Improved Hammond's Landform Classification and Method for Global 250-m Elevation Data

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Abstract

In 1964, E.H. Hammond proposed criteria for classifying and mapping physiographic regions of the United States. Hammond produced a map entitled "Classes of Land Surface Form in the Forty-Eight States, USA", which is regarded as a pioneering and rigorous treatment of regional physiography. With the advent of computer processing and availability of digital elevation models (DEMs), several researchers have since developed digital landform models to map the distribution of physiographic regions using Hammond's classification. These models have been applied in number of areas with varying size and physiographic complexity, and have emphasized different classification criteria and raster processing techniques. We propose a new algorithm for mapping Hammond's regional landform classes using a global 250-meter DEM, and we characterize the results of that model with a new map of global Hammond landforms. The new algorithm incorporates slope, relative relief, and profile type as parameters, and uses varying neighborhood analysis sizes to characterize these parameters. We compare the new map to other global landform maps and compare its visual alignment with a global multi-directional hillshade dataset. We present potential applications of the map, and discuss important distinctions between physiographic regions and discrete landforms.

1 Introduction

Landforms are natural features on the Earth's surface that both reflect and shape geophysical and ecological process. The result is a defining part of landscapes that so often impact on human perception and interactions with environment. Blascyznki (1997) defines landforms as, "specific geomorphic features on the surface of the Earth, ranging from large-scale features such as plains and mountain ranges to minor features such as individual hills and valleys," and suggests that the analysis and quantification of the Earth's surface contributes to a better understanding of the physical, chemical and biological progressions that appear within the landscape. Landforms are one of the most important and intrinsic elements of landscape analysis and exploration (Booth, 1983). Landforms provide a physical context for describing the landscape, topography, and ecological units within the environment (MacMillan et al., 2000). Understanding the physical and historical context of the landscape is necessary in order to understand the temporal and spatial scales of ecosystems. Landforms are ecologically important elements because ecosystems develop within landform regions, and material and energy flows occur within the landform system (Swanson et al., 1988).

Landforms provide temporal and spatial perspectives for examining soil, vegetation, and aquatic characteristics, and for interpreting ecosystem pattern and process (Bailey, 2006). Landforms also mediate, bind, and influence macroclimates and microclimates. Bailey (2006) writes:

> *On a mesoscale within the same macroclimate, we commonly find several broad-scale landform patterns that break up the zonal pattern. Hammond's (1954) landform classification (based on surface geometry) is useful in capturing this effect on zonal climate and provides a basis for further differentiation of ecosystems, known as landscape mosaics.*

Swanson et al. (1988) characterized four effects of landforms on ecosystem pattern and process:

1. Elevation, steepness of slope, and aspect, in combination with temperature, moisture, and nutrients within the landform region produce many different patterns in the physical setting, and these patterns determine ecological potential.
2. Landform regions affect flow of organisms, propagules, energy and material.
3. Landform regions may affect the spatial pattern of non-geomorphic disturbance by fire and wind.
4. Landforms constrain the spatial pattern, frequency, and rate of geomorphic processes that alter biotic features and processes.

The understanding of landform distributions is therefore key to mapping and understanding ecosystem patterns and distributions (Blasczynski, 1997). The importance of this understanding has been recognized in ecosystem mapping approaches which incorporate landform as a fundamental element in the modeling process (Sayre et al., 2014).

1.1 Hammond's (1954) Landforms

Many geographers have described landforms from a genetic perspective, based on the geomorphological processes that formed the landscape (Zakrzewska, 1967). Murphy (1968), for example, mapped global physiographic regions from analysis of tectonic origins, macroclimate, and intensity of dissection of the landscape by drainage channels. While genetic approaches focus on delineating large area (e.g. continental and sub-continental scales) physiographic regions, and emphasize the origins of terrain development, they are less suitable for characterizing changes in relief and physiographic structure(Hammond, 1954).

Hammond (1954) identified challenges in applying genetic landform classifications to small-scale (global / less detailed) representations of the landscape, citing problems of inaccurate, overly complex, and sometimes ambiguous results. In 1964 he developed and published a quantitative, empirical methodology for classifying and mapping landforms using a set of morphological characteristics (Hammond, 1964). The approach has been considered a macro-morphological classification based on the shape of the landform (Brabyn, 1998), where individually mapped landscape features are associated with landform regions (Chorley, 1967). Hammond (1954) emphasized that small scale characterization of landforms requires regional characterization rather than individual feature identification:

> *In all small-scale maps, much is left out, notably the arrangement of features within the areas distinguished, but it is hoped that in general the most diagnostic and distinctive characteristics have been shown. Since the different terrain types are capable of quantitate definition, rough inter-regional comparison is possible. Further the representation is based on a system which permits any desired amount of expansion of detail as the scale of mapping increased. Finally, the maps do not attempt to indicate the probable origin of the terrain features but present the configuration empirically as an element of the natural landscape.* (Hammond, 1954 pg. 42)

Hammond's (1954) landform classification methodology was considered "systematic, relatively objective, applicable to all types of terrain, suitable for medium and small scale mapping, and useful for individual and comparative landform studies" (Zakrzewska, 1967). Hammond's (1954) extensive field experience provided the basis for the empirical definition of slope, local relief, and profile type as the essential parameters for classifying and mapping regional landform classes. Slope indicates the flatness or steepness of a location on the surface of the Earth. Local relief is the amount of elevation change within an analysis area. Profile separates uplands from lowlands, evaluates the amount of gentle slope within the uplands, and identifies tablelands. Hammond assessed those parameters for the conterminous United States through visual analysis of 1:250,000 topographic maps, and produced a pioneering map entitled "Classes of land surface form in the forty-eight states, USA" (Hammond, 1964). This remarkable resource was developed essentially in the field using topographic maps, prior to the availability of advanced computer technologies and geographic information systems (GIS) (Smith and Clark, 2005). At that time, the approach could not be implemented globally due to a general lack of global topographic information and the immensity of the manual effort required for deriving quantitative landforms without computers.

