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Automated Detection of Austere Entry Landing Zones

A "GRAIL Tools" Validation Assessment

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Final report

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103 Army Pentagon
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Preface

This study was conducted for the Assistant Secretary of the Army for Acquisition, Logistics, and Technology with funding for this project provided by the Geospatial Research and Engineering (GRE) Army Terrestrial Environmental Modeling and Intelligence System Science Technology Objective-Research (ARTEMIS STO-R) program.

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COL Christian Patterson was the commander of ERDC and the director was Dr. David W. Pittman.

Automated detection of austere entry landing zones: A “GRAIL Tools” validation assessment

Abstract

The Geospatial Remote Assessment for Ingress Locations (GRAIL) Tools software is a geospatial product developed to locate austere entry landing zones (LZs) for military aircraft. Using spatial datasets like land classification and slope, along with predefined LZ geometry specifications, GRAIL Tools generates binary suitability filters that distinguish between suitable and unsuitable terrain. GRAIL Tools combines input suitability filters, searches for LZs at user-defined orientations, and plots results. To refine GRAIL Tools, we: (a) verified software output; (b) conducted validation assessments using five unpaved LZ sites; and (c) assessed input dataset resolution on outcomes using 30 and 1-m datasets. The software was verified and validated in California and the Baltics, and all five LZs were correctly identified in either the 30 or the 1-m data. The 30-m data provided numerous LZs for consideration, while the 1-m data highlighted hazardous conditions undetected in the 30-m data. Digital elevation model grid size affected results, as 1-m data produced overestimated slope values. Resampling the data to 5 m resulted in more realistic slopes. Results indicate GRAIL Tools is an asset the military can use to rapidly assess terrain conditions.

1 | INTRODUCTION

The ability to rapidly conduct accurate terrain assessments and detect associated hazards remotely is a top U.S. Army priority. Presently, austere entry landing zone (LZ) and drop zone (DZ) identification and assessment is determined using on-site observations that place both personnel and operation planning at risk (Shoop et al., 2018). To ameliorate these issues, the Geospatial Remote Assessment for Ingress Locations (GRAIL) Tools software was developed to facilitate the process of remotely locating austere entry LZs and DZs for military applications (Shoop & Wieder, 2018).

Specifically created for the U.S. Army, GRAIL Tools is a toolbox that works within ArcGIS (version 10.4.1) and incorporates unique spatial datasets and LZ geometry specifications to locate LZs and DZs. Input datasets, such as land classification and slope, are used to generate binary suitability filters that distinguish between suitable and unsuitable terrain for potential LZ locations. Suitability filters are created by either selecting multiple unique values or a single threshold value compatible with LZ requirements (Figure 1). For example, users can specify a single slope threshold value (such as less than 7%) or multiple unique land classification values (such as barren land, pastureland, grassland, etc.) that meet compatibility needs. Output LZ geometry is dictated by defined input parameters, which are typically associated with a specific type of military aircraft. LZ requirements are different for fixed-wing and rotary-wing aircraft, and GRAIL Tools focuses primarily on fixed-wing applications. LZ dimensions for some aircraft can be chosen from a list, for the C-130 and C-17 aircraft, for example, but other unique geometries, such as a LZ or DZ of specific length, width, or radius, can also be specified. The software combines all input suitability filters into a master grid, searches for LZs at user-defined orientations (such as every 15°, for example), and plots results with 95 and 100% suitability acceptance levels (Figure 1). LZs that are 95% suitable are comprised of up to 5% unsuitable pixels (i.e., those that do not meet one or more of the specified compatible criteria), while LZs that are 100% suitable are comprised entirely of suitable pixels (i.e., a single unsuitable pixel will prohibit LZ placement). Where soil moisture data is available, a supplemental soil strength calculation tool, which uses soil moisture and soil classification datasets to generate soil strength maps, can be used to generate strength suitability filters that may also be incorporated into LZ and DZ searches.

GRAIL Tools represents a substantial advancement in the process of locating LZs and DZs remotely. This article presents an initial verification and validation assessment of the software. For the purposes of this study, *verification* is defined as the process of confirming that the software behaves as is expected and places generated LZs in correct regions (i.e., over pixels classified as suitable). *Validation* is defined as the process of demonstrating that GRAIL Tools results represent the actual situation on the ground. The GRAIL Tools software is unique in that it can accommodate a wide variety of dataset types of any resolution (see Table 1 in Shoop et al., 2018), but the impact of dataset resolution on LZ output has not been investigated previously. Therefore, in this study, we: (a) verified GRAIL Tools output in two unique climatic regions; (b) conducted a robust validation assessment using five known unpaved LZ sites; and (c) assessed the effect of input dataset resolution on perceived outcomes using 30 and 1-m resolution input data.

2 | STUDY SITES

Two study sites were selected to assess performance over a wide range of possible terrain and climatic conditions. Fort Hunter Liggett (FHL) is a U.S. Army training facility in central California selected for detailed assessments due to the presence of five established unpaved LZs (designated as the Milpitas, Jolon, Schoonover, Tule, and El Piojo LZs) that are currently—or have historically—been used for training purposes (Figures 2A and 2C). The terrain at FHL is topographically variable, consisting of both wide valleys and steep hills with slopes ranging between 0 and 67° (Figure 2D). Land cover is predominantly grassland, shrubs, and forest. Annually, this region receives an average of 23 cm of rain.

