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Automated Mapping of Hammond's Landforms

Alisa L. Gallant, Douglas D. Brown, and Roger M. Hoffer

***Abstract*—We automated a method for mapping Hammond's landforms over large landscapes using digital elevation data. We compared our results against Hammond's published landform maps, derived using manual interpretation procedures. We found general agreement in landform patterns mapped by the manual and the automated approaches, and very close agreement in characterization of local topographic relief. The two approaches produced different interpretations of intermediate landforms, which relied upon quantification of the proportion of landscape having gently sloping terrain. This type of computation is more efficiently and consistently applied by computer than human. Today's ready access to digital data and computerized geospatial technology provides a good foundation for mapping terrain features, but the mapping criteria guiding manual techniques in the past may not be appropriate for automated approaches. We suggest that future efforts center on the advantages offered by digital advancements in refining an approach to better characterize complex landforms.**

***Index Terms*—Classification, digital elevation model (DEM), geographic information system (GIS), Hammond, landform, mapping, terrain.**

I. Introduction

LANDSCAPE topography is highly integral to ecosystem development. Topography affects air and ground temperatures, moisture and nutrient availability, the flow of energy, organisms and propagules, patterns and frequency of disturbance, and patterns and frequency of processes that alter biotic systems [1]. Variations in environmental phenomena are frequently associated with topographic features. On a continental scale, steep topographic gradients affect climatic patterns, which in turn affect the distribution of regional ecosystems (e.g., [2] and [3]). At the scale of individual watersheds, topographic hillslope position relates to the transport of sediments and moisture [4].

Past interest in mapping topography at continental scales resulted in the need for developing a method to generalize or classify broad patterns of topographic detail [5]. Approaches have incorporated elevational, morphological, textural, geological, genetic, and/or spectral (periodicity) characteristics (e.g., [5]–[9]). Originally, these approaches relied on labor-intensive, manual characterization of information from paper maps. Problems with interpreter consistency and data availability and resolution made it difficult to derive characterizations over large landscapes. Addressing challenges associated with large landscapes has become easier in the last two decades as digital data availability and geographic information system (GIS) technology have provided an ever-improving means for quantifying and categorizing topographic components.

We were interested in developing a statewide digital classification of landforms for Alaska, but wanted to focus on data and automated methods that would be applicable globally. We pursued a rule-based landform classification approach modeled after the manual method developed by Hammond [10], [11]. Hammond's classification has been considered a standard in landform mapping [12], and a few implementations of the classification have already been tested on smaller geographic extents [7], [12]–[14]. The patterns depicted on Hammond's [11] landform maps relate well to regional patterns of other environmental characteristics (e.g., [15] and [16]) and correspond with patterns of landforms that we have observed on the ground. In addition, Hammond's classification approach allows for adjustment for other parts of the world [5]. These were motivating factors in our choice to use Hammond's classification rules. We selected a global elevation dataset so that our methods could be readily applied elsewhere in the world.

II. Methodology

A. Study Area and Data

Alaska is the largest state in the U.S., with an area greater than 1.477×10^6 km^2. It has a variety of physiographic features, ranging from extensive, nearly level coastal plains to high, rugged mountain ranges [17].

We obtained digital elevation data from the U.S. Geological Survey [18]. These digital elevation model (DEM) data have approximately 1-km cell resolution and are provided in latitude/longitude coordinates referenced to the World Geodetic Survey system of 1984. The data were reprojected to an Albers equal-area conic projection following parameters typically used for Alaska by the U.S. Geological Survey [19].

B. Hammond's Classification Rules

Hammond's [10], [11] hierarchic landform classification is based on properties of slope, relief, and profile. The coarsest level of hierarchy is defined by four classes of local slope character; the next level is defined by six classes of local relief; and the finest level recognizes four classes of local profile [11] (Table I). The profile type categories defined by Hammond indicate the location of the gently sloping areas in the landscape. It is a particularly useful concept for distinguishing tableland topography, where the gentler slopes occur primarily in the uplands, from hill and valley topography, where gentler slopes occur primarily in the lowlands. Hammond's class breaks were arbitrary

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A. L. Gallant was with the Remote Sensing and GIS Program in the Forest Sciences Department, Colorado State University, Fort Collins, CO 80523 USA. She is now with the U.S. Geological Survey, EROS Data Center, Sioux Falls, SD 57198 USA (e-mail: gallant@usgs.gov).