Today, with the availability of digital elevation models (DEMs) and GIS technology, it is possible to map landforms using quantitative models and computer visualization (Smith and Clark, 2005). GIS has become a fundamental and essential tool in the management and analysis of quantitative data (Dikau et al.1991). In a series of innovative terrain characterizations, Dikau and others (1991) became the first to automate Hammond's semi-quantitative system using GIS, producing a digital landform map of New Mexico (Dikau et al., 1991 and 1995). They used the same parameters (slope, relief and profile) to classify landform regions, but while Hammond used a 1:250,000 scale topographic map, Dikau et al. (1991) used a 200-meter resolution DEM. Hammond used a 9.65 km neighborhood analysis window (NAW) as the local analysis region within which the three parameters were computed. The Dikau et al. (1991) analysis used a 9.8 km NAW. Subsequently, several researchers have followed a similar GIS methodology in mapping landform classes for other specific study areas (Brabyn, 1998; Gallant et al., 2005; Morgan and Lesh, 2005; Hrvatin and Perko, 2009).

True (2002) published a map of the Landforms of the Lower Mid-West (excerpted, Figure 1) using an alternative method, which omitted the profile type parameter. For that analysis, the 30-m spatial resolution National Elevation Dataset (NED) (Gesch et al., 2002) was used with a 1-km NAW. This method, also referred to as the MoRAP (Missouri Resource Assessment Partnership) (True, 2002) approach, is easier to implement as it uses only slope and local relief. Although it can result in a granular texture, and regions can sometimes appear as fragmented blends of two or more landform classes, the output is generally accurate.

The MoRAP method was subsequently implemented by the United States Geological Survey (USGS) and others to map Hammond's landforms of South America (Sayre et al., 2008), the conterminous United States (Sayre et al., 2009), Africa (Sayre et al., 2013), and most recently, the world (Sayre et al., 2014). The global landforms (excerpted, Figure 2) were developed as inputs to a global ecosystem mapping effort (Sayre et al., 2014), with the understanding that landforms are critical elements of ecosystem structure (Bailey, 2006). This (Sayre et al., 2014) global landform map was developed from a 250 m global DEM (Danielson and Gesch, 2011) using the MoRAP approach and a 1 km NAW. This (Sayre et al., 2014) global landform map was the first of its kind, produced at a relatively high spatial resolution (250 m) for the world.

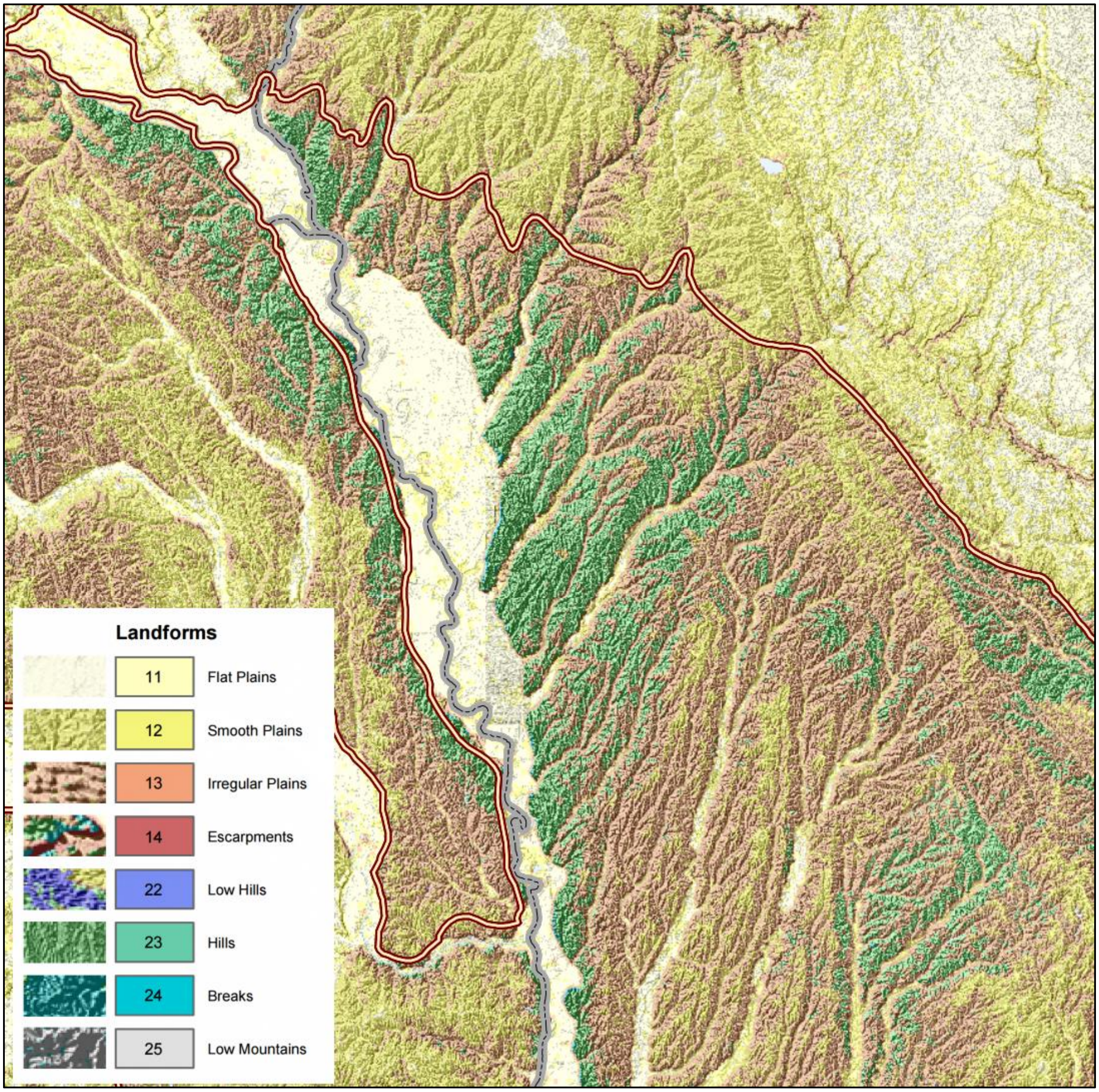

Figure 1 Subset of the 30-m spatial resolution map 'Landforms of the Lower Midwest (True, 2002) produced using the MoRAP (Missouri Resources Assessment Partnership) model. This portion of the map shows the Missouri River Valley between Iowa and Nebraska.

