Automated Measurement of Sand Dune Migration Using Multi-temporal LiDAR Data and GIS*

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Abstract. Remote sensing has been used for coastal and desert sand dune studies over the past four decades, yet only one automated method has been developed for detection and measurement of dune migration directions and migration rates in large dune fields. Using high-resolution, high-accuracy, and multi-temporal LiDAR data acquired in the White Sands Dune Field in New Mexico (USA) on January 24, 2009 and June 6, 2010, a new method named Pairs of Source and Target Points (PSTP) was developed in a GIS environment for automated detection and measurement of sand dune migration directions and rates. As markers for dune movement, dune slip faces were automatically extracted from LiDAR-derived digital elevation models (DEM), based on the range of the angle of repose, and converted into source lines and target lines through vectorization. Random target points were then generated on target lines and used to search for source points on source lines to form pairs of source and target points, thereby obtaining source direction, migration distance, and migration rate for each target point. Continuous raster datasets for dune migration rates were also created through spatial interpolation and point statistics to show dune-field scale spatial patterns of dune migration rates. The study obtained important results both in methodology development and in the study area.

Keywords: Multi-temporal LiDAR, GIS, digital elevation model, dune migration, White Sands

1. Introduction

Sand dunes are one of the most amazing landforms on Earth and some other planets such as Mars, Venus and Titan (Fenton 2006, Hugenholtz et al. 2007, Bourke et al. 2010). Understanding how sand dunes form and change has long been a research topic in Earth and planetary surface processes (e.g. Bagnold 1941, Wasson and Hyde 1983, Lancaster 1995, Rubin and Hesp 2009, Bridges et al. 2012). In the 1970s and 1980s, many single-dune studies were carried out to understand the basic controls on the form of individual dunes (Livingstone et al. 2007). The rapid development in data collection and processing technology in the 1980s and 1990s led to more sophisticated studies of single dunes. Since 2000 there has been a shift in sand dune research focus from studying single dunes to studying dunes as complex systems (Livingstone et al. 2007). In addition to numerous field studies around the world (e.g. Rubin 1990, Ha et al. 1999, Dong et al. 2000 & 2004, Elbelrhiti et al. 2005, Ewing and Kocurek 2010a, Zhang et al. 2012), many other methods have been developed for sand dune studies, including cellular automaton models (Narteau et al. 2009, Zhang et al. 2010, Barrio-Parra and Rodríguez-Santalla 2014), numerical models (Alhajraf 2004, Hersen 2004, Zhang et al. 2012, Araújo et al., 2013), flume experiments (Taniguchi et al. 2012), landscape-scale experiments (Ping et al. 2014), and interpretation of remotely sensed images (Hunter et al. 1983, Gay 1999, Jimenez et al. 1999, Bailey and Bristow 2004, Levin et al. 2004, Yao et al. 2007, Mohamed and Verstraeten 2012). These studies have improved general understanding of sand dunes. A review of research progress in geomorphology of desert sand dunes can be found in Livingstone et al. (2007).

In comparison with traditional remote sensing techniques, light detection and ranging (LiDAR) has provided unprecedented datasets for sand dune studies, mostly in the form of high-resolution and high-accuracy DEMs. Early LiDAR-based sand dune studies focused on coastal dunes (Woolard and Colby 2002, Mitasova et al. 2004, Saye et al. 2005). Since 2010, several studies have been conducted for desert dunes (Reitz et al. 2010, Ewing and Kocurek 2010b, Baitis et al. 2014, Ewing et al. 2015). However, progress in developing and applying objective spatial analysis methods for characterizing dune field patterns has been limited (Hugenholtz et al. 2012). The manual methods have typically restricted analysis to small study areas. To facilitate investigation of large dune fields, effective and efficient methods for information extraction from remotely sensed data are needed. This paper demonstrates, for the first time, that sand dune migration directions and rates in large dune fields can be automatically detected and measured using multi-temporal LiDAR data and a new approach, named Pairs of Source and Target Points (PSTP), implemented in a geographic information system (GIS).

2. Study Area and Data

2.1 Study Area

The study area is a 9 km by 2.4 km representative area in the White Sands Dune Field (WSDF) in New Mexico, USA (**Fig. 1**). Situated within the Tularosa Basin between the San Andres Mountains to the west and the Sacramento Mountains to the east, the White Sands gypsum dune field has an area of about 500 km^2. WSDF has four types of dunes – barchans, transverse, parabolic , and dome dunes; the first three types are present in the rectangular study area. The three crescentic dune types at WSDF range up to 15 m in height. The NNW-trending (345°) crestlines have an average length of 247 m and an average spacing of 136 m (Ewing et al. 2006). During the winter-spring, the dominant winds from the SW–W are strongest. Winds from the N–NW occur during the fall-winter, while winds from the S–SE occur during the spring–summer (Kocurek et al. 2007). The sediment source of WSDF is from deflation of evaporite beds of Lake Otero and other playa lakes in the basin (Kocurek et al. 2007). The dune field has been investigated in numerous studies (e.g. McKee 1966, Fryberger 2000, Langford 2003, Kocurek et al. 2007). Like many dune fields, WSDF exhibits a downwind transition pattern from forward-pointing barchans dunes to stabilized backward-pointing parabolic dunes.

