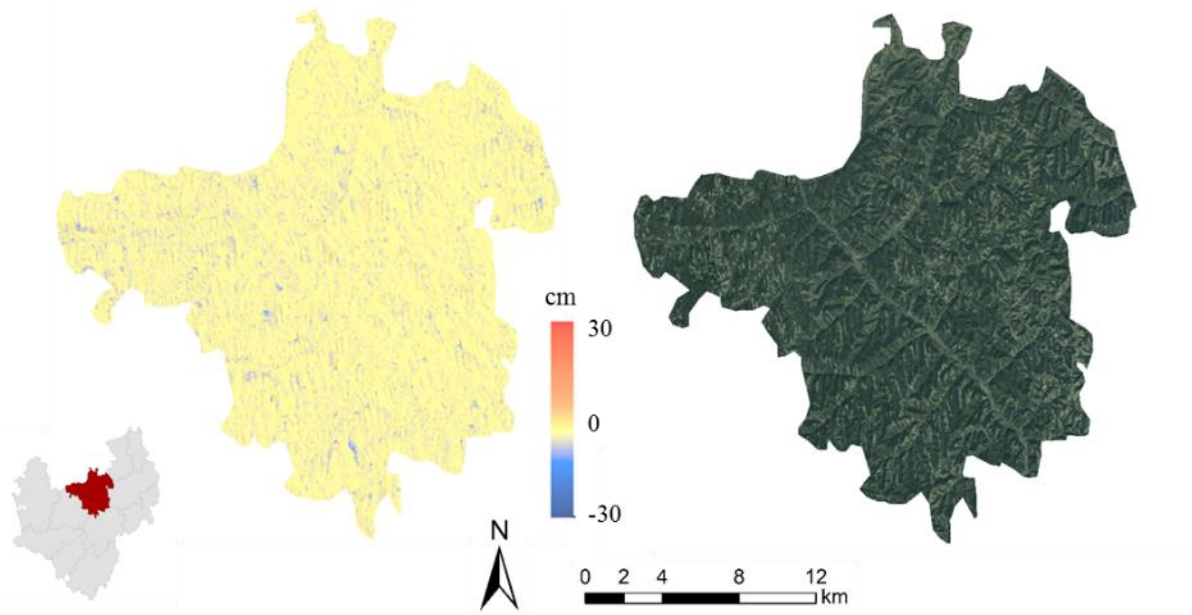
## 4. RESULTS AND DISCUSSION

### 4.1 Overall trend

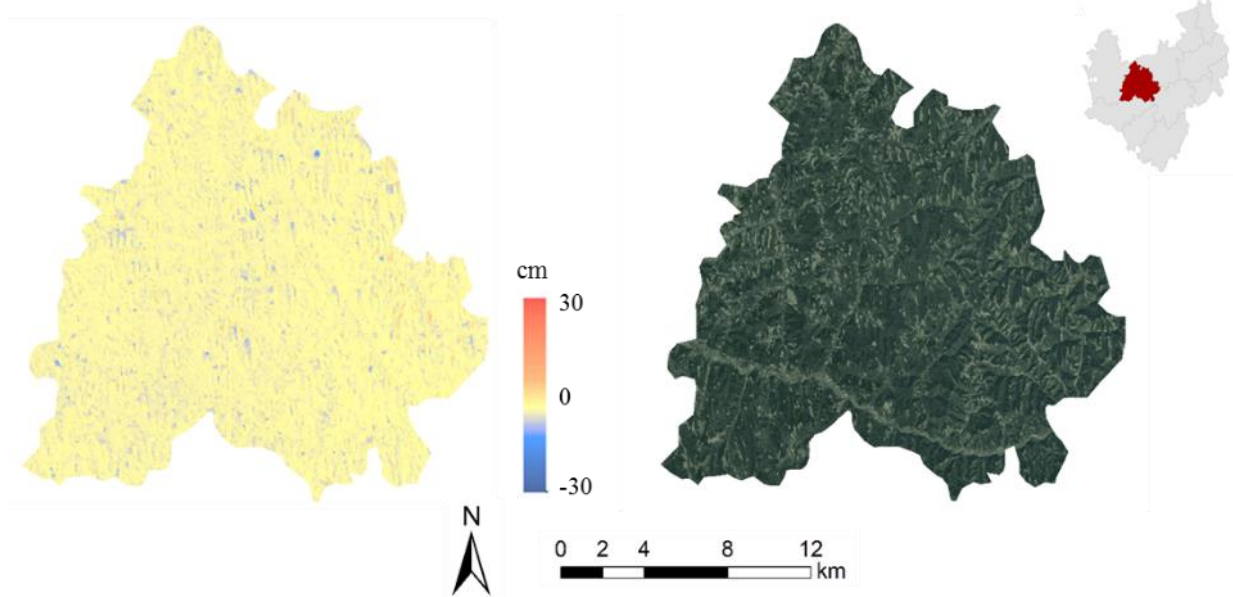
The Displacement maps (Feb. 2, 2008 to Mar. 25, 2010) is shown in Fig. 4, 5 and 6. Blue area indicates decrease in altitude by soil erosion and landslide, by contract red area indicates increase in altitude by sediment deposition. Yellow area shows almost 0 level of displacement. Most of the cells are ensconced in the level less than  $\pm 10$  cm/2 years. Then, the deformation show the large value around the hills as shown in Fig. 4, 5, and 6. As shown these figures, the hot spots of decrease and increase were not observed, so that the displacement range is not much different among these townships.