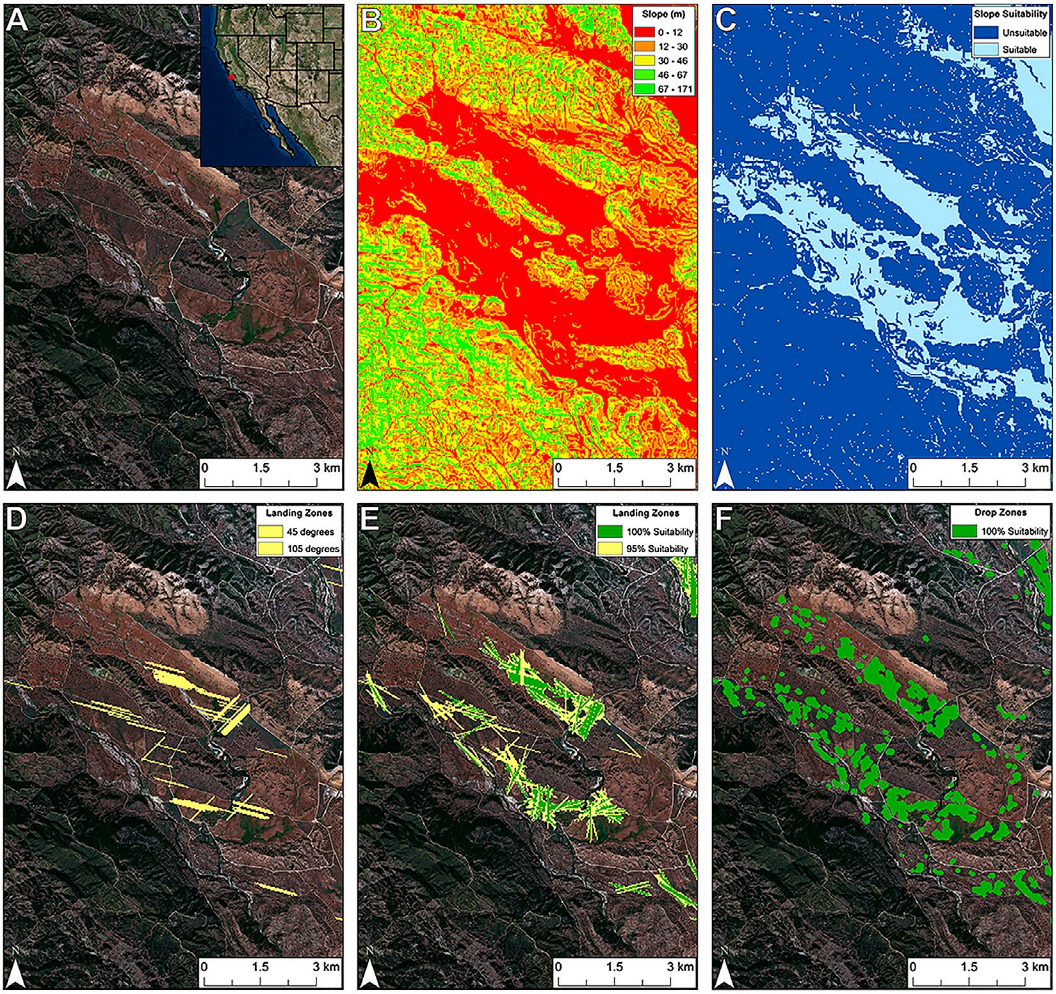

FIGURE 1 GRAIL Tools suitability filter generation and example LZ and DZ output. Each panel depicts the same aerial extent of Fort Hunter Liggett (FHL), CA shown by the inset in panel A. Panel B is a 30-m slope map used to generate the slope suitability filter shown in panel C, where areas with slopes of less than 7% are classified as suitable. The bottom panels show example GRAIL Tools output for two LZ orientations (45° and 105°; panel D), LZs with 95% (yellow) and 100% (green) suitability (panel E), and drop zones with a radius of 50 m (panel F)

A second study site in the Baltics (BT) was selected for its stark contrast in terms of climatic and terrain conditions compared to FHL (Figure 2B). The region of BT selected for detailed analysis is predominantly flat, with slopes ranging between 0 and 35°, while the landscape is dominated by agricultural areas (open fields), forests, lakes, and wetlands (Figure 2E). Several small towns are located across the region. Precipitation rates are substantially higher in BT compared to FHL, with annual totals around 81 cm.

3 | METHODS

3.1 | Input datasets and preprocessing procedures

The GRAIL Tools software was designed to accommodate any type of geospatial data (Shoop et al., 2018). Five datasets of both coarse and fine resolution were used to assess GRAIL Tools output in different climatic regions

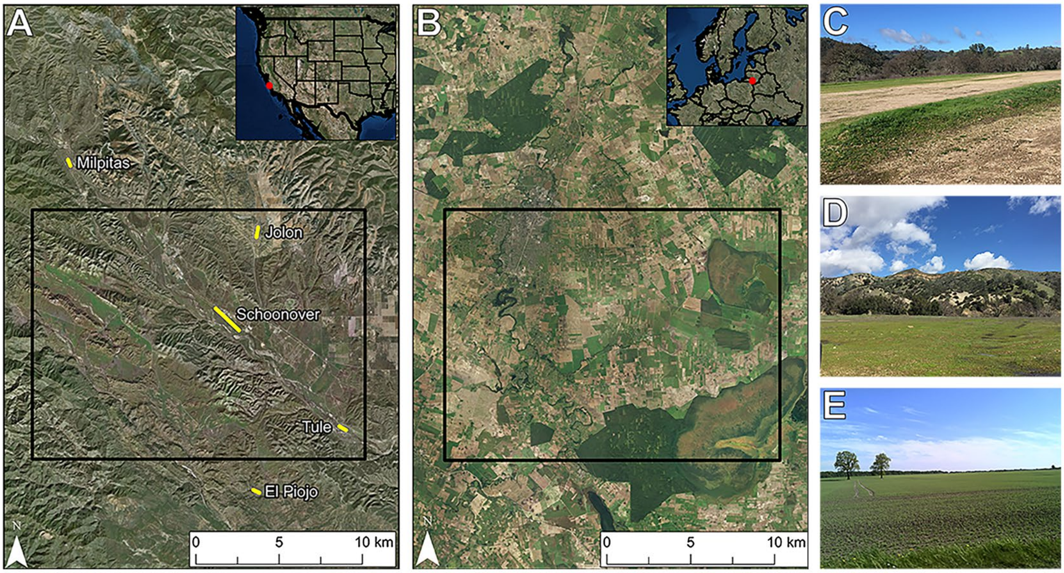

FIGURE 2 FHL (panel A) and BT (panel B) study sites, showing location insets in the upper right corners. Five FHL unpaved LZs are labeled and highlighted in yellow in panel A. The black rectangles outline the 15 × 20-km region where GRAIL Tools verification analyses were conducted. Panel C: Photograph of one of the LZs at FHL. Panels D and E show photographs of the typical terrain observed at FHL and BT, respectively

and examine the effects of input dataset resolution on results. GRAIL Tools verification was conducted using 30-m datasets of FHL and BT. Validation was conducted using both 30 and 1-m datasets of FHL. Details on the specific datasets used are as follows:

- 30-m U.S. Geological Survey (USGS) National Land Cover Database (NLCD) land classification data (FHL data);
- 1-arcsec (resampled to 30 m for this study) National Geospatial-Intelligence Agency (NGA) Shuttle Radar Topography Mission (SRTM) digital surface model (DSM) elevation data (FHL and BT data);
- 30-m NGA Visual Navigation (VISNAV) land cover data (BT data);
- 1-m bare earth digital elevation model (DEM) elevation data (provided by FHL); and
- 1.85-m (resampled to 1 m for this study) DigitalGlobe WorldView-2 (WV2) multispectral imagery (FHL data).