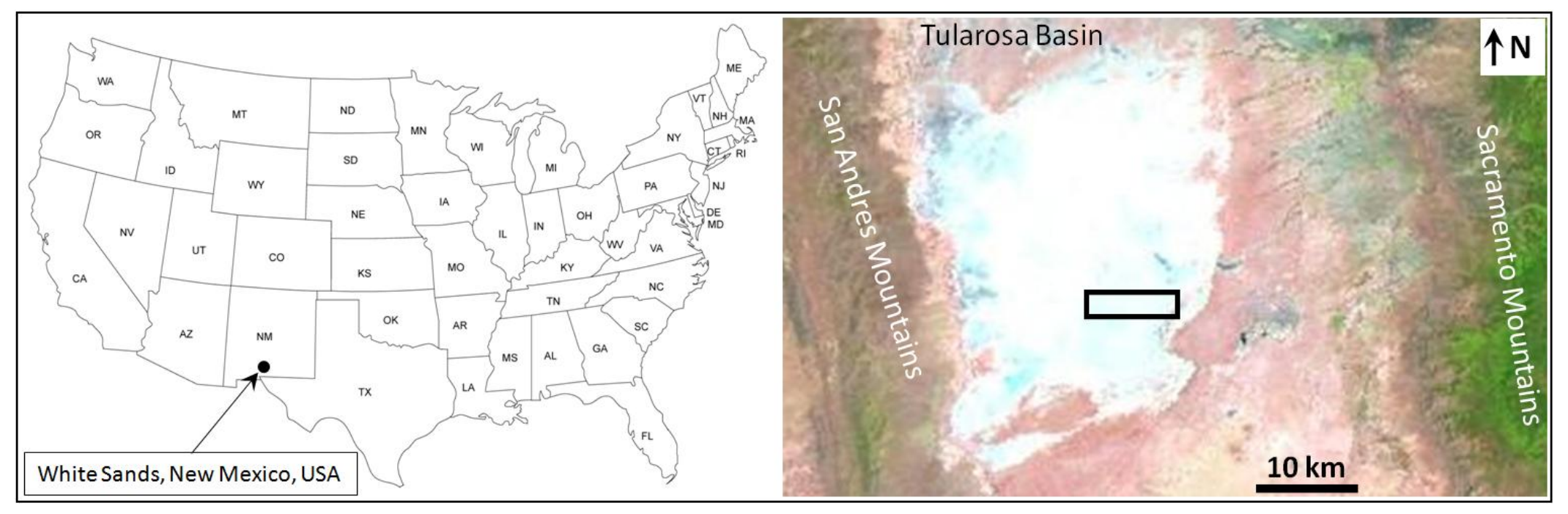


Fig. 1. Location of study area shown as a point (left) and a black rectangle (right) over a Landsat TM image acquired on June 14, 2010 and displayed as color composite of bands 5(R), 4(G), and 3(B).

2.2 Data

LiDAR datasets acquired on January 24, 2009 and June 6, 2010 in the study area were downloaded from the OpenTopography Facility (www.OpenTopography.org) at the San Diego Supercomputer Center. LiDAR data acquisition and processing was completed by the National Center for Airborne Laser Mapping (NCALM - http://www.ncalm.org). The January 24, 2009 data has a point density of 4.19 points/m^2, and the June 6, 2010 data has a point density of 4.62 points/m^2. The horizontal coordinate system is NAD83 UTM Zone 13N, and the vertical coordinate system is NAVD88. **Fig. 2** shows the digital elevation models (DEM) created from the LiDAR point clouds using Inverse Distance Weighted (IDW) interpolation with a cell size of 1 m by 1 m. **Fig. 3** shows two west-east topographic profiles extracted from multi-temporal LiDAR DEMs along the center line of the study area.

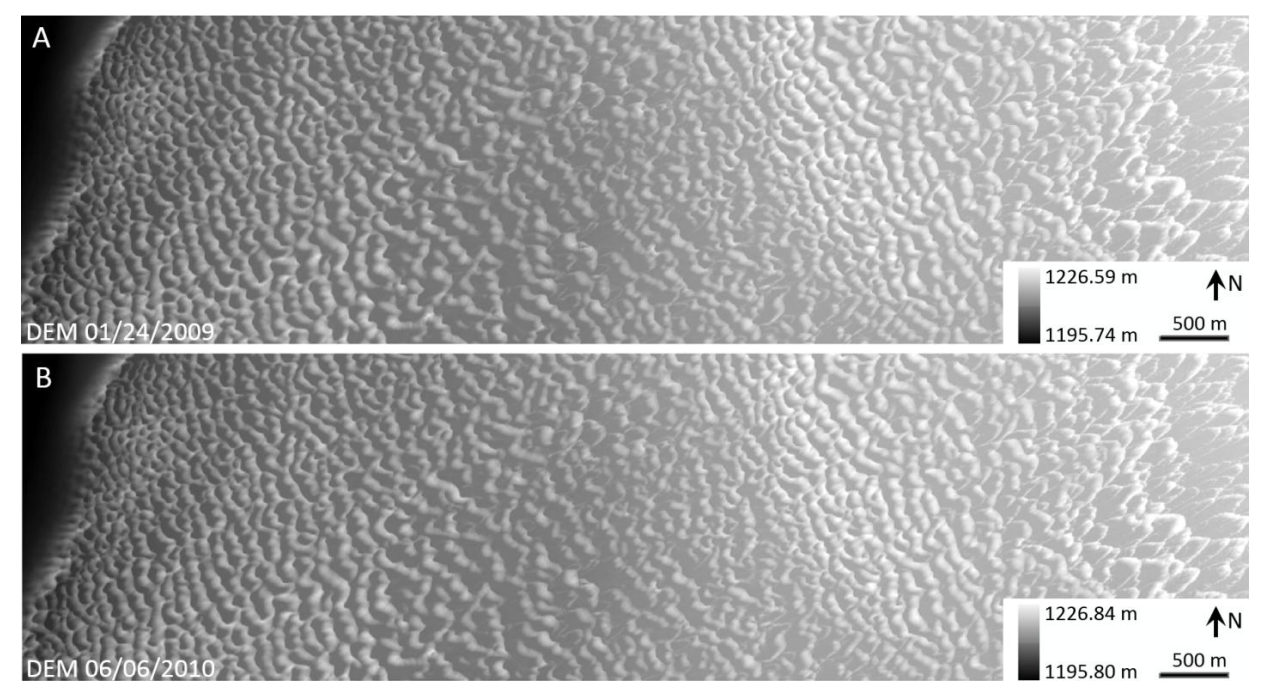


Fig. 2. Digital elevation models (DEM) with 1 m by 1 m cell size created from multi-temporal LiDAR point clouds covering the study area of 2.4 km by 9 km. Top: DEM for January 24, 2009. Bottom: DEM for June 6, 2010.