### 4.2 Relationships between displacement and land condition

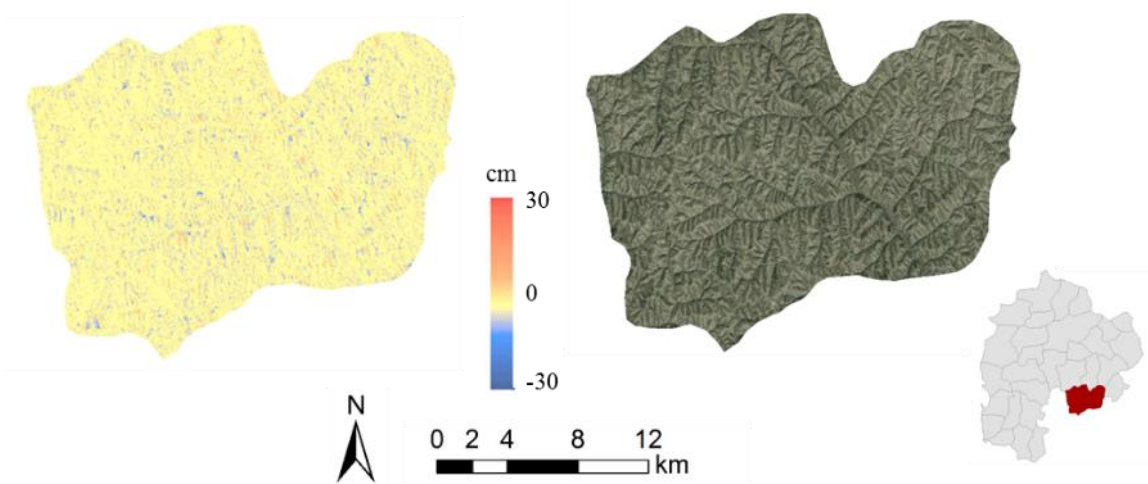
The estimated displacement values are different by the direction of dip (Fig. 7), and minimum value can be found at the southwest-facing while maximum value at east- and northeast-facing in Wucangbu Township of Wuqi County. These trends are also found at the reforestation site in Jingbian County (Fig. 2). However, the displacement at northeast-facing is less than at east and the peak is a little different from others due to the regional difference or accidental error. The locations showing the low quartiles of displacement value  $-10\text{mm/yr}$  and  $\pm 10\text{mm/yr}$  in some cells were explored and we found that most of them were on the northeast-facing which was on the opposite side of the slope from the satellite. In addition, the values of south- to northwest-facing is less than the values of FRNs approach in Jingbian County. It is thought to be due to potential small intensity of soil erosion in this township or the effective soil conservation activities in this township.



**Fig. 4** Displacement map and IKONOS image (2009) in Wucangbu Township, Wuqi County.



**Fig. 5** Displacement map and IKONOS image (2009) in Xinzhai Township, Wuqi County.



**Fig. 6** Displacement map and IKONOS image (2009) in Xin'anbian Town, Dingbian County.

The intensity of deformation on the steep slope is larger than gentle at the north- to east-facing. Whereas, the dispersion of value is large and distinctive trend is not observed as shown in Fig. 8. Totally, any distinctive trend cannot be detected between displacements and the slope angle in Fig. 8, which indicates the different feature from the results of FRNs approach in An'sai County (Yang et al., 2006). This county has obvious gaps among displacement values between top of ridge and gully at a site. On the other hand, in Wuqi and Dingbian Counties, it can be considered that soil is lost at not only the gully slopes but also the gentle areas such as the ridge and floor formulated by agricultural activities as shown in Fig. 9. In addition, comparing positive and negative displacements, any extensive differences cannot be observed at the most of the direction of dip (Fig. 8). Regarding the standard deviation of displacement range of positive displacement, the extensive differences are not found among the direction of dip (Fig. 7). These results shows that positive displacement is occurring with the absence of bias over the area even though investigating that by the direction of dip.