The 30-m NLCD, VISNAV, and NGA input datasets were preprocessed in ArcGIS. Each dataset was projected to the correct coordinate system (World Geodetic System [WGS] 1984, Universal Transverse Mercator [UTM] zone 10 north [FHL] or 34 north [BT]), clipped to the specified bounding boxes, and resampled to ensure the pixels were the exact same size and all input data were aligned to a common grid (i.e., overlapping).

WV2 multispectral imagery was collected over FHL in 2015. Sopher, Shoop, Stanley, and Tracy (2016) applied a supervised image classification using discriminant analysis and conditional probability distribution techniques to the WV2 imagery in order to determine and classify soil strength values. The imagery was classified into 10 groups: water, heavy vegetation (primarily trees/forest), and eight groups based on California Bearing Ratio (CBR) values, which are a measurement of the load-bearing capacity associated with specific soil types.

3.2 | Verification

Verification assessments were required to ensure output LZ placement was located in correct (i.e., suitable) regions. Analyses were conducted at both FHL and BT within 20 × 15-km bounding boxes that contain a representative subsample of the variety of terrain conditions found at each location, including both favorable and unfavorable areas for LZ placement (see Figure 2). For example, while the area selected at FHL contains the Tule, Schoonover, and Jolon LZs, it also contains steep hillsides, forests, and wetlands that are unsuitable for LZ placement. The region selected in BT contains flat agricultural fields, urban environments, peat, and lakes. The 30-m NGA data were used to generate a 30-m slope map and slope suitability filter with a threshold value of less than 7%, while the 30-m NLCD and VISNAV datasets were used to generate 30-m land classification suitability filters with barren land, grassland, and pasture (at FHL) or agricultural and grassland (at BT) defined as suitable. LZ geometry dimensions specific to a C-130 aircraft (915 × 20 m) and a LZ orientation angle search increment of 15° were selected for LZ searches at each study site. Results were plotted against background suitability filters and original input datasets to assess output LZ placement.

3.3 | Validation

The validation tests were conducted to determine if the software could replicate ground-truth conditions and locate actual, known, unpaved austere entry LZs. To simultaneously investigate the influence of input dataset resolution, we conducted the validation tests using both coarse-resolution (30-m NLCD and NGA DEM data) and fine-resolution (1-m DEM and supervised classification WV2 imagery) datasets. These data were preprocessed in ArcGIS following the methodology presented in Section 3.1. The 30-m datasets were used to generate slope and land classification suitability filters using the same criteria discussed for verification analysis. The 1-m DEM data were used to generate a 1-m slope map and slope suitability filter with a threshold value of less than 7%, whereas the 1-m WV2 classified image was used to generate a 1-m land cover suitability filter with vegetation and water defined as unsuitable and all the soil strength classes defined as suitable.

To facilitate runtimes, LZ searches were reduced to 5 × 5-km bounding boxes that were drawn around each of the five known LZ sites. Because the FHL LZs vary substantially in size (the Schoonover LZ is 1,920 m long while the El Piojo LZ is only 340 m long), we chose the shortest LZ length (340 m; El Piojo) and width (45 m; Jolon) for search criteria to ensure LZ dimensions did not prohibit identification. LZ searches were conducted at orientation intervals of 15° and results from 30 and 1-m datasets were compared.

4 | RESULTS

4.1 | Verification results

Results from the GRAIL Tools verification analyses are shown in Figure 3. Potential LZ locations were identified over the vast majority of the search area selected in BT, excluding the urban environments and regions composed of lakes, wetlands, and forests. Although the majority of unsuitable areas were correctly excluded from output results, there were a small number of locations where LZs were placed in unrealistic and seemingly incorrect areas. For example, Figures 3B and C show several 95% suitable LZs placed across a meandering, s-shaped river. It initially appeared that a LZ had been placed over unsuitable terrain classified as water, but several pixels within the river are in fact classified as “agricultural,” which is a suitable land classification for LZ placement. These pixels appear to have been misclassified, resulting in a strip of suitable terrain that crosscut the river and led to inappropriate LZ placement at this site. The LZs that crosscut the river are only 95% suitable, which indicates that they contain up to 5% unsuitable pixels. The unsuitable pixels that comprise the LZs are located along the river and were, in fact, correctly classified as water.

Verification results at FHL were strikingly different from those in BT as a substantially fewer number of LZs were identified across the FHL region, as shown in Figure 3D. This was an anticipated result, as the terrain at FHL is significantly more variable and contains numerous steep hillsides and land classes that restrict the amount of suitable terrain for LZ placement. Regions specified as unsuitable were generally avoided; however, limitations in input dataset quality and resolution again led to instances of LZ placement in unreasonable areas. Figures 3E and F accentuate a region of FHL composed of infrastructure where GRAIL Tools identified multiple 95 and