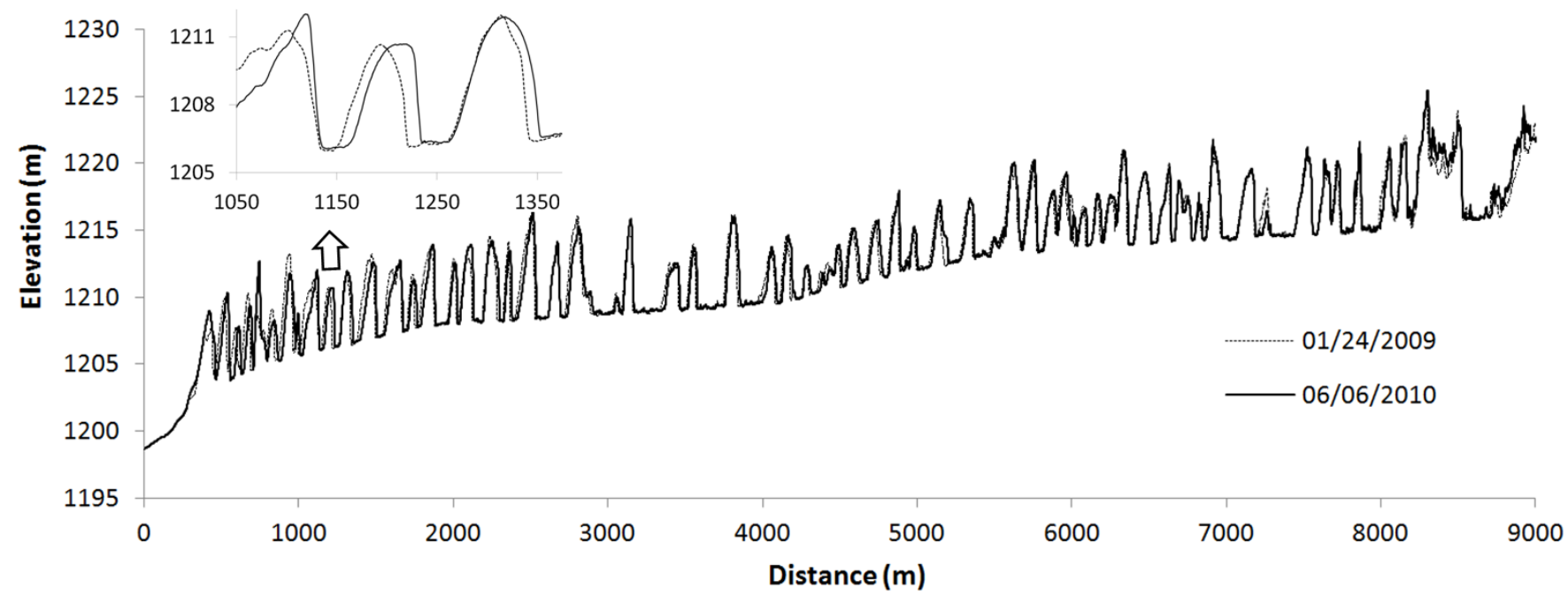


Fig. 3. Topographic profiles extracted from multi-temporal LiDAR DEMs along the center line of the study area from west to east. An enlarged section is also shown. Note that profiles are vertically exaggerated.

3. Methodology

Based on the analysis of single-dune migration distance (**Fig. 4**), an automated method named Pairs of Source and Target Points (PSTP) for measuring migration directions and migration rates of dune fields is proposed (Figure 5). The theoretical foundation of the PSTP method is that sand avalanching and slumping events caused by gravity occur in the inclination direction of the slip face (Bagnold 1941). The centerlines of old slip faces are referred to as source lines, and the centerlines of new slip faces are referred to as target lines. The basic concept of the PSTP method is explained as follows: For any point B (target point) on a target line (**Fig. 5**), there might be a nearest point A (source point) on a source line (or the extension of the source line) within a certain search radius, and the vector *AB* is normal to the source line at point A. The length of the vector *AB* is the dune migration distance, and the direction of the source point A relative to the target point B is called source direction, counting clockwise from 0° (north) to 360° . Source directions do not necessarily follow the prevailing wind direction, but may reflect the prevailing wind direction statistically. Random points can be generated on the target line, thereby pairs of source and target points can be identified for automated calculation of migration distance and source direction. More details of the methodology are shown in **Fig. 6 – 9.**

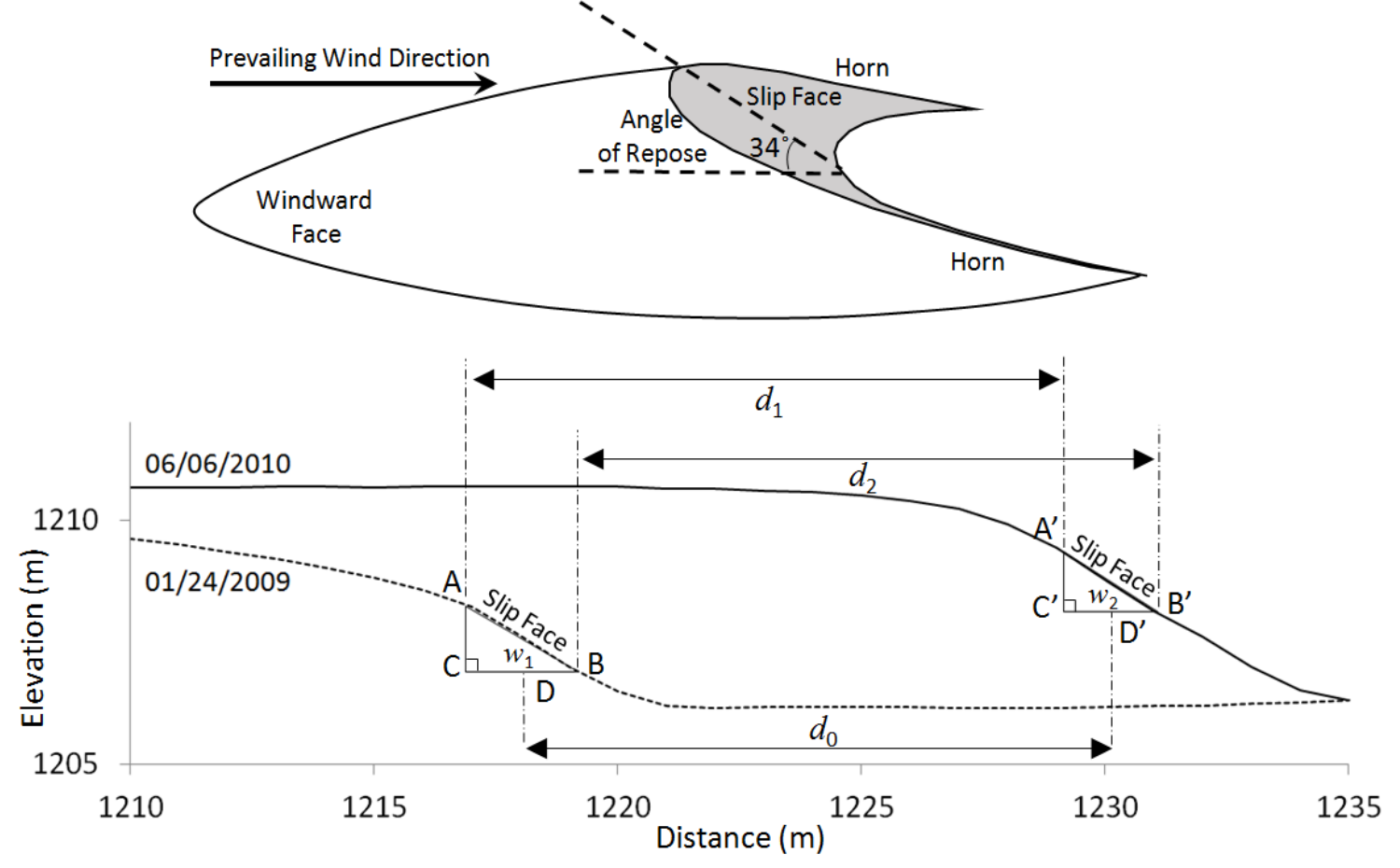


Fig. 4. Migration distance of a single dune. It can be proven that d_0 is the average of d_1 and d_2.