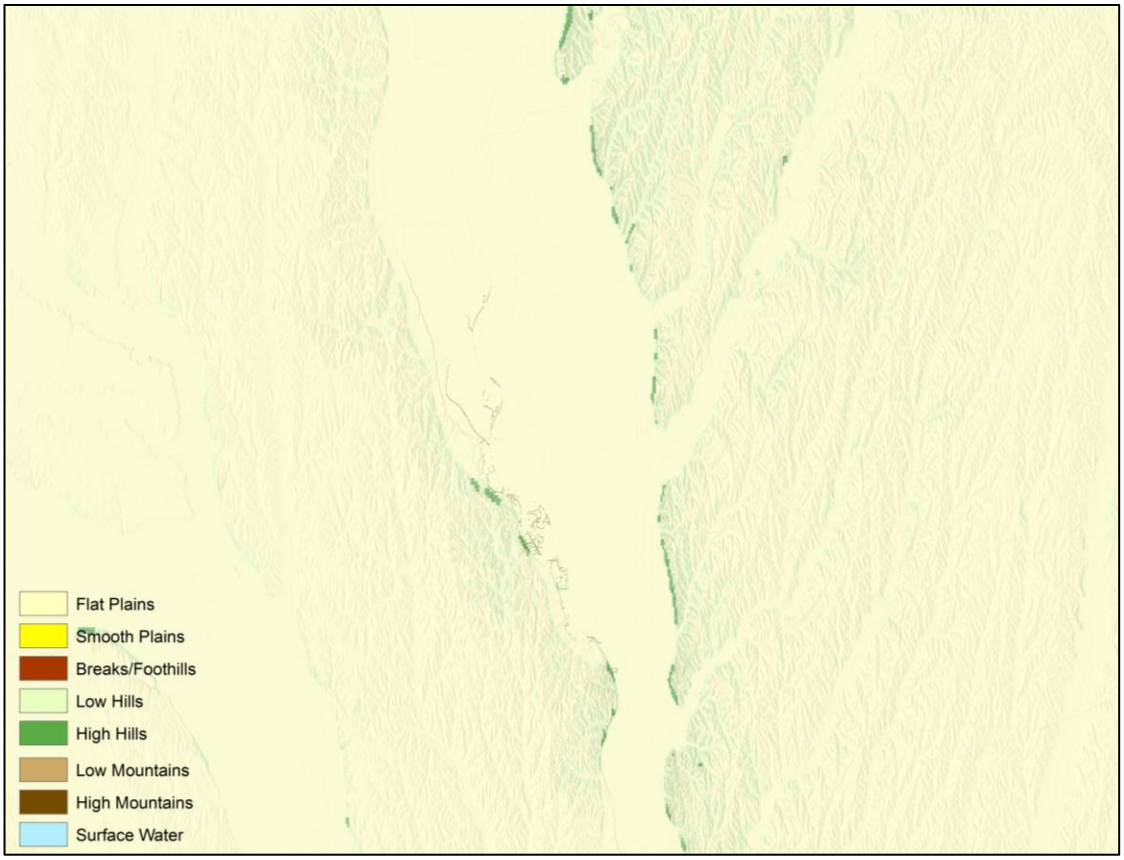

Figure 2 Subset of 250-m World Landforms-MORAP Method 2014 dataset. This portion of the map shows the Missouri River Valley between Iowa and Nebraska (Esri, 2014).

We used a panel of in house experts with experience in different areas of the world. We reviewed areas these experts knew, by using a multidirectional hill shade. This review yielded the following conclusions: First, landforms appeared to be strongly faceted and fragmented as opposed to regionally homogenous. Second, some important terrain types (e.g. tablelands) appeared to be missing. Finally, some areas classified as mostly plains were popularly regarded as regions of hills or low hills; examples include the Wisconsin Dells, a highly incised terrain, where only the slopes were characterized as hills; and the Flint Hills in eastern Kansas, which are terraced hills. These discrepancies were revealed through spot check comparisons of regions that had the words hills or escarpments in the name (e.g. Flint Hills), but the corresponding locations were not so classified. A global, multi-directional hill-shaded terrain dataset (Esri, 2014) was used for these comparisons, and the missing classes were found to be globally consistent. There was an interest in improving the capture of "missing" relief that occurred in large regions classified as flat or irregular plains. It was additionally noted that the MoRAP method could not produce ecologically significant landform classes such as tablelands because the MoRAP method did not take into account Hammond's (1954) profile type parameter.

As the review proceeded, it was felt that the "missing" relief may have been caused by omitting profile type, the third of Hammond's (1954) classification parameters, as a classifier. It was also felt that the profile type parameter might be essential for imbuing a less-fragmented, regional quality to the resulting map. Some of the fine granularity that was evident in the product may have resulted from using a NAW that was too small, indicating that an important ratio exists between the resolution of the DEM and the size of the analysis window. Moreover, it was felt that varying the size of the NAW based on which of the three parameters being assessed (slope, local relief, and profile type) might produce better results than using a fixed NAW size for each of the three classifiers. Jasiewicz and Stepinski (2013) used a 30 meter DEM to map the distinct terrain geometries (geomorphones) of Poland. They found that adjusting NAW size to local relief improved the delineation of these landform elements, and so incorporated a varying NAW into their model.

1.2 Goals and Objectives

There are many ways to identify landforms and landform regions. The overall goal of this study is to identify regional landform classes phenomenologically adequate to characterize and define ecosystems. This paper is primarily intended as a description of the GIS procedures used to generate global Hammond landforms from 250 m DEM data. Our intention is to present these techniques and procedures in sufficient detail as to be replicable by others at the level of detailed GIS instructions. In addition to providing these procedures, our primary objectives for this analysis were to 1) further test and characterize the relationships between classifier parameters and NAW sizes, 2) evaluate a new model to improve the upon 2014 USGS/MoRAP global landforms map, and 3) produce a new global Hammond landforms map. We evaluated the use of an alternative model to the MoRAP algorithm seeking to improve regionalization in the landform classification in order to update the map of global ecological land units produced by Sayre et al., in 2014. We felt that an improved, better-regionalized landform map would reduce the spatial complexity of the ecological land units (ELUs) initially produced from that model.