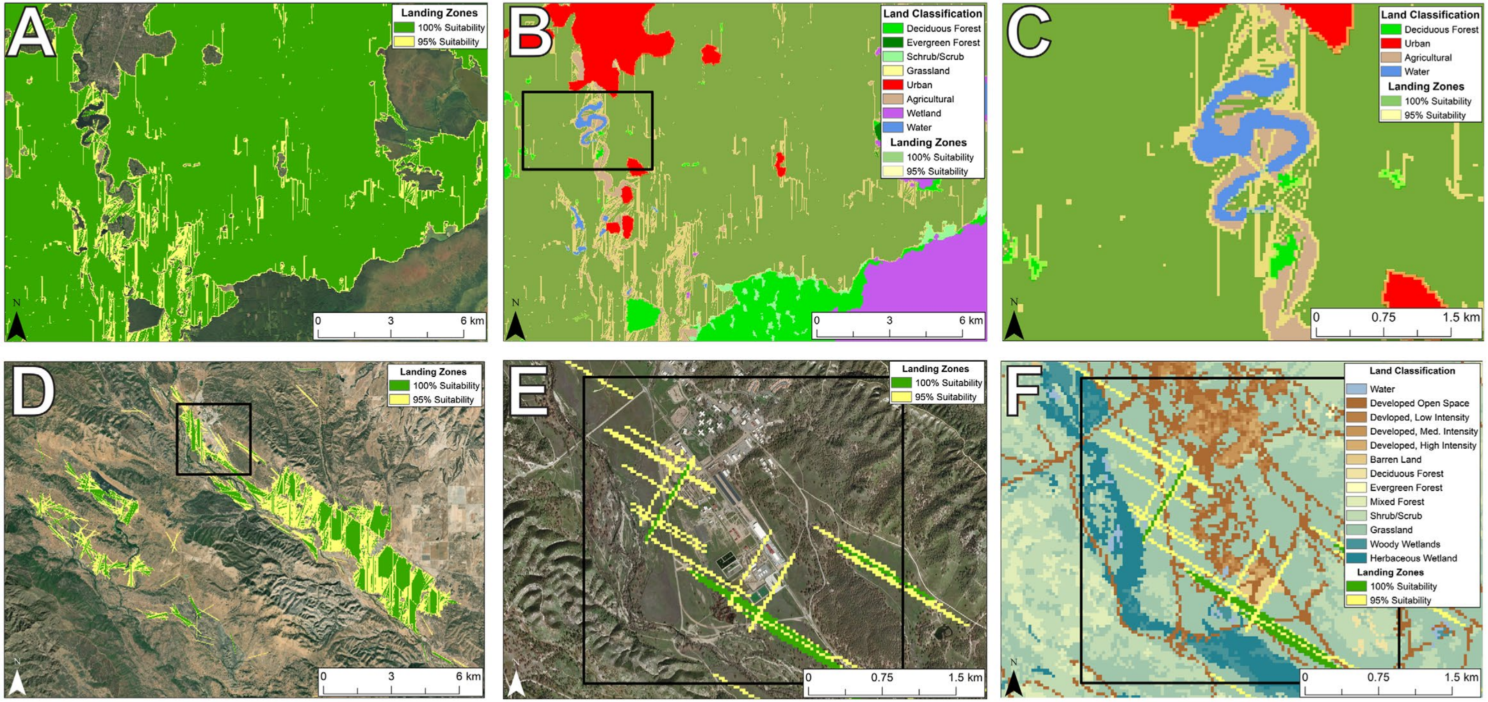

FIGURE 3 GRAIL Tools verification results in BT (panel A) and FHL (panel D). Panel B depicts LZ results plotted over land classification data. A close-up view of the region in the black rectangle is given in panel C, showing LZs crossing a river due to misclassified land classification data. Panel D depicts GRAIL Tools verification results in FHL. A close-up view of the region in the small black box is shown in panel E, where LZs are plotted over background imagery. Panel F depicts the same LZ output over land classification data and shows that the built-up area in panel E is primarily classified as "grassland"

100% suitable LZs. A substantial portion of the 30-m NLCD land classification dataset at this built-up location is incorrectly classified as "grassland" and "barren land" (which are suitable for LZ placement). Most of the infrastructure built in this region is substantially larger than the resolution of the dataset (e.g., >30 m) and, therefore, should have been detected and correctly classified. This misclassification is likely due to the NLCD data being generated prior to this area being developed, a situation that is not uncommon with land classification data.

4.2 | Validation results

Validation assessments conducted at the five LZ sites at FHL are summarized in Table 1, shown in Figures 4A and B, and discussed in detail by specific LZ below. In Table 1 and the text below, the terms "match" and "mismatch" are used to describe whether or not the software output correctly parallels ground conditions and identifies actual LZ locations.

TABLE 1 GRAIL Tools validation results at the five FHL LZs. "Match" refers to GRAIL Tools identifying correct conditions at a LZ site, while "mismatch" indicates that the LZ and ground conditions were not correctly identified by GRAIL Tools (and the reason for the mismatch is placed in parentheses)

LZ	30-m data output	1-m data output
Milpitas	Partial match (missed partial unsuitable land classification)	Match
Jolon	Match	Mismatch (incorrect slope values)
Schoonover	Match	Match
Tule	Match	Match
El Piojo	Match	Mismatch (incorrect slope values)

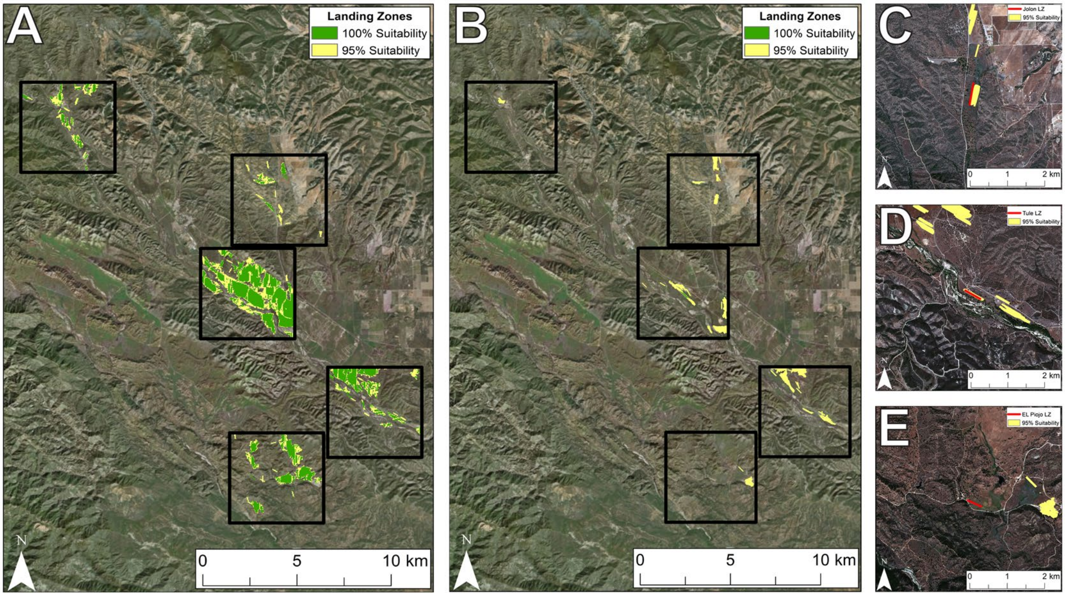

FIGURE 4 30-m (panel A) and 1-m (panel B) GRAIL Tools validation results at FHL. The extent of panels A and B is shown in Figure 2A. The five black boxes in each panel represent the 5 × 5-km search areas around each of the FHL LZs. Panels C through E show three of the runways (red lines) and depict LZs plotted adjacent to the Jolon LZ (panel C), on top of the Tule LZ (panel D), and missing the El Piojo LZ (panel E)

4.2.1 | Milpitas LZ

Thirty-meter datasets: The Milpitas LZ, which is 390 m long by 70 m wide, was partially identified as a potential LZ site. Approximately 45 m of one end of the Milpitas LZ was correctly classified as unsuitable due to changes in slope that range between 8 and 10%, which are above our chosen threshold value of 7%. As such, GRAIL Tools output was located along 345 m of the suitable portion of the LZ. Multiple potential LZs with 100 and 95% suitability acceptance levels at a bearing angle of 165° were identified at this site. This was only considered a "partial match;" however, as known unsuitable land classification at one end of the LZ was not detected (using the datasets provided).