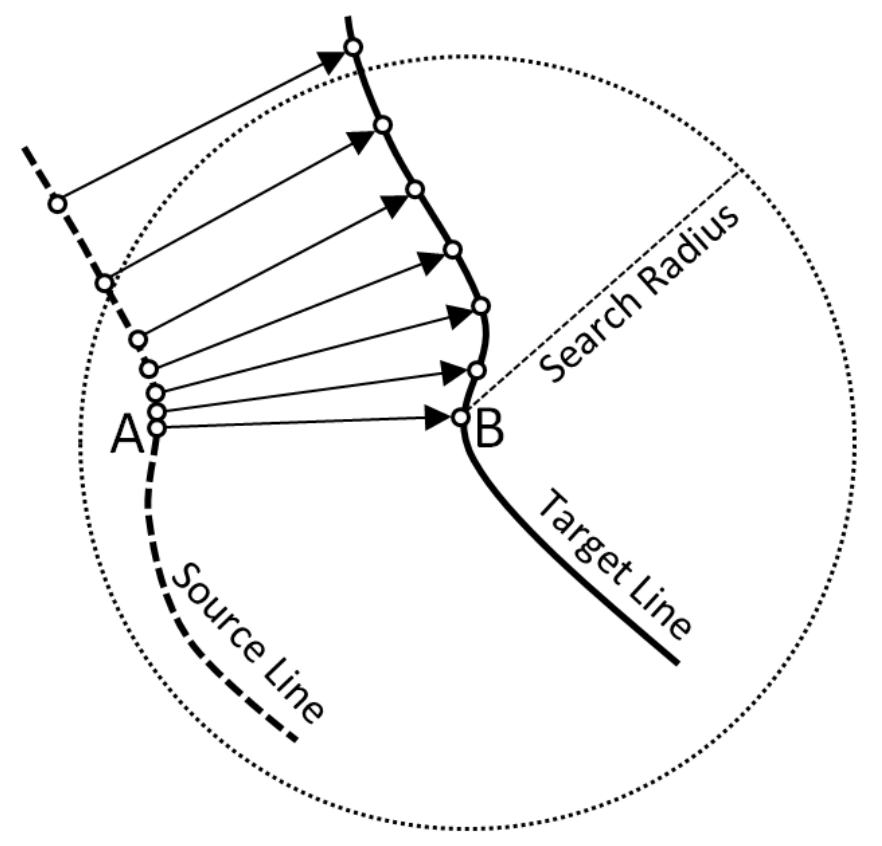


Fig. 5. Pairs of source and target points on source lines and target lines.

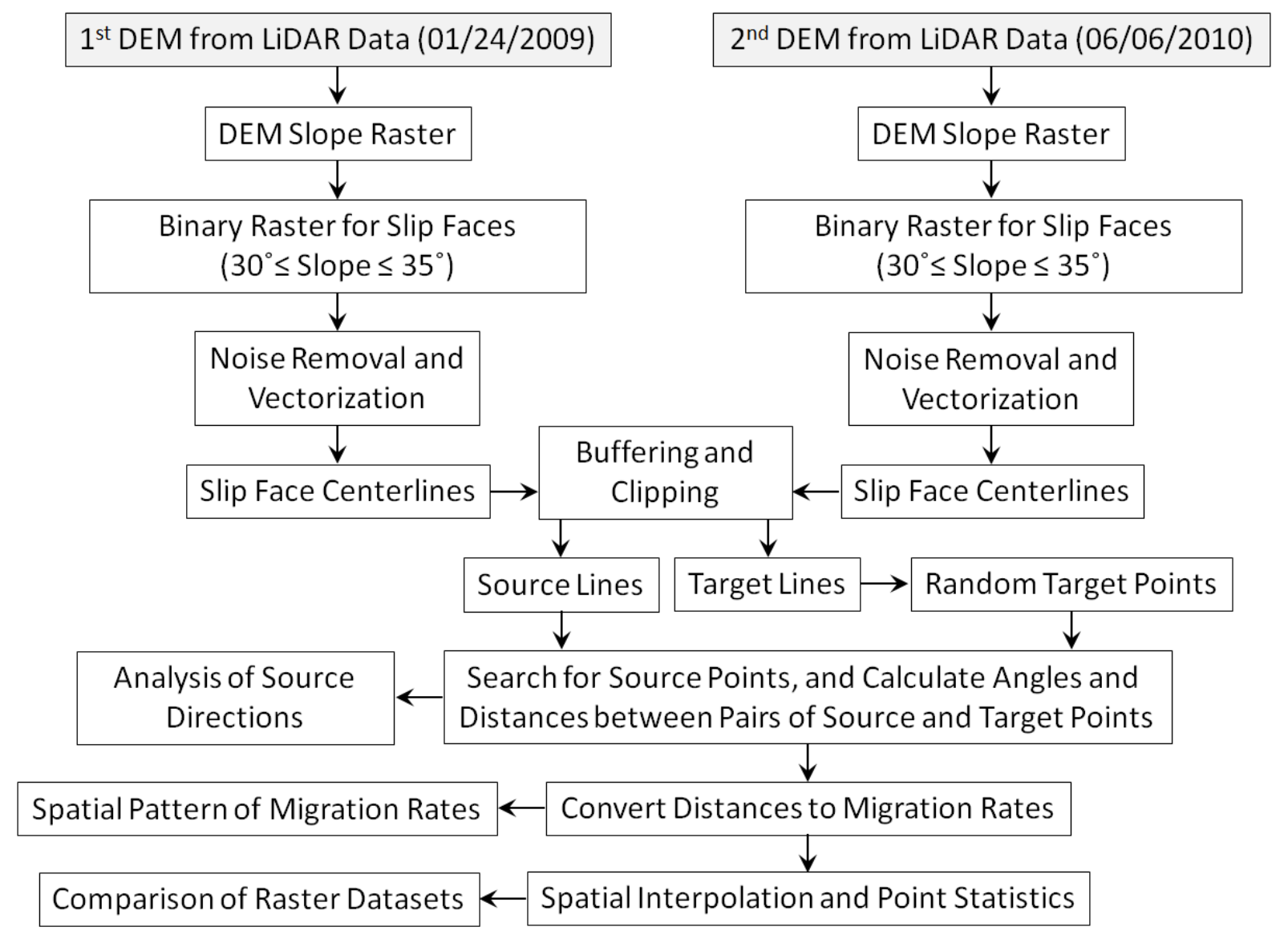

1st DEM from LiDAR Data (01/24/2009)
DEM Slope Raster
Binary Raster for Slip Faces (30°≤ Slope ≤ 35°)
Noise Removal and Vectorization
Slip Face Centerlines
2nd DEM from LiDAR Data (06/06/2010)
DEM Slope Raster
Binary Raster for Slip Faces (30°≤ Slope ≤ 35°)
Noise Removal and Vectorization
Slip Face Centerlines
Buffering and Clipping
Source Lines
Target Lines
Random Target Points
Search for Source Points, and Calculate Angles and Distances between Pairs of Source and Target Points
Analysis of Source Directions
Convert Distances to Migration Rates
Spatial Pattern of Migration Rates
Spatial Interpolation and Point Statistics
Comparison of Raster Datasets

Fig. 6. Flowchart for automated measurement of sand dune migration using multi-temporal LiDAR data and GIS.