2 Methodology

As an alternative to the MoRAP approach, we implemented a GIS-based articulation of Hammond's model (Morgan and Lesh, 2005) as an ArcGIS geoprocessing script tool, with the script written in Python. The implementation used the same 250-m source DEM, the Global Multi-resolution Terrain Elevation Data (GMTED) 2010 (USGS, 2010) used to develop the original global landforms map (Sayre et al., 2014). Morgan and Lesh (2005) had successfully followed Hammond's (1954) landform classification approach based on the Dikau et al. (1995) model using 30-meter resolution DEM data as their input source data to map landforms in the state of Maryland. The Morgan and Lesh spatial model, developed for local landform mapping using a 30-m input DEM, was used in a global application using 250-m resolution DEM. The global application of the Morgan and Lesh (2005) model required identification of optimal NAW sizes.

The Morgan and Lesh (2005) model used 36 steps to derive landforms from a DEM. Their model first projects the DEM to a projected coordinate system suitable for distance-based calculations, then produces classifications of slope, relief, and profile type before combining them into a single expression of Hammond (1954) landform classes. Morgan and Lesh implemented their model using a 30-m resolution DEM in the Maryland State Plane projected coordinate system as their input data. They used a 600-m radius circular neighborhood (NAW) to establish regional character. Their input DEM extent was for a 7.5 minute USGS quadrangle representing approximately 55 square miles (142.4 square kilometers). The model produced twenty-four Hammond landform classes. These landform classes are shown in Table 1.

Table 1 Morgan and Lesh (2005) Twenty-Four Landform Classes

Mountains	Hills
High Mountains Low Mountains Open High Mountains Open Low Mountains Plains with Low Mountains Plains with High Mountains	Plains with Hills Plains with High Hills Open Very Low Hills Open Low Hills Open Moderate Hills Open High Hills Very Low Hills Low Hills Moderate Hills High Hills
Tablelands	**Plains**
Tablelands with Moderate Relief Tablelands with Considerable Relief Tablelands with High Relief Tablelands with Very High Relief	Flat or Nearly Flat Plains Smooth Plains with Some Local Relief Irregular Plains with Low Relief Irregular Plains with Moderate Relief

Instead of the Maryland State Plane projected coordinate system used by Morgan and Lesh, this study projected the GMTED 2010 from the original WGS 1984 geographic coordinate system to World Equidistant Cylindrical. This ensured that the same size of analysis window could be used everywhere in the world. We projected the GMTED data using the ArcGIS Project Raster geoprocessing tool, with the bilinear sampling option. There was no change in the minimum or maximum data values and there was no significant change in the overall sum of values.

As discussed above, the evaluation of the True (2002) and Sayre et al. (2014) landform outputs had led us to conclude that the optimal size of a moving NAW for calculating slope, relief and profile parameters is resolution dependent. To determine the optimal NAW size and shape, we empirically tested several neighborhood sizes. Dikau et al. (1995) used a 200-meter resolution DEM, and a 9.8 km NAW. Hammond (1954) used 1:250,000 scale topographic maps instead of a DEM and a moving window of 9.65-kilometers. Therefore our 250 m global implementation of the Morgan and Lesh model, we tested 12.5 km, 6 km, and 3 km NAW sizes.

2.1 Gentle Slope

We used ArcGIS to calculate percent slope using a 12.5 cell (3 km) NAW. Each cell in the NAW is assigned a value that is the average of the slopes between that cell and the eight surrounding cells, and these slope values are then averaged within the NAW. Hammond (1954) uses the amount of gentle slope within the NAW to classify slope into four categories (Table 2). The definition of gentle used was “any inclination of less than 8%” (Hammond, 1964 pg 15). Appendix A contains a list of the steps used to calculate slope.

Table 2 Gentle slope classes and description.

Percent of Neighborhood Over 8% Slope	Gentle Slope Class
0 - 20%	400
21 - 50%	300
51 - 80%	200
81 - 100%	100

Depending on relative local relief, DEM resolution affects derived slope values. To demonstrate this, we evaluated three levels of local relief: high (greater than 900 meters), medium (between 150 meters - 300 meters), and low local relief (less than 90 meters) using four different DEM resolutions. The results are shown in Table 3.

Table 3 Slope percentages by different resolutions

DEM Resolution	High Relief	Medium Relief	Low Relief
250m	25.5%	4%	0.5%
90m	27%	4.5%	1.6%
30m	30.3%	7%	2%
10m	37%	10.5%	2.6%
Percent change from 10 meter	32%	61%	80%

The percentages in table 3 were produced using these steps. First we used local relief dataset generated as part of this work. Next, we chose ten locations well within each relief zone and recorded slope values for each different DEM resolution. We calculated mean values for these sample locations. The change in slope is inversely proportionate to the change in DEM resolution. This analysis of slope and DEM resolution validates the 8 percent threshold as recommended by Hammond.

2.2 Calculation of Local Relief

Local relief is the amount of elevation change within a circular 6 km (25 cell) NAW. Hammond (1954) defined six classes (Table 4) of local relief. Appendix B contains a list of steps used to calculate Local Relief.

Table 4 Relief classes and description of how elevation changes in the 6 km analysis window.

Change in Elevation	Relief Class
0 – 30 m	10
31 – 90 m	20
91 – 150 m	30
151 – 300 m	40
301 – 900 m	50
over 900 m	60

2.3 The Profile Parameter

The combination of Hammond’s (1954) slope and relief classes define some landform regions like mountains, hills, or plains. However, the ecologically useful landform class of tablelands requires the profile type parameter. The MoRAP approach used in the Sayre et al. (2014) global landforms did not include tablelands as a landform region. Profile determines whether each cell in the DEM is uplands or lowlands, and if uplands, the amount of gentle slope (Figure 3) is calculated.

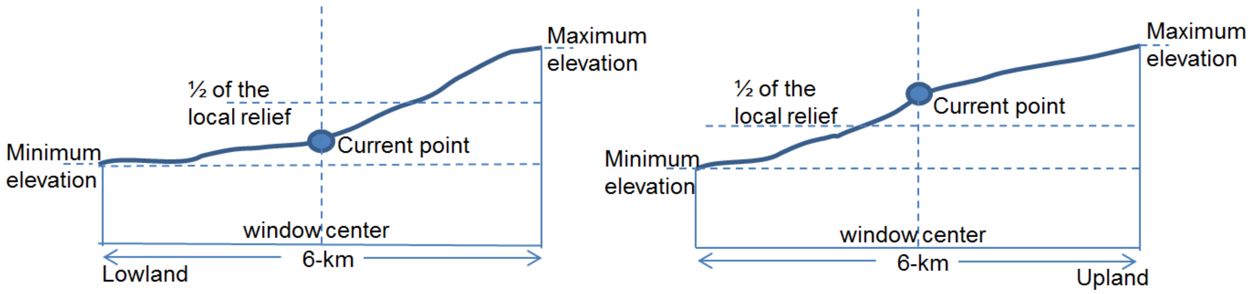

Figure 3 Diagrams of hypothetical slopes showing how each cell is evaluated and classified as either upland or lowland given the slope of other cells within a 6-km NAW (reproduced from similar diagrams in Dikau et al. (1995).