D. D. Brown was with the U.S. Forest Service Rocky Mountain Research Station, Fort Collins, CO 80526 USA.

R. M. Hoffer, retired, was with the Remote Sensing and GIS Program in the Forest Sciences Department, Colorado State University, Fort Collins, CO 80523 USA.

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TABLE I
HAMMOND'S LANDFORM CLASSIFICATION RULES

% Local Area Gently Sloping	Local Topographic Relief (m)	Profile Type (topographic position of the gentle slope)
A. >80	1. 0-30	a. >75% in lowland
B. 50-80	2. 30-91	b. 50-75% in lowland
C. 20-50	3. 91-152	c. 25-50% in lowland
D. <20	4. 152-305	d. <25% in lowland
	5. 305-914	
	6. >914	

[1]Column categories are hierarchic, from left (most general) to right (finest).

TABLE II
HAMMOND'S LANDFORM CLASSES

Plains	
A1	Flat plains
A2	Smooth plains
B1	Irregular plains, slight relief
B2	Irregular plains
Tablelands	
B3c,d	Tablelands, moderate relief
B4c,d	Tablelands, considerable relief
B5c,d	Tablelands, high relief
B6c,d	Tablelands, very high relief
Plains with Hills or Mountains	
A,B3a,b	Plains with hills
B4a,b	Plains with high hills
B5a,b	Plains with low mountains
B6a,b	Plains with high mountains
Open Hills and Mountains	
C2	Open low hills
C3	Open hills
C4	Open high hills
C5	Open low mountains
C6	Open high mountains
Hills and Mountains	
D3	Hills
D4	High hills
D5	Low mountains
D6	High mountains

and intentionally limited in number so that the combinations of landform types did not become too complex for description or depiction [11] (Table II).

Hammond's procedures for applying the classification rules were manual, primarily through visual analysis of 1 : 250 000-scale topographic contour maps [10]. He periodically examined 1 : 63 360-scale quadrangles to calibrate visual estimates of the smaller-scale maps. Terrain was characterized within a local window (9.7 km × 9.7 km) that was moved without overlap across the 1 : 250 000-scale maps. Within each window, he quantified the percent of the area occupied by *gentle* inclination (<8% slope gradient, a threshold he defined as pertinent to erosion potential in agricultural areas), the difference between the lowest and highest elevation points (relief), and the percent of the gently sloping topography that occurred in the lower half of the local relief. Regarding this latter characteristic, he explained that he did not determine profile type for flat plains (no upland-lowland distinction possible) or unbroken hill and mountain systems (little or no gradual terrain present) [10].

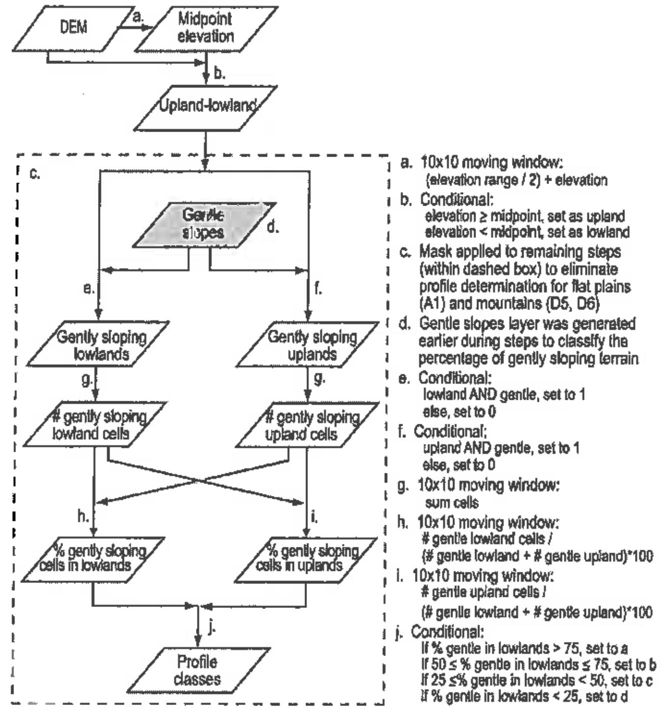

Fig. 1. Steps used for generating a raster layer of Hammond's [10], [11] profile type classes. Letters in the flowchart correspond with processing steps described to the right. Note that the "Gentle slopes" layer was generated during previous steps while classifying slope character.