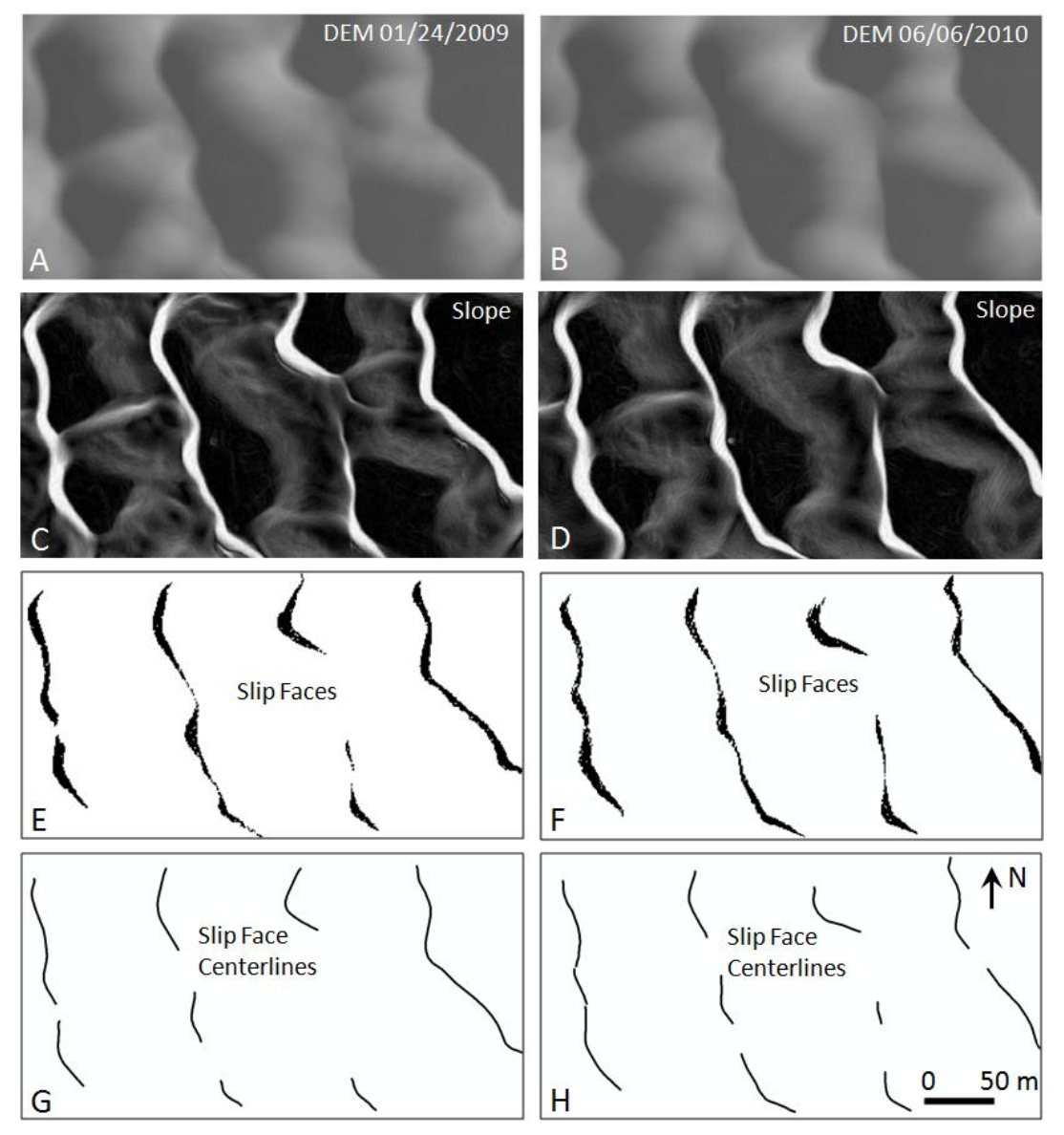


Fig. 7. Extraction of slip face centerlines from multi-temporal LiDAR data in a small area.