Tablelands only occur in uplands where at least 50% of the upland area within the NAW contains gentle slopes. We calculated the profile parameter using a 25-cell (6-km) NAW (Figure 4).

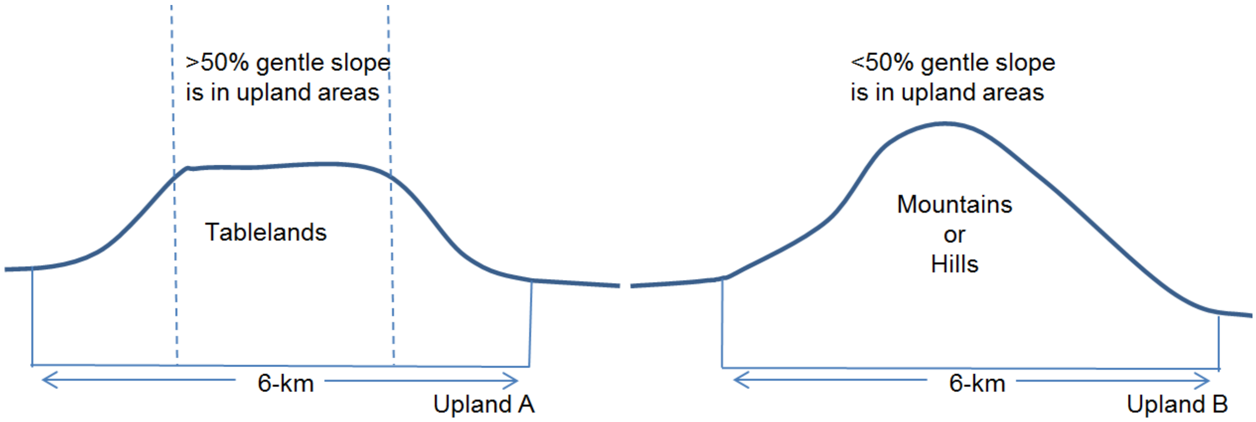

Figure 4 Diagrams of hypothetical upland profiles showing Upland A, representing a tableland, Upland B representing mountains or hills depending on the slope and relief parameters. Lowlands represent plains and hills depending on the gentle slope and relief parameters.

Hammond (1954) defined four classes of profile type. The complexity of the profile type parameter calculation required several iterations of development and testing. During these iterations, we noted that earlier efforts to automate Hammond's classification only accounted for a portion of the potential range of output profile values. Therefore we produced five classes of profile type (Table 5), introducing a class for 0.

Table 5 Profile classes and descriptions.

Percent of Neighborhood Over 8% Slope	Profile Class
Under 50% of upland or lowland is gentle slope	0
Over 75% of lowland is gentle slope	1
50% - 75% of lowland is gentle slope	2
50% - 75% of upland is gentle slope	3
Over 75% of upland is gentle slope	4

The profile class of 0 (zero) represents upland areas of hills or mountains, and lowland areas of hills. We do not interpret the omission for handling these cells in the earlier automation efforts as anything more than a by-product of the complexity of the automation steps and communicating them, because the affected areas were already implicitly classified correctly using the slope and relief parameters. Appendix C lists the steps to compute profile classes.

2.4 Attribute Combination and Issues with Plains Classes

We calculated the global Hammond landform class by adding the slope, relief, and profile outputs. We used the classifier combination schema from Morgan and Lesh (2005) where labels contained three digit numbers. The hundreds digit identifies slope class, the ten digit identifies local relief class, and the ones digit identifies profile type. Appendix D contains a master table of combination outcomes for each attribute.

Our initial implementations revealed areas of plains within relief features that were strongly influencing the landform class assignment. We visually evaluated the results with a hillshade model overlay. Dual classes such as “Plains with Hills” or “Plains with Low Mountains” appeared over-represented. For example, When the true landscape is Low Mountains, a mountainous region was labeled “Plains with Low Mountains” instead of Low Mountains when just a few plains cells occurred within the region. We interpreted these outcomes as the result of using an inappropriate NAW size; specifically that plains features require a smaller NAW. For this reason we extracted Plains features separately in a single global implementation to produce plains vs. non-plains features. For that two-class implementation, we empirically determined to use a 1 km NAW. We then “enforced” the plains features onto the multi-class global landform model to allow all plains features to override the underlying classes. Appendix E contains the steps used to calculate plains-only cells using slope and relief parameters with a 1-km neighborhood.

2.5 The Final Landform Generation Model

Having now empirically evaluated appropriate NAW size to use for the classifiers, and devised an adjustment to allow a plains-centric override approach, we finalized the global Hammond landform modeling approach according to the schematic presented in Figure 5 below:

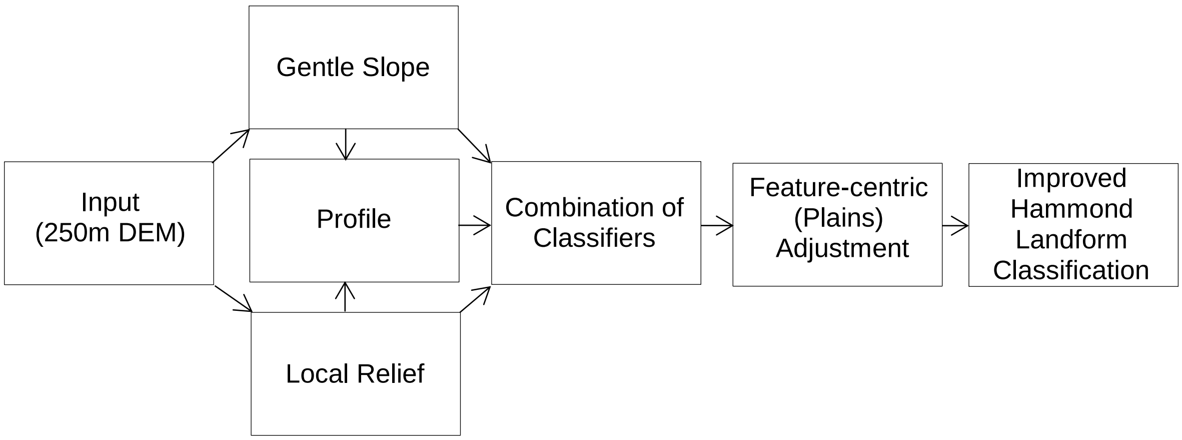

Figure 5 Conceptual Summary of the process to produce the Improved Hammond Landform Classification.