### 5. CONCLUSION

This study tried to clarify the intensity of displacement by soil erosion in Wuqi and Dingbian Counties, the northern part of Shaanxi Province. In conclusion, the present study indicate the adaptive possibility of InSAR approach for measuring the surface displacement by soil erosion. One concrete evidence can be described as, comparing the association of displacement and direction of dip in InSAR approach with that in FRNs approach, the results of both approaches showed similar trend. It can be said that this study explored the new possibility for soil erosion science and regional planning in monitoring approach. Understanding the spatial characteristics of soil erosion dynamics at

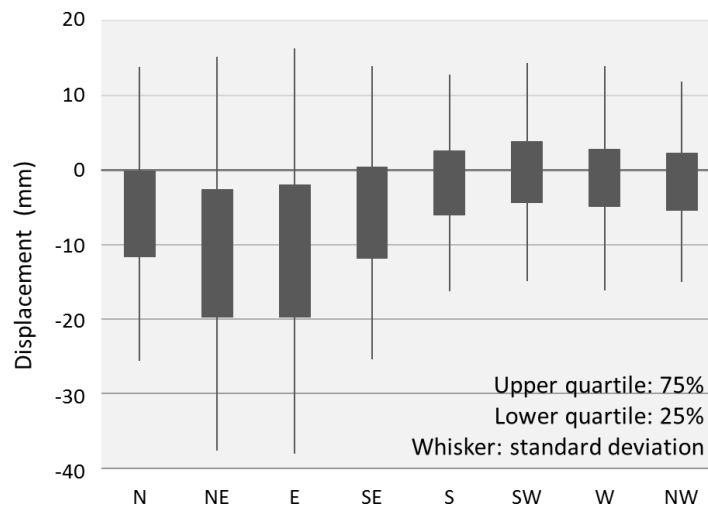


Fig. 7 Estimated displacement during 2 years by the direction of dip in Wucangbu Township

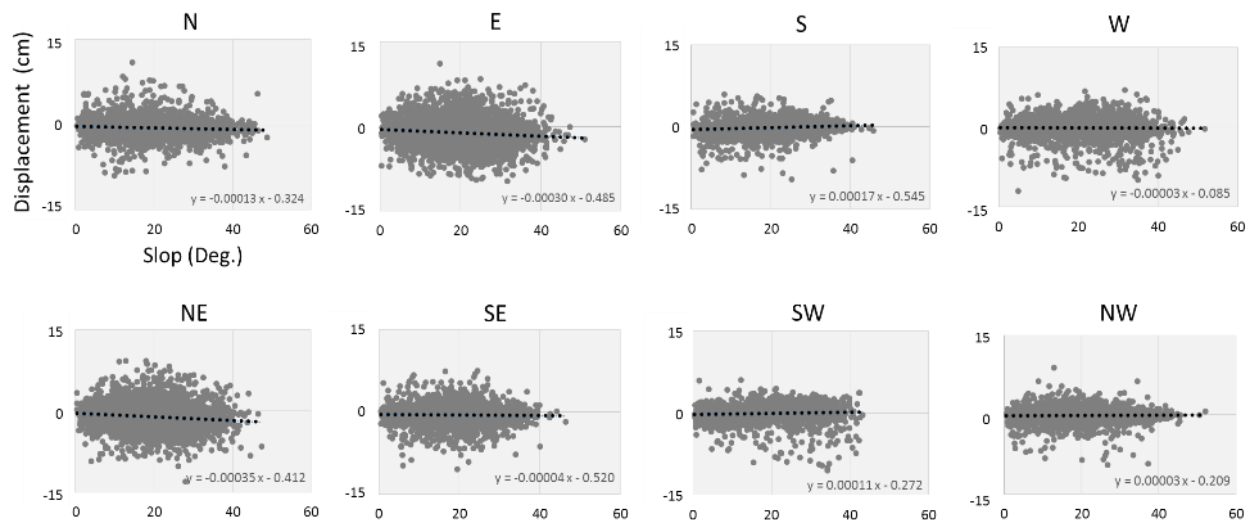


Fig. 8 Estimated displacement values by the direction of dip and slope angle during 2 years in Wucangbu township



**Fig. 9** Typical rural landscape in loess-hilly region in Xin'anbian Town, Dingbian County.

a macroscopic scale will contribute to improve the environmental conditions in the Loess Plateau.

However, some displacements detected in this study would include excessive values, especially at the opposite side of the slope from the satellite. Further studies are needed for the development such as the collaboration with the field monitoring, and the analysis of the more elaborate displacement at the each slopes by time-series InSAR techniques like SBAS and PS-InSAR.

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