One-meter datasets: The software did not identify the Milpitas LZ as a potential LZ site. Several pixels in the 1-m slope suitability filter were classified as unsuitable due to a slope of 7.2% narrowly exceeding the threshold value of 7%. Also, a substantial number of pixels in the 1-m WV2 imagery suitability filter were correctly classified as unsuitable vegetation at the south end of the LZ, which is a region of protected vegetation (high shrubs). In addition to correctly identifying the protected and sloped south end of the Milpitas LZ, GRAIL Tools (correctly) did not identify any other potential LZ sites within 900 m of Milpitas. This was considered a "match," as the software correctly assessed the terrain according to the chosen criteria.

4.2.2 | Jolon LZ

Thirty-meter datasets: The GRAIL Tools software did not identify the Jolon LZ, which is 600 m long by 45 m wide, as a potential LZ site, which is a correct assessment. Although the slope conditions are suitable at this location, the terrain is classified as an "emergent herbaceous wetland," which is not suitable for LZ placement. This was considered a "match" since the current conditions at Jolon are not suitable for LZ placement without improvement and, therefore, were correctly identified. LZ sites immediately next to Jolon were identified as potential LZs as the terrain is classified as "grasslands."

One-meter datasets: GRAIL Tools partially identified the Jolon LZ as a potential LZ site. Along the exact path of the LZ, there are several trees and shrubs that were correctly classified as unsuitable in the 1-m WV2 imagery and numerous pixels that incorrectly exceed 12% slope. However, multiple LZs were identified immediately adjacent to and partially over the Jolon LZ with 95% acceptance (Figure 4C). Because the WV2 imagery used in place of NLCD data was developed to classify soil strength, and not land cover, there is no classification for an emergent herbaceous wetland. However, wet and weak soils are common at this site. The majority of the area around the Jolon LZ was classified as suitable in terms of vegetation cover. This is considered a "mismatch" as erroneous slope values do not mimic what is on the ground at the Jolon LZ.

4.2.3 | Schoonover LZ

Thirty-meter datasets: The Schoonover LZ, which is the largest at FHL at 1,920 m long by 50 m wide, was identified as a potential LZ site by GRAIL Tools. A small portion of the LZ is classified as "developed, open space" and therefore unsuitable, as this classification includes structures and developed vegetation (e.g., golf courses, parks, lawns, etc.). However, this small unsuitable area, which appears in the data as a thin strip that crosscuts the LZ perpendicularly, shows the continuation of a road onto the LZ that does not actually exist. In other words, this area was likely misclassified and should be classified as "barren land," as is the other portion of the LZ. In addition, while a smooth road surface could indeed be suitable for landing, the developed, open space land classification includes vertical structures and, therefore, was chosen as an unsuitable land classification by the user. This illustrates the importance and impact of both the accuracy of the dataset (being outdated in this case) and the suitability criteria chosen by the user. The software placed numerous potential LZ sites with

100% acceptance at a bearing angle of 135° on either side of the developed, open space section of the LZ. This is considered a "match."

One-meter datasets: GRAIL Tools identified the Schoonover LZ as a potential LZ site. The full length of the LZ is entirely suitable both in terms of land classification and slope, and potential LZs were plotted with 100 and 95% suitability acceptance levels at a bearing angle of 135°. The LZs with 95% suitability acceptance extended slightly past the length of the existing LZ into (up to 5%) pixels with slope values that exceeded 7% and, therefore, reduced overall LZ suitability to 95%. This is considered a "match."

4.2.4 | Tule LZ

Thirty-meter datasets: Grail Tools identified the Tule LZ, which is 400 m long by 60 m wide, as a potential LZ site. The slope and land classification at this site are 100% suitable, and multiple LZs with 100 and 95% suitability at a bearing angle of 120° were identified. As with the Schoonover LZ, LZs with 95% suitability were placed beyond the bounds of the Tule LZ and, therefore, extended into unsuitable pixels that reduced the overall suitability acceptance. This is considered a "match."

One-meter datasets: GRAIL Tools identified the Tule LZ as a potential LZ site. Multiple LZs with 95% accuracy at a bearing angle of 120° were identified (see Figure 4D). Because the slope suitability filter erroneously contained several unsuitable pixels with slope values that were between 8 and 12%, and because the WV2 imagery contained up to 5% of pixels with shrubs, LZs with 100% accuracy were not identified at this location. This is considered a "match" because the shrubs were accurately identified, which correctly reduced overall LZ suitability to 95%.

4.2.5 | El Piojo LZ

Thirty-meter datasets: GRAIL Tools identified the El Piojo LZ, which is 340 m long by 45 m wide, as a potential LZ site. The slope and land classification are 100% suitable at this site along the full length of the LZ. Numerous LZs with 100 and 95% accuracy were identified at a bearing angle of 120°. Those that were only 95% accurate extended beyond the length of the LZ into terrain classified as "developed, open space." This is considered a "match."

One-meter datasets: GRAIL Tools did not identify the El Piojo LZ as a potential LZ site (see Figure 4E). Although the WV2 imagery land cover classifications are suitable at this location, multiple pixels (incorrectly) contain slope values in excess of 8%, which is greater than the 7% criteria for suitable LZ placement. The 1-m slope values are highly variable across this region, which is not an accurate representation of the actual site. As such, the GRAIL Tools software did not identify any potential LZ sites within 1 km of the El Piojo LZ. This is considered a "mismatch" due to incorrect slope values, even at the 95% suitability level.