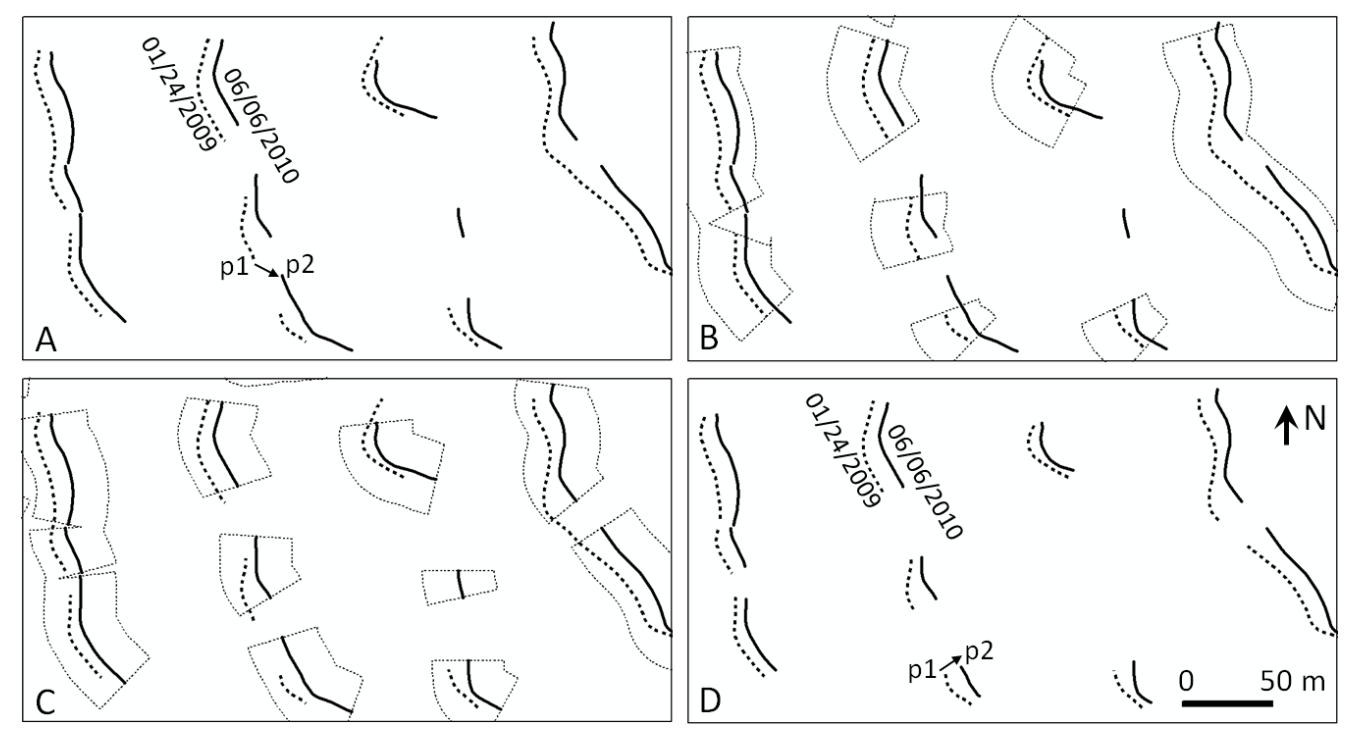
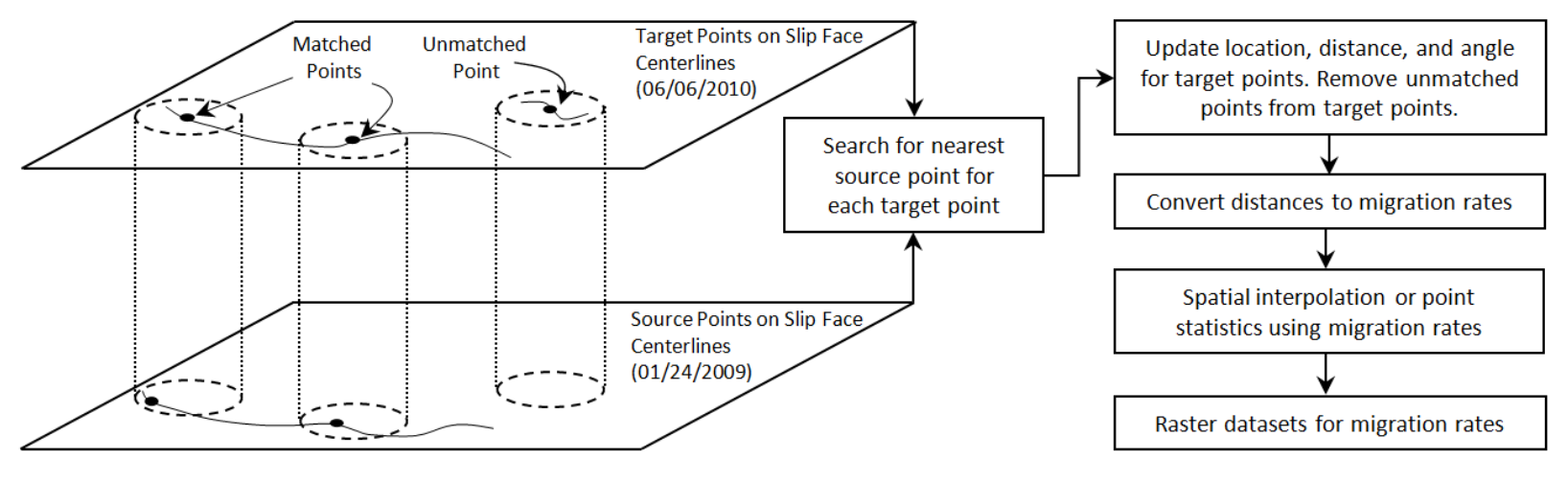


Fig. 8. Processing of source and target lines using buffering and clipping.



Search for nearest source point for each target point
Update location, distance, and angle for target points. Remove unmatched points from target points.
Convert distances to migration rates
Spatial interpolation or point statistics using migration rates
Raster datasets for migration rates

Fig. 9. Matching target and source points to calculate migration distances and rates.

4. Results

Fig. 10 – 14 show some of the results obtained from the study area.

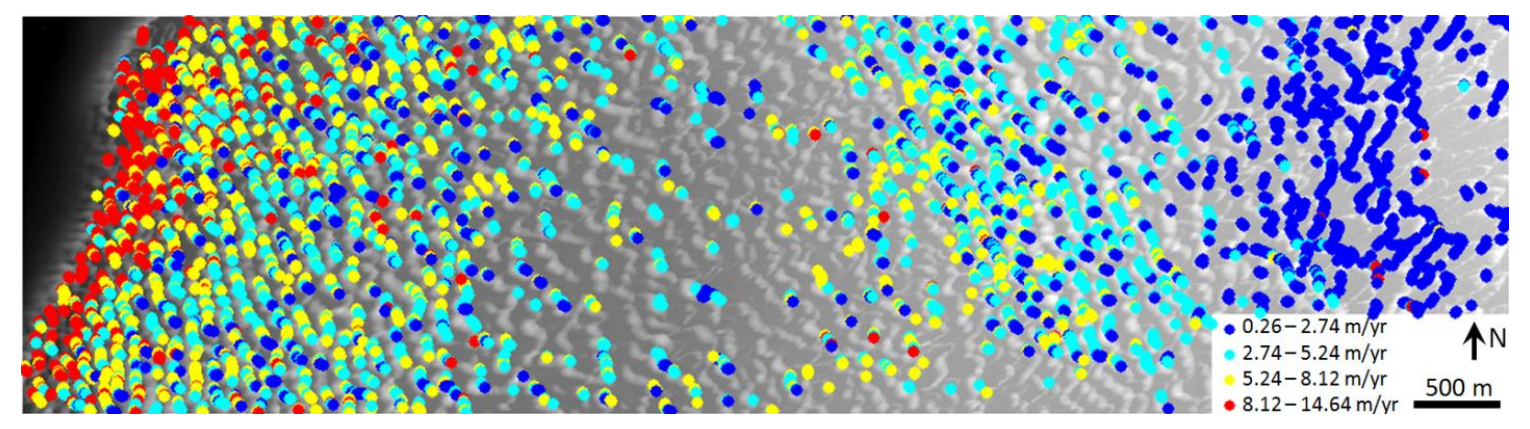


Fig. 10. Sand dune migration rates at 5,396 target points randomly selected from target lines.