C. *Automation of Hammond's Classification Procedures*

1) Analysis Window: We used a 10 × 10 moving window for implementing most of the steps in Hammond's classification. This equated with a square that was 10 km on a side, similar to Hammond's window of 9.7 km per side. Unlike Hammond, we incremented the window one cell (1 km) at a time across the DEM (an easy accommodation for the computer), as moving the window without overlap would have produced blockier results. A benefit of our window dimensions was that each cell represented 1% of the total window area, making it simple to determine membership within the classes of Hammond's scheme. A disadvantage is that when the number of cells along the side of a window is even, there is no center cell; hence, the results of window calculations are applied to an off-center cell (at window position 5, 5 in our study). We could have followed Brabyn's [12] approach, which was to apply calculations based on a circular moving window centered around each cell, but the added computational demand associated with circular windows was not worth a slight improvement in locational precision, given the general nature of the classification scheme and landscape extent we were addressing. We also could have enlarged the window dimensions to 11 × 11, as did Worstell [7], but we preferred to remain as close as possible to Hammond's window size.

2) Slope Character: This category required developing a slope map from the DEM, then determining the percent of gently sloping land that occurred in each window. Slope can be calculated using a variety of methods and windows sizes. We used ARC/INFO GIS software (Environmental Systems Research Institute Inc.), which fits a plane to the 3 × 3 neighborhood surrounding each cell (the window size cannot be adjusted) and uses the average maximum technique described by Burrough