5 | DISCUSSION

5.1 | Verification

The GRAIL Tools software was successfully verified at sites in both FHL and BT, as potential LZs were only located in regions that contained either 100 or 95% suitable terrain (see Figure 3). This provides assurance that the software functions in the intended manner, as originally designed, and that it can be used across variable terrain conditions. This does not mean, however, that LZs identified are located in sensible regions for actual LZ placement. LZs shown in Figures 3C and F, for example, are entirely suitable according to defining input parameters and datasets used, but are located in unrealistic and potentially hazardous areas for an operational LZ. This issue is a direct result of input dataset quality. As such, users should be cautious of GRAIL Tools results that are not based on high-quality, current, and accurate input data, particularly when utilizing coarse-resolution data.

It is likely, however, that many of the LZs shown in Figures 3A and D represent plausible LZ locations that would have gone unconsidered as potential sites without the use of GRAIL Tools. We therefore consider that the GRAIL Tools software serves best in a "first pass" or preliminary capacity when searching for LZs across a new domain, as it is a powerful tool that can rapidly eliminate broad regions of unsuitable terrain and provide a variety of potential LZ locations, but is also susceptible to placing LZs in unreasonable areas when input data are not high quality or are outdated. For mission planning purposes, GRAIL Tools results can be used to guide additional and more detailed LZ site reconnaissance.

5.2 | Validation

The GRAIL Tools software was successfully validated at FHL as actual austere entry LZs were accurately identified. When using the 30-m input datasets, four of the five LZ site conditions (at Schoonover, Tule, El Piojo, and Jolon) were correctly identified at FHL. A "partial match," or incorrect output, occurred at the Milpitas LZ because of vegetation at the site that was not recorded in the land classification dataset. GRAIL Tools output was not generated at the Jolon LZ (which is a correct and anticipated result) as it is located over unsuitable terrain (an emergent herbaceous wetland). Field studies conducted at FHL confirm that this is an accurate land classification, as the soils at Jolon are weak and wet largely due to the abandonment of the LZ in years prior (the Jolon LZ was utilized in the 1960s but has not been used actively for decades). As multiple LZs were positively identified, we argue that GRAIL Tools is capable of detecting pre-existing LZs across a new domain when using coarse-resolution data. A caveat to this statement, however, is that input LZ geometry specifications largely dictate GRAIL Tools success. The LZs at FHL are primarily used for vertical take-off and landing (VTOL) and short take-off and landing (STOL) aircraft, which do not require the long LZ lengths necessary for landings by fixed-wing aircraft. Input LZ dimensions were deliberately set to accommodate the short LZ lengths throughout the region in order to conduct a robust validation assessment. If validation studies had used the preset C-130 or C-17 LZ geometry specifications, only the Schoonover LZ would have been positively identified as a potential LZ site. The LZs shown in Figure 4, therefore, represent LZs suitable for rotary or STOL aircraft, as opposed to larger, fixed-wing aircraft.

When using the 1-m input datasets, three of the five LZs (Schoonover, Tule, and Milpitas) were positively identified by GRAIL Tools. Variations in slope that exceeded the threshold limit restricted LZ identification at Jolon and El Piojo. At Jolon, LZs were placed directly adjacent to, but not on top of, the LZ in regions where LZs were not identified using the 30-m datasets.

When comparing the two dataset resolutions, such as at Jolon, for example, unsuitable land classification prevented LZ placement at the coarser scale, while unsuitable slopes restricted LZ identification at the finer scale. These results highlight three key findings: (a) there is inherent value in utilizing both land classification and imagery when conducting LZ searches, as unsuitable land classifications (such as the emergent herbaceous wetland at Jolon) may go undetected in the imagery but prove hazardous for an actual landing site; (b) changes in surface roughness and vegetation that could be missed in coarse-resolution data yet be of concern for LZ placement may be detected with fine-resolution data; and (c) fine-resolution DEM grid spacing can result in overly steep slope values.

When analyzing validation results at the 1-m resolution, it is apparent that there are inherent issues with the 1-m grid spacing. In particular, slope values between 7.2 and 12% were recorded in the data across the five LZs; however, these values are inconsistent with measurements and observations made on-site (see Figure 5). Measured slopes were less than 1% at each LZ, excluding the slightly steeper portion of the Milpitas LZ discussed in Section 4.2.1. Therefore, problems with 1-m dataset quality and vertical accuracy, and not the software itself, led to unidentified LZs at the 1-m resolution.

FIGURE 5 Photo of typical surface morphometry seen at the five FHL LZs. Note that this surface is very flat and does not have slope values in excess of 12% as reported in the 1-m elevation data

5.3 | Dataset resolution

As highlighted previously, there are apparent advantages and disadvantages to using both fine- and coarse-resolution input datasets with the GRAIL Tools software. In general, coarse-resolution data provide faster runtimes (the average runtime for LZ searches in the 5 × 5-km bounding boxes was 6.5 min when using the 30-m data and 31 min when using the 1-m data) and a greater number of potential LZ options, though the reliability of the LZs identified may vary. Conversely, fine-resolution data produce a smaller number of LZ options that may be placed in more reasonable areas but can falsely eliminate some potential LZs. The application and desired end results should dictate proper input dataset resolution. For example, if a user is simply looking to rule out unsuitable terrain and acquire a general overview of potential LZ sites across a new domain, coarse-resolution data is likely sufficient. If, however, a user is looking for legitimate places for the landing of a particular type of aircraft, finer-resolution data should be utilized to detect small changes in terrain conditions, such as roughness or obstacles (i.e., vegetation, infrastructure, etc.). The overarching conclusion, in either case, is that both the accuracy and the acquisition date of the input data are critical.

Previous studies have shown that there is a direct correlation between DEM grid spacing size and slope calculation (Grohmann, 2015; Smith, Rheinwalt, & Bookhagen, 2019; Zhang, Drake, Wainwright, & Mulligan, 1999). Specifically, an increase in DEM grid size results in a smoothed surface and a decrease in mean slope values (Smith et al., 2019; Zhang et al., 1999). Slopes calculated from coarse-resolution data are, therefore, underestimates of the actual slope (Zhang et al., 1999). Conversely, slopes calculated using high-resolution DEMs (such as the 1-m data in this study) produce overestimates.

Errors in slope calculations are a function of truncation error, caused by projecting a continuous surface onto an evenly spaced grid, and propagated elevation uncertainty or DEM elevation measurement uncertainty (Smith et al., 2019). Smith et al. (2019) conducted a study to determine the optimal DEM grid size resolution for conducting morphometric analyses and observed that the finest grid size was not the most optimal for their purposes. The overly steep slopes calculated at the LZs in this study are potentially a result of using a grid spacing that was too high-resolution (Figure 6). However, calculating slope with coarse-resolution data (e.g., 30 m) also causes issues due to elevation attenuation (Grohmann, 2015).