2.6 Resampling

As is common in many raster-based classification and analyses, resampling of the modeled output was necessary to remove or smooth the salt-and-pepper effect caused by a few isolated cells within larger otherwise homogenous regions. The initial result of combining the slope, relief and profile outputs included many one- and two- cell landform “features” within most regions. For example, occurrences of isolated cells of hills or plains within regions of low or high mountains were noted. These outlier classes made the larger surrounding regions appear speckled and less definitive. We used the ArcGIS Spatial Analyst Focal Statistics tool with the majority filter option and a 1-km circular window to aggregate these isolated cells into the larger region. A “side-effect” of this tool is converting these cells to no data values when there is a tie in the count of two or more types of majority cells within the NAW. Even though this implementation used a larger neighborhood, the results did include some no data cells. These cells were reset to their original value by reclassifying all No Data to 1000, then using the Local Statistics tool, with the Minimum option. We then found that using the Majority Filter tool also removed some of the artificial patterns from the circular NAW, and if run repetitively, progressively addressed this problem. We successively filtered the data in this manner with four iterations.

3 Results and Discussion

We first implemented the Morgan and Lesh (2005) model globally using a 12.5 km square NAW, and although it processed relatively quickly, it produced numerous peculiar spatial artifacts along the edges of landform classes. The results were visually evaluated using a hillshaded terrain representation, and the authors felt that hilly and mountainous regions included too much of the surrounding plains regions. Some regions contained ‘skirts’ of plains at the edges of landform regions. We proceeded to implement the model with 6 km NAW size for local relief and profile, and 3 km NAW size for the gentle slope, and evaluated the results. While the 6 km NAW size produced good results for the local relief and profile parameters, a 3 km NAW generally worked best for the slope parameter. These NAWs were empirically determined as the most appropriate neighborhood analysis sizes for minimizing edge-related anomalies given the 250 meter DEM, and for best visual correlation with hillshade interpretations.

The final global landform analysis used a 3 km NAW for the slope classifier, and a 6 km NAW for the local relief and profile type classifiers. In addition to identifying classifier-specific NAW size for landform generation, we also determined appropriate NAW size (1 km) for a single feature-specific (plains) implementation.

3.1 Plains-Centric Override Adjustment

The plains-centric adjustment produced a more intuitive result, without the problematic dual landform classes like Plains with High Mountains. A graphic depiction of the result produced from the plains override approach is presented in Figure 6. The plains override adjustment eliminated (four) dual-landform classes.

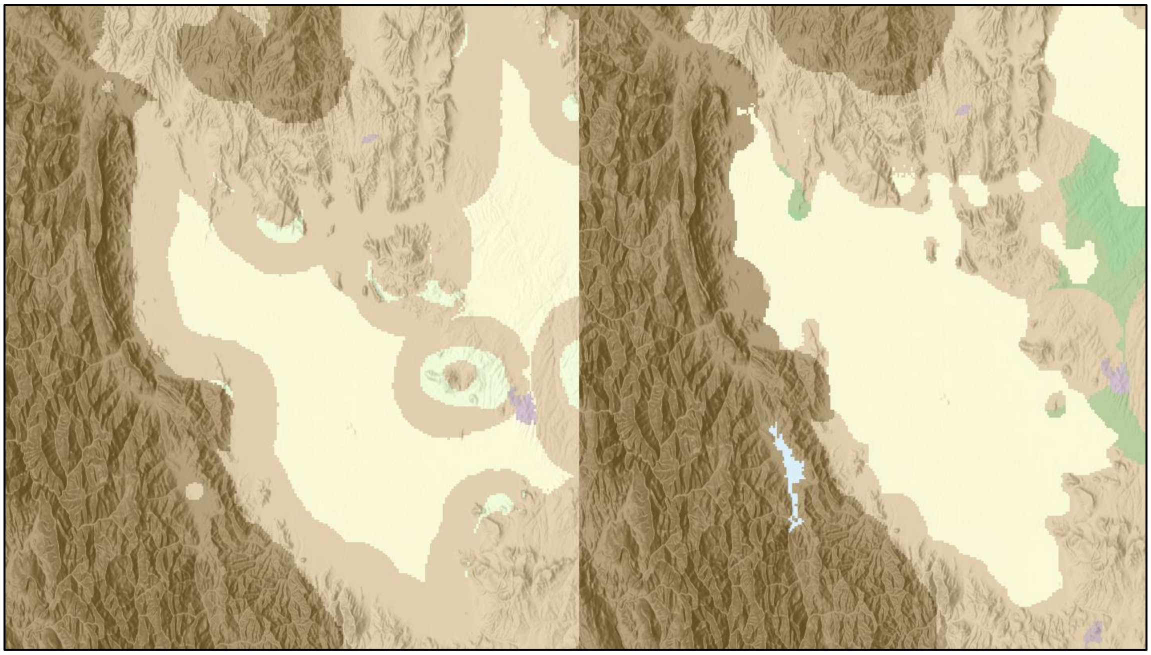

Figure 6 Left image represents before overriding with Plain Areas. Right image represents after overriding with plain areas. Effect of applying a plains-centric override to remove edge-related classification anomalies. The hillshading provides a sense of where the terrain is most rugged. Note the removal of the artificial “skirt” of low mountains (left panel) which existed prior to the adjustment.

3.2 Data Filtering

The results of the application of the Focal Statistics Majority resampling process are shown in Figure 7, below. Application of the filter removed numerous small inclusions and contributed to a stronger sense of regionalization in the results. Visual inspection of the filtered result against the hillshade dataset confirmed a match for numerous locations on all continents for each class of landform.