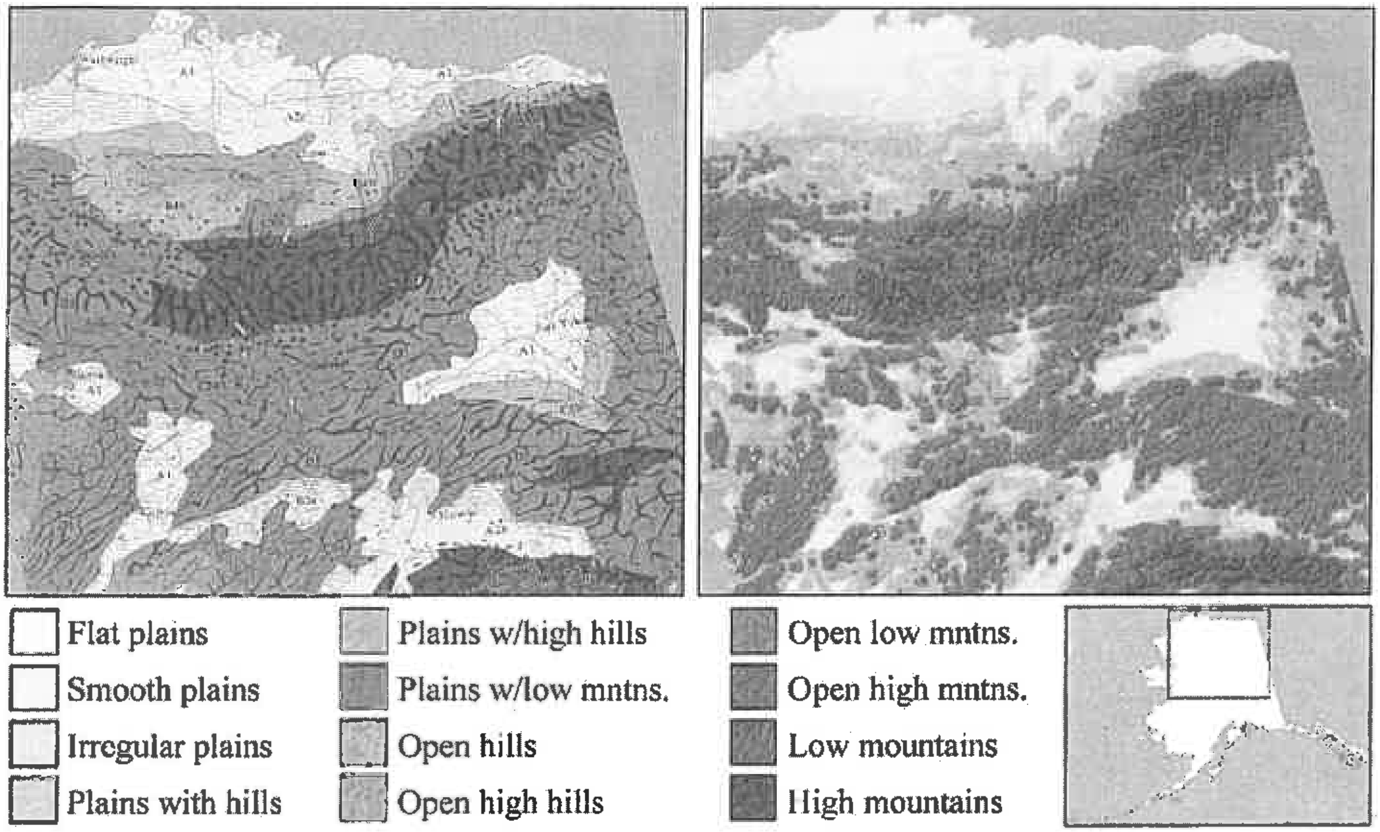

Fig. 2. Variety of landform classes represented in a portion of Alaska that shows a good example of how Hammond's classification of landforms (map on left) compared with results from the automated approach (map on right). The automated approach produced more spatial detail, as would be expected from raster-based GIS processing, and generally agreed with Hammond's classes in areas of flat plains (A1), smooth plains (A2), low mountains (D5), and high mountains (D6). Areas where Hammond classified the landscape as having slope classes "B" or "C" were typically classified as "A" or "B" (not respectively) by the automated approach. Hammond's assignment of relief class corresponded well with the results from the automated approach.

[20] to calculate slope. The slope algorithm resulted in a map with cell values ranging from 0% to 109% slope. The values from this map were then reclassified to yield a binary map indicating gentle slope (grid cells <8% slope assigned a value of 1) versus nongentle slope (assigned a value of 0).

To calculate the percent of local area in gentle slope, the number of cells in the binary map having a value of "1" was summed within a moving 10 × 10 window. Results were reclassified into the four categories defined by Hammond (Table I, left column).

3) Local Relief: A moving, 10 × 10 window was used for determining local topographic relief by determining the maximum change in elevation within the window. The difference between the lowest and highest elevation cells was calculated, and resulting values were reclassified into the six categories of local relief defined by Hammond (Table I, center column).

4) Profile Type: Classifying profile type required finding the midlevel of the elevation range represented within a map unit and determining the fraction of the gently sloping lands occurring below that level [10] (Fig. 1). We used the elevation midpoint within a moving window as the baseline for determining the four profile classes (Table I, right column). Like Hammond, we did not calculate profile for flat plains (Table II, A1) or rugged mountains (Table II, D5 or D6).

5) Generating a Landform Map: We merged the information for slope character, local relief, and profile type for each cell to yield a landform map.

III. Results and Additional Analyses

The map produced by the automated procedures was visually compared with Hammond's published landform map of Alaska [11]. A statistical comparison would have required access to Hammond's classification results at the resolution of his analysis window (the 9.7 km × 9.7 km areas into which he divided his paper contour maps and for which he derived the classification metrics). These data were not available; his results were published only as a small-scale (1 : 7 500 000) map, which considerably generalized the classification information. These circumstances limited us to visual evaluation of outcomes from the two approaches. We proceeded by examining our results at a scale comparable with Hammond's published map, then selected a number of areas throughout the state for closer scrutiny (approximate scale 1 : 250 000) to better evaluate the performance of our algorithm. Three major observations were made. First, there was general agreement in the pattern of landforms from both approaches. Certain landforms, such as flat plains, smooth plains, and high mountains, corresponded particularly well (Fig. 2). Second, there was very close agreement on assignment of all classes of local relief. Third, the two approaches produced substantial differences in estimating the amount of local area having gentle slope. This is a key difference because it affects both the most general level of the classification scheme (percent area gently sloping), as well as the finest level (profile type). For areas classified by Hammond as belonging to the middle two categories of percent gentle slope (50% to 80% and