In order to obtain slope values that are representative/expected for the region, we suggest using high-resolution data (e.g., 1 m) to reduce elevation attenuation issues, and then subsequently resampling the data to a coarser resolution (e.g., 5 m) to minimize overly steep slope values. To determine whether high-resolution DEMs or slope maps should be coarsened, we generated a 5-m slope map using two approaches at the Jolon LZ. First, the 1-m NGA DEM was used to generate a 1-m slope map, which was then resampled to 5 m. Then, for comparison, the 1-m NGA DEM was resampled to 5 m, which was then used to generate a 5-m slope map (see Figure 6). We determined that resampling the high-resolution slope map to a coarser resolution did not ameliorate the issue, as unrealistic slopes along the Jolon LZ were present even at the 5-m resolution. However, resampling the DEM to a coarser resolution prior to generating the slope map did, in fact, eliminate the steep and incorrect slopes along the Jolon LZ and provided realistic, uniform slopes. We therefore recommend resampling high-resolution DEM data to a coarser resolution (in this instance, 5 m was coarse enough to produce expected slope values) prior to generating slope maps, as this will reduce the overly steep slope values typical of fine-resolution data (see Figure 6). If multiple-resolution datasets are available for a given region, there is inherent value in running the analysis with both. For example, there were numerous instances during our validation assessments where 100% suitable coarse-resolution LZs were located in areas classified as unsuitable in the fine-resolution data. Many of these cases were the product of an area that contained one or two large trees that prohibited the fine-resolution input datasets from passing as suitable (see Figure 7). Although individual trees cannot be observed at the scale of coarse-resolution data, they could pose a significant threat to LZ operations. Knowledge of these instances could be useful to an end user, as minimally obstructive vegetation could be removed, which would then make the region LZ suitable. For example, this could be applicable in instances where a small aircraft (i.e., a helicopter) could deploy and remove small obstructions prior to the landing of a larger aircraft.

5.4 | Future work

In addition to land classification and slope, soil strength is a crucial aspect of LZ stability that affects both the type and weight of aircraft that can land and the number of landings that can occur. In areas where soil classification and soil moisture data are available, GRAIL Tools can also be used to generate soil strength maps (in terms of CBR values) and suitability filters. While this supplemental soil strength tool is a unique capability, its usage is limited based on the availability of regional climatological data. Additionally, current soil moisture predictions being used in soil strength algorithms within the GRAIL Tools software were developed for minimally compacted, natural soil surfaces, not manmade structures like the LZs at FHL. The applicability of these calculations for compacted soils requires further investigation, refinement, and validation.

Additional future work to expand geospatial analysis tools includes developing a new methodology to accommodate LZ searches over ice- and snow-covered terrain. Presently, the GRAIL Tools software cannot be utilized in high-latitude ice- and snow-covered regions, as there is a limited amount of: (a) geospatial ice cover data; (b) information regarding ice thickness and extent required for suitable LZs; and (c) knowledge of how to query this information for LZ search applications. We plan to calculate snow and ice suitability criteria for various military aircraft, develop new algorithms, and add an additional capability to GRAIL Tools that uses snow cover and ice thickness data to search for LZ sites. This will enhance the overall global footprint of GRAIL Tools applicability.

Additional studies could consider the addition of criteria for entry and exit pathways (Wieder & Shoop, 2017). The two-dimensional maps generated using GRAIL Tools do not currently provide information about vegetation/infrastructure height directly adjacent to the potential LZ, and particularly in the aircraft flight paths. Certain land classifications categorized as unsuitable using current selection procedures, such as shrubs, may be short enough in certain areas that they do not pose a hazard to LZ placement. A three-dimensional component for vegetation and other obstacle height could be developed using high-resolution LiDAR data, which could be used to determine

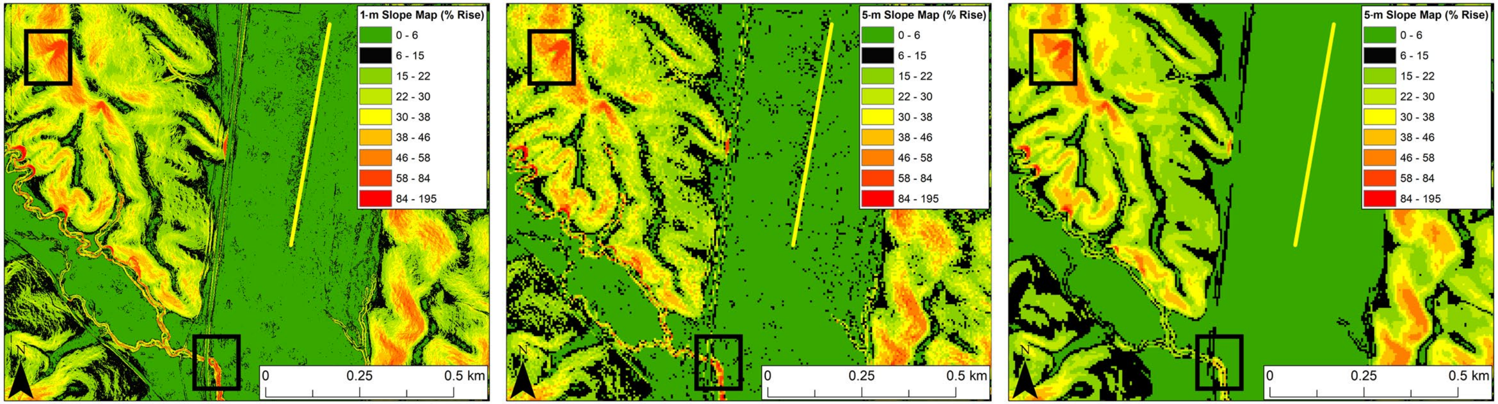

FIGURE 6 Example of the effects of DEM grid spacing on slope calculations. Each panel depicts a slope map at the Jolon LZ (yellow line). Left: 1-m slope map generated using the 1-m NGA DEM. Note all the pixels classified in the 6–15% slope range (i.e., unsuitable) along the length of the LZ. Middle: 5-m slope map generated by resampling the 1-m slope map to 5 m. Note all the pixels along the LZ that are still >7% (i.e., unsuitable). Right: 5-m slope map generated by resampling the 1-m NGA DEM to 5 m, then subsequently creating a 5-m slope map. Note that all of the pixels along the LZ are <7% (i.e., suitable). The two black boxes in each panel depict a steep hillside and riverbank. At the 1-m resolution, these features are overly steepened. Smoothing caused by coarsening the data to 5 m results in shallower slopes in the same areas