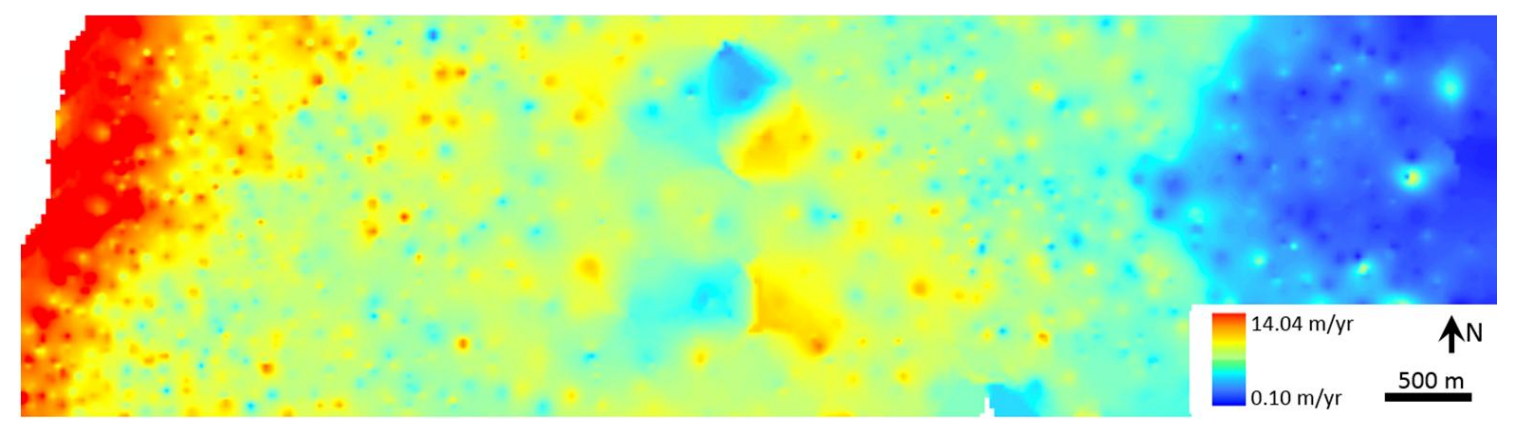


Fig. 11. Rater for sand dune migration rates created from IDW interpolation to show dune-field scale patterns of migration rates.

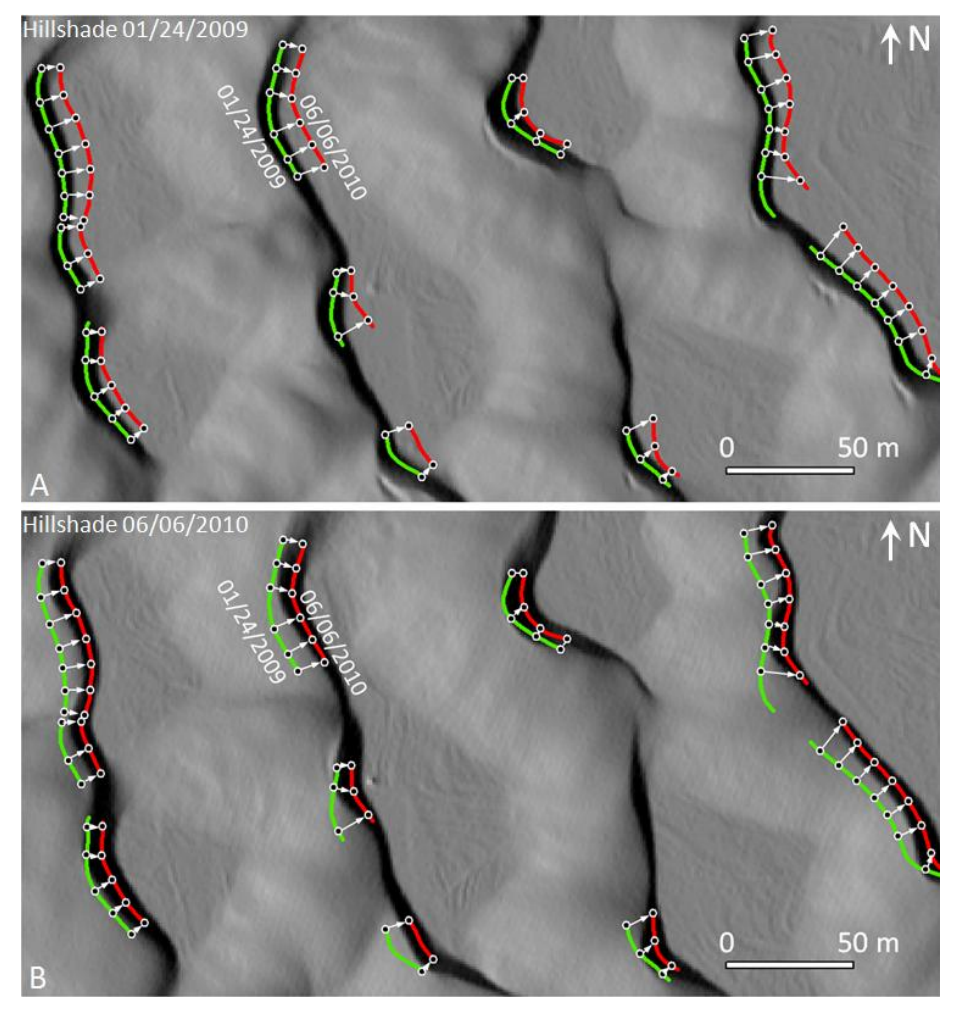


Fig. 12. Source lines (green), target lines (red), and pairs of source and target points.