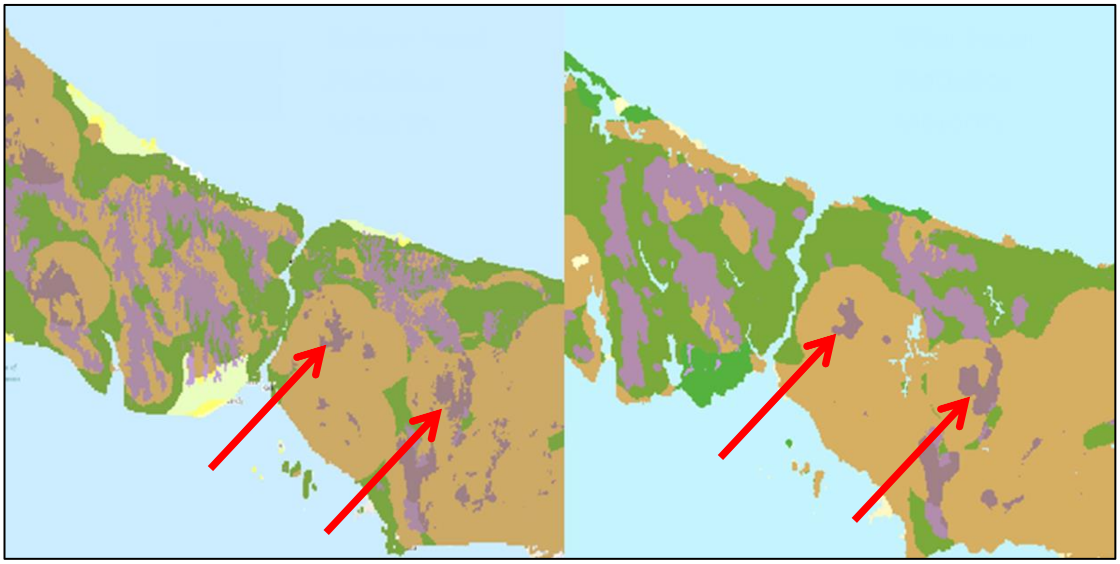

Figure 7 Left panel represents before focal statistics majority, and right panel represents after focal statistics majority. Results from application of Focal Statistics Majority tool. Substantial filtering was achieved, using four iterations, leading to a smoother and regionalized appearance.

3.3 The Improved Global Hammond Landforms Product

The landforms produced from this analysis represent a substantial revision of the global Hammond landforms produced using the MoRAP method and presented in Sayre et al. (2014). The new landforms are depicted in Figure 8.

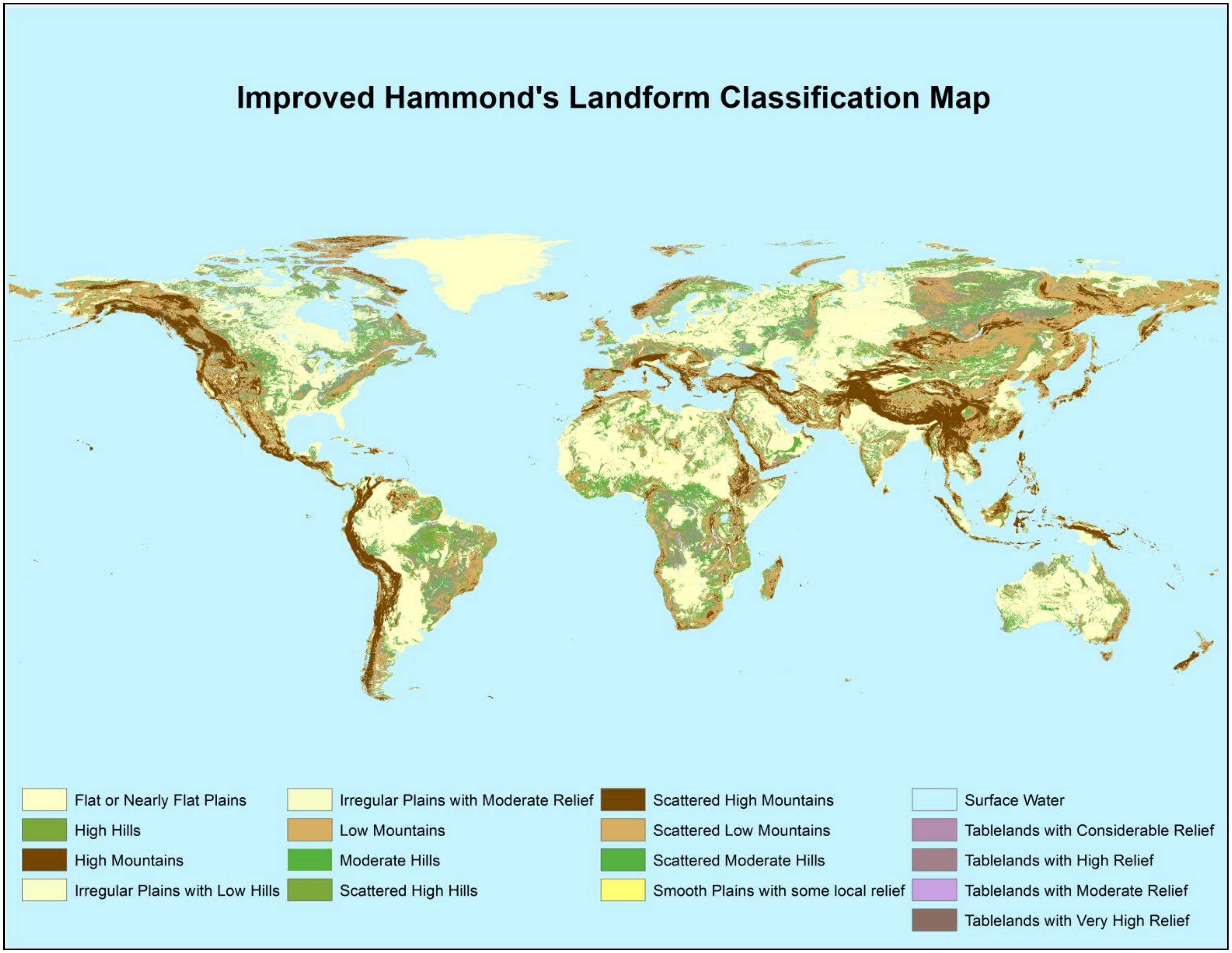

Figure 8 The improved map of global Hammond landform classification with sixteen landform classes.