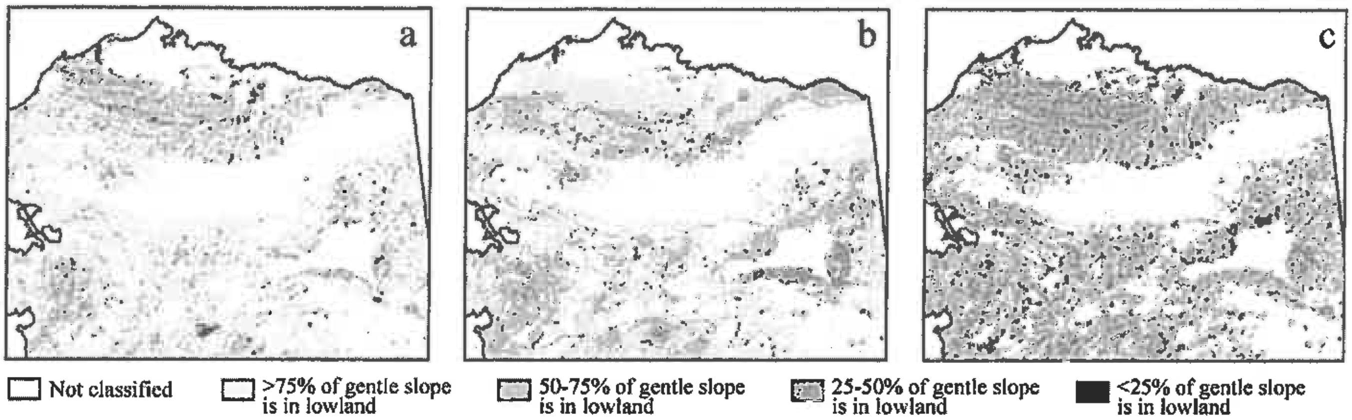

Fig. 3. Classification of profile type using three different elevation thresholds, the midpoint elevation of (a) the 10 × 10 window, (b) the midpoint elevation of contiguous pixels having identical combinations of slope and relief classes, and (c) the median elevation of the 10 × 10 window. Areas having concentrations of darker tones in map (a) generally match Hammond's assignment of profile class b (refer to Table I). Hammond did not use profile classes c or d in Alaska. Note that the area shown is the same as in the Fig. 2 inset map.

20% to 50% gentle slope), the automated procedures frequently indicated one or two class levels more gentle. This result was similar to that identified by Dikau *et al.* [14], who noted problems in obtaining Hammond's intermediate classes. In regard to classifying profile type, the automated approach generally agreed with Hammond's map on which portions of Alaska have <75% of the gently sloping terrain in the lowlands. Elsewhere, areas that Hammond categorized as profile class b (with one exception, he did not use profile classes c or d in his small-scale map of Alaska), were assigned classes of b, c, or d in the automated approach [Fig. 3(a)].

A. Diagnosing the Differences in Results From the Two Approaches

To better understand the reasons for differences between Hammond's results and ours, we pursued several diagnostic evaluations. First, we tested the automated approach on another geographic area, the entire conterminous U.S. As before, we used 1-km DEM data [18] and found results comparable with those observed for Alaska.

Second, we recognized that our digital elevation data were of coarser spatial resolution than depicted on the 1 : 250 000-scale map series used by Hammond. To investigate the effect of spatial resolution on our results, we applied our automated algorithm to 100-m DEM data (derived from 3-arcsecond DEM data [21]) over 23% of Alaska. Although the results from these higher resolution data depicted a greater amount of topographic detail, there was no increased detection of the two middle slope categories.

Third, we considered whether the slope algorithm applied by our GIS software might be responsible for the discrepancies between Hammond's results and ours. Although the exact method by which Hammond measured slope is not published, he did report [11] that his calculations were based on a mapping area equivalent to a unit square, six miles (9.7 km) across. Because the algorithm used by the ARC/INFO software calculates slopes based on a 3 × 3 window, our unit square area was only 3 km across. The relation between the area being measured and the actual scale of a pattern on the ground has a direct effect on the assessment results [22]. Larger neighborhood units can accommodate more local variation in topographic features [7] than our 3 km × 3 km area, perhaps accounting for Hammond's assessment of comparatively lesser amounts of gently sloping area in the landscape. To address this possibility, we developed a program to calculate slope for larger neighborhoods. We used a 10 × 10 window and purposely exaggerated the estimation by calculating slope based on the highest and lowest elevations within the window and the straight-line distance between them. Surprisingly, little difference was observed in the landform map produced using this exaggerated slope algorithm versus the one derived using the ARC/INFO slope algorithm. The principle exception was that the spatial extent of area classified as mountainous was greatly increased, a result comparable with that described by Worstell [7]. Because the main disagreement between Hammond's results and ours centered around the middle two slope categories (rather than the flattest or most mountainous categories), application of a larger window and exaggerated slope algorithm did not offer further insight into the discrepancies.