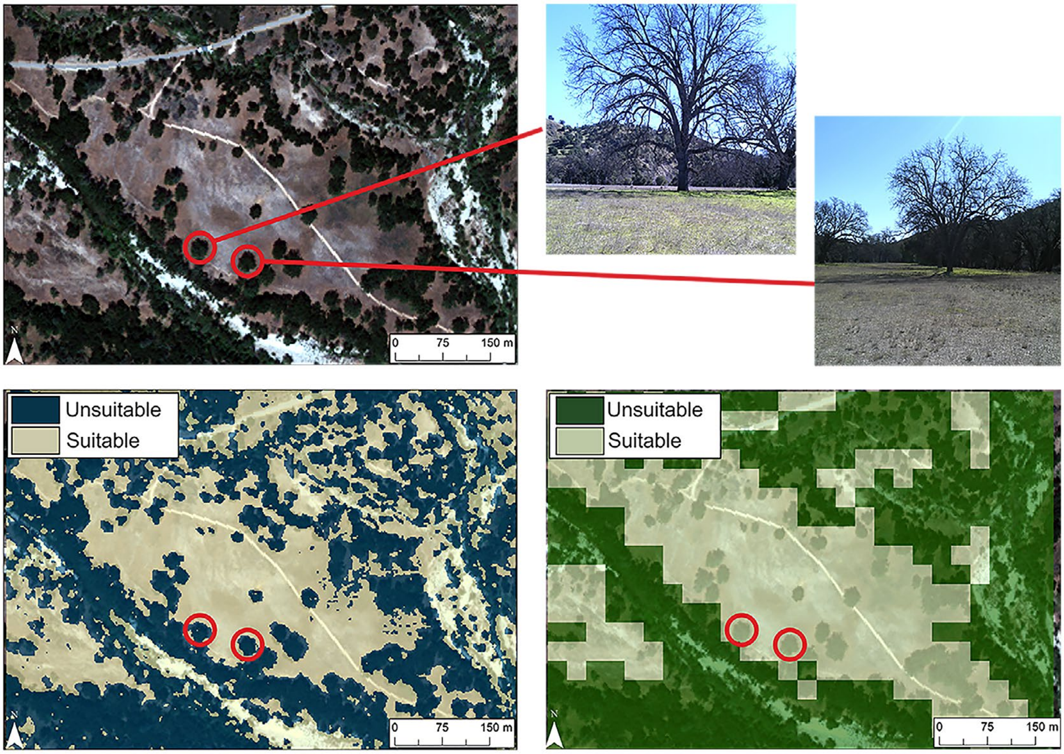

FIGURE 7 Vegetation obstruction depicted at different dataset resolutions. The top image and photos highlight a region of FHL that is predominantly classified as "grassland" but contains several large trees. The bottom two images depict a 1-m suitability filter (left) and 30-m suitability filter (right) in which the trees pictured above are circled in red. At the 1-m scale, these trees were included in terrain that was classified correctly as unsuitable, but incorrectly as suitable in the 30-m data

vegetation and obstacle height in the scenario described above. Conversely, large obstacles directly adjacent to a potential LZ may preclude its use. Preferable flight patterns may exist for certain LZs (i.e., it is safer to approach the LZ from one direction based on the surrounding terrain). This information could be beneficial to an end user for mission planning applications and is something that should be considered for future enhancements. As a result, we recommend that future studies utilize both digital terrain model (DTM) and DSM data to acquire information about both the bare-earth and vegetation surfaces in the region.

6 | CONCLUSIONS

In this study, the GRAIL Tools software was verified and validated using coarse- and fine-resolution geospatial datasets. Verification analyses at FHL and BT were conducted using LZ requirements for a C-130 aircraft, and results were plotted with 95 and 100% acceptance over suitable terrain. We conducted validation assessments using both 30 and 1-m input datasets at five known LZ sites at FHL. When using the coarse 30-m resolution data, four of the five LZs were successfully identified by GRAIL Tools. When using the 1-m resolution data, only three of the five LZs were correctly identified. Discrepancies between the output datasets were the product of: (a) unsuitable terrain (i.e., individual trees) detected in the 1-m datasets that did not meet LZ suitability criteria and were not detected in the coarse-resolution data; (b) land classifications defined in the coarse-resolution data that were not present in the fine-resolution imagery; and (c) incorrect slope values in the 1-m DEM. As with any geospatial analysis, the application and desired end results should dictate input dataset resolution selection. Software like GRAIL Tools serves best in a “first pass” or preliminary capacity when searching for LZs over a new domain as it can quickly eliminate broad regions of unsuitable terrain and provide a variety of potential LZ locations. The GRAIL Tools software enhances mission-planning capabilities for austere entry LZ site detection for military applications.

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14. ABSTRACT

The Geospatial Remote Assessment for Ingress Locations (GRAIL) Tools software is a geospatial product developed to locate austere entry landing zones (LZs) for military aircraft. Using spatial datasets like land classification and slope, along with predefined LZ geometry specifications, GRAIL Tools generates binary suitability filters that distinguish between suitable and unsuitable terrain. GRAIL Tools combines input suitability filters, searches for LZs at user-defined orientations, and plots results. To refine GRAIL Tools, we: (a) verified software output; (b) conducted validation assessments using five unpaved LZ sites; and (c) assessed input dataset resolution on outcomes using 30 and 1-m datasets. The software was verified and validated in California and the Baltics, and all five LZs were correctly identified in either the 30 or the 1-m data. The 30-m data provided numerous LZs for consideration, while the 1-m data highlighted hazardous conditions undetected in the 30-m data. Digital elevation model grid size affected results, as 1-m data produced overestimated slope values. Resampling the data to 5 m resulted in more realistic slopes. Results indicate GRAIL Tools is an asset the military can use to rapidly assess terrain conditions.

15. SUBJECT TERMS

Airborne operations (Military science), Airmobile operations (Military science), Austere entry, Computer programs, Geographic infomation systems, Landing zone, Maneuver, Remote sensing, Terrain, Trafficability

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