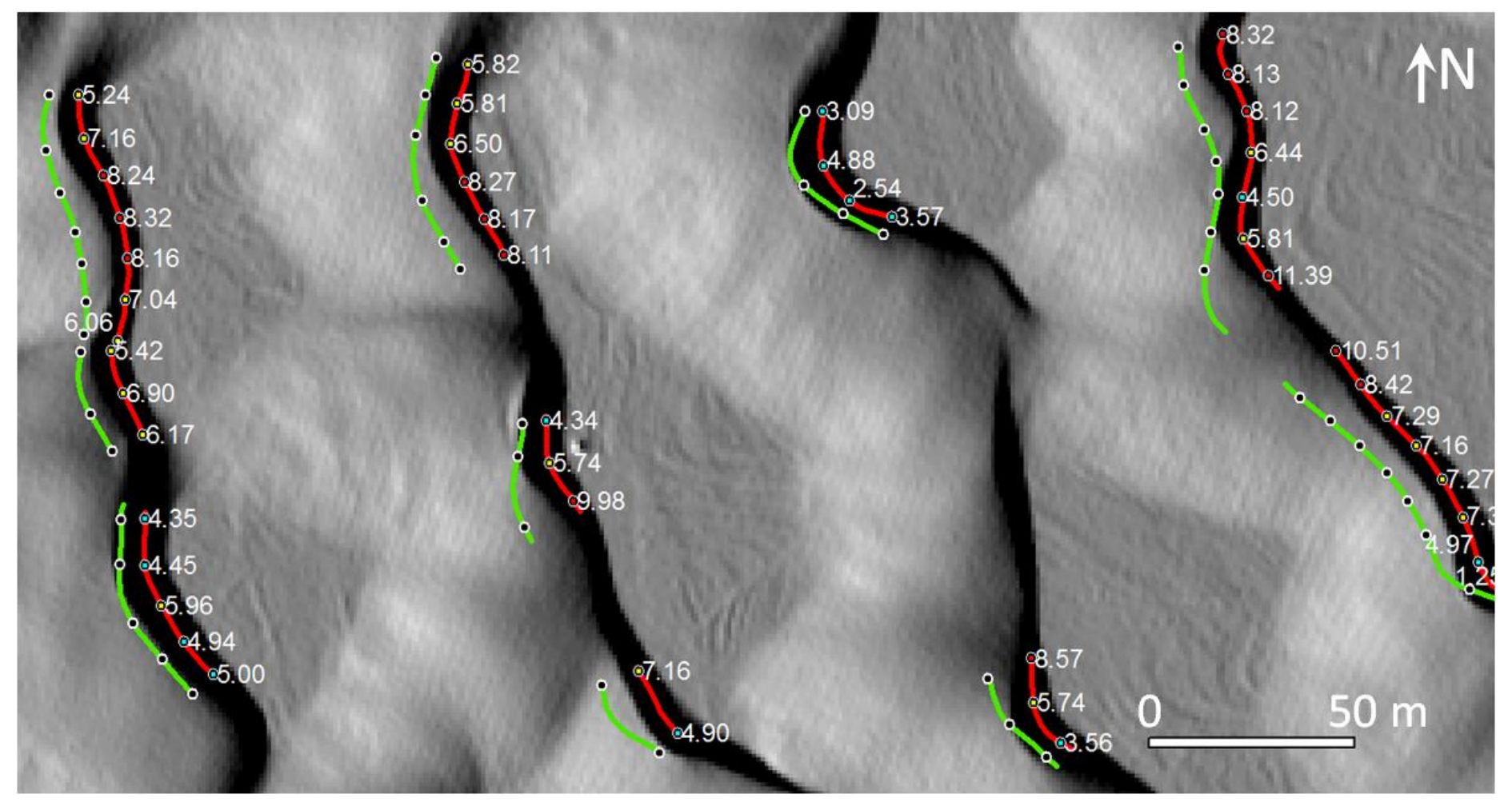
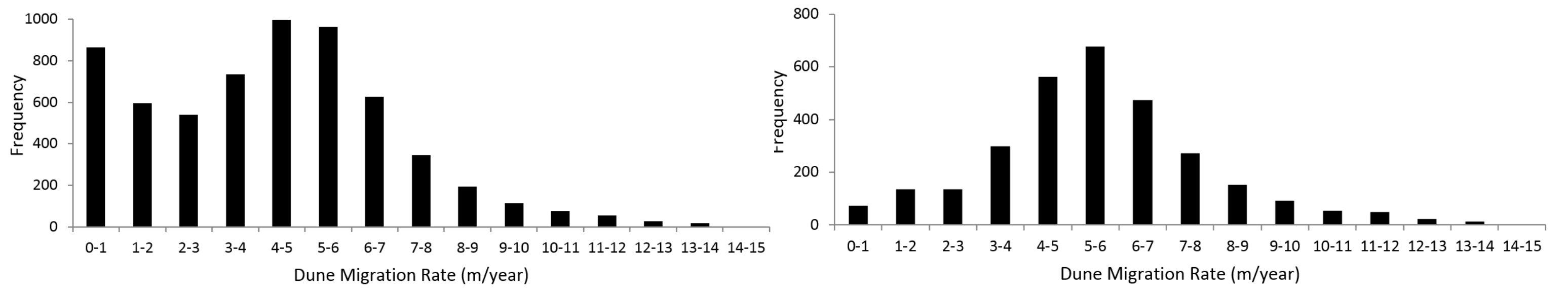
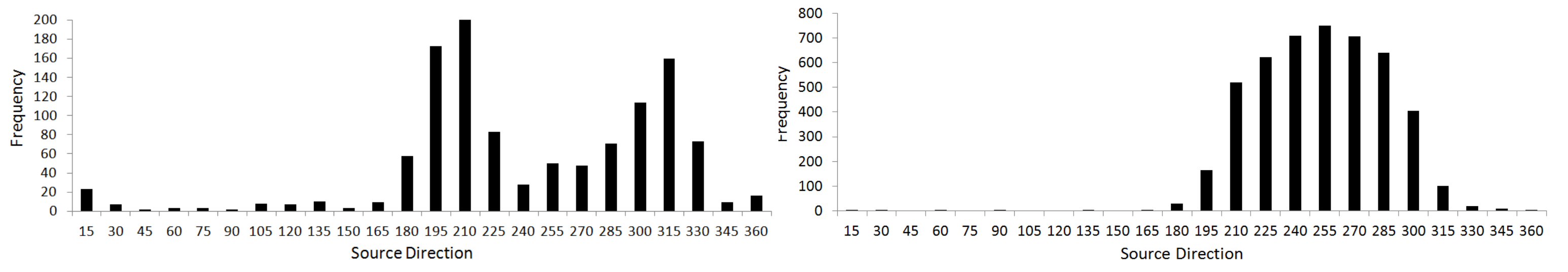


Fig. 13. Sand dune migration rates automatically calculated for individual target points.



(*a*) Histogram of dune migration rates (m/year) for 5936 target points.

(*b*) Histogram of dune migration rates (m/year) for 3025 target points with source direction in the range of 225°-285°.



(*c*) Histogram of source direction for 1225 target points with migration rates less than or equal to 2 m/year.

(*d*) Histogram of source direction for 4711 target points with migration rates greater than 2 m/year.

Fig. 14. Histograms for dune migration rates and source directions.

5. Conclusions

Compared with traditional methods which involve labor-intensive and time-consuming measurements at individual locations, the PSTP method enables automated measurement of sand dune migration directions and rates at hundreds or thousands of randomly generated locations on slip face centerlines in a sand dune field, allowing for generation of continuous raster datasets showing the dune-field scale spatial pattern of sand dune migration rates. In the study area of 9 km by 2.4 km, a total of 5,936 pairs of source and target points were identified, producing dune migration directions and migration rates at 5,936 locations. Histogram analysis revealed that a majority of the 3,025 target points with source direction in the range of 225° -285° (direction of prevailing winds) have a migration rate of 4-7 m/year and an average migration rate of 5.56 m/year. Target points with source directions in 255° ±15° and 255° ±30° were used for creating raster datasets for dune migration rates along the prevailing wind direction. Both basic statistics and correlation coefficients suggest that the raster datasets are very similar, which indicates that source direction deviations of up to ±30° from the prevailing wind direction do not significantly affect dune-field scale spatial patterns of migration rates produced by prevailing winds.

The PSTP method proposed in this study is the second automated method for measuring sand dune migration using remotely sensed data for Earth and planetary surfaces. Compared with the existing COSI-Corr method (Leprince et al. 2007), PSTP has several advantages in providing more accurate measurements and detecting anomalous sand dune migration patterns. Moreover, it should be noted that the PSTP method is not limited to sand dune migration studies using multi-temporal LiDAR data. The PSTP method can potentially be used as a more generic approach to change detection and measurement. Locations of source lines and target lines can be digitally or manually extracted from other remotely sensed images or collected by GPS devices for change detection and measurement applications, such as measuring the rate of ice cap retreat, the rate of pollutant plume dispersion, and the rate of shore line change, among others.

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References: (52 references omitted)

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