Another consideration was the threshold used to define gentle slope. Previous work [17] had indicated that regions in Alaska having slope gradients of 3.5% or less (calculated from 1-km DEM data) coincided with lands classified as poorly drained ecosystems [23]. In addition, research by Worstell [7] demonstrated how slope thresholds might be altered to adjust for different DEM data resolutions. Worstell's example showed that a 1% threshold applied to 1-km DEM data produced results comparable with a 5% threshold applied to 100-m DEM data. Application of a 3.5% threshold to our Alaska data had no effect in areas of flat to smooth plains, and increased the amount of "speckle" in assigning landform classes throughout hill and mountain areas. Application of a 1% threshold degraded the areas that previously corresponded well with Hammond's classification, and imposed the class assignment of "low mountains" (D5) throughout much of the state.

Fourth, we examined two alternative methods for deriving the profile class. Hammond's [11] map of Alaska landforms has a single profile class assigned per landform polygon (though this is not always the case for his landform map of the conterminous U.S.). Therefore, we tested the effect of applying the profile algorithm on the basis of contiguous pixels having the same combination of slope and relief classes, rather than using a moving window approach. This did not improve profile classification results; rather, it often reversed the assignment of the gently sloping terrain classes [Fig. 3(b)] from those assigned using the moving window approach [Fig. 3(a)]. Next, we tested a different interpretation of "midpoint" for the moving window. We wondered whether isolated peaks were having a large effect on the midpoint, such that very little area would actually qualify as occurring in the uplands. We used the median window elevation value for the upland/lowland threshold. This resulted in classifying excessive area as uplands [Fig. 3(c)].

IV. Discussion and Conclusion

Having explored several avenues to understand the underlying reasons for the differences in Hammond's results and ours, we concluded that the basis for the differences lies with the consistency, objectivity, and expertise with which the procedures were implemented. Automated procedures provided consistent and objective means for applying classification criteria. Manual procedures permitted geographic expertise to intervene when classification criteria fell short of accommodating perceived features of importance. It is also plausible that certain terrain features were unintentionally emphasized during manual interpretation. Humans can be swayed by their reactions to certain elements in the landscape, producing biased summary results. This has been noted in other products of geographic characterization (e.g., [24] and [25]). There can be a tendency toward demarcating features when they are sparse and generalizing them when they are numerous [26]. Hammond discussed the difficulty of analyzing the nature of slope in terrain "having few sharp slope breaks, predominant inclinations distributed closely about the 8 percent value, and represented on maps having a contour interval of 100 feet or more" [10]. Even in mountainous areas, where breaks in slope gradient are sharp, it may be easy to overlook the more gradual elements of the terrain, such as on valley floors and along ridgetops. Hammond not only had to determine which portions of the landscape were above and below the slope gradient threshold, but also had to estimate the percent map area of those portions. He had the added challenge of adjusting for contour intervals that differed from map to map (e.g., 6–9 m on maps of gradual terrain, to 62–124 m on maps of rugged, mountainous terrain). These are types of calculations and adjustments where computers provide more objective and consistent calculations.

The availability of global DEM data and geospatial analysis tools provide a good foundation for developing automated methods for characterizing landforms. We developed an automated implementation of Hammond's manual classification procedures, as his landform categories impart useful ecological information and his published maps offer a basis for comparison of results. Our investigation revealed that the mapping criteria guiding the manual techniques of the past may not be the most appropriate for an automated approach. The terrain varies in a complex fashion [26], and today's geospatial technologies provide the means to characterize that complexity more efficiently and effectively. Future research based on the advantages of current data and tools will help in refining automated procedures that recognize complex landform configurations, such as those represented in Hammond's classification.

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