These revised landforms demonstrate a clear transition from facet-style landform characterization produced by the MoRAP approach (Sayre, et al. 2014) to a more intuitive expression of regional landform classes. An iterative review process ensured that the resulting classes were regional, intuitive, and suitable for contributing to the description of ecological land units. The application of the improved Hammond's algorithm to the GMTED 2010 250-meter global DEM produced 16 landform classes (Table 6) compared to Morgan and Lesh's (2005), 26 classes. There were two reasons for the reduction in classes: 1) removal of dual classes containing plains, and 2) four classes from Dikau et al., (1991) were not realized with a 250-meter DEM as opposed to a 30-meter DEM. Figure 9 presents a comparison of the original Landform Classification Map (Sayre et al., 2014) with the new global Hammond landforms for the Grand Canyon region in the United States.

Table 6 Classes produced by the Improved Hammond Landform Classification model

Mountains	**Hills**
High Mountains	Scattered Moderate Hills
Low Mountains	Scattered High Hills
Scattered High Mountains	Moderate Hills
Scattered Low Mountains	High Hills
Tablelands	**Plains**
Tablelands with Moderate Relief	Flat or Nearly Flat Plains
Tablelands with Considerable Relief	Smooth Plains with Some Local Relief
Tablelands with High Relief	Irregular Plains with Low Relief
Tablelands with Very High Relief	Irregular Plains with Moderate Relief

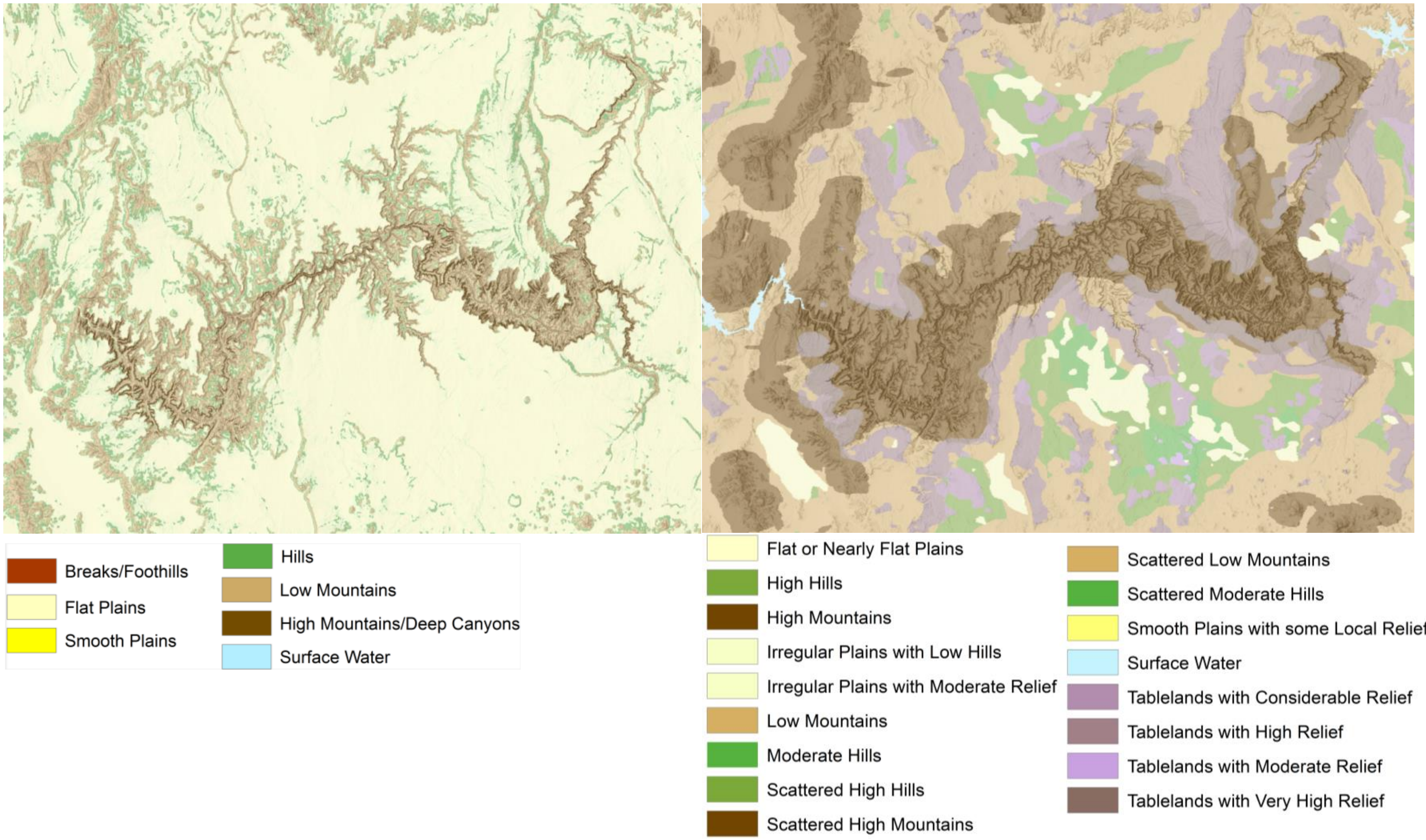

Figure 9 Comparison of the Improved Hammond's Landform classes (the new map on the right side) produced using the Morgan and Lesh (2005) (right map) approach with the global landforms from Sayre et al. (left map) (2014), for a portion of the Grand Canyon in the U.S.

Two significant improvements are noted from the comparison of landforms in the Grand Canyon shown in Figure 9. First, our implementation of the Morgan and Lesh (2005) model produces a less fragmented, more regionalized characterization than the Sayre et al (2014) implementation. Moreover, our model captures more hills landform regions in a plains matrix. The improved physiographic regionalization and the improved capture of the plains with relief features were the primary motivations for revising the Sayre et al., (2014) global landforms map.

Figure 10 is another comparison between the Sayre et al. (2014) and our implementation of the Morgan and Lesh (2005) model, and includes the original Hammond (1964) map. The three characterizations are presented for the State of New Mexico. These comparisons show the progressive increase in terrain feature detail from Hammond (1964) to Sayre et al. (2014) to this study. The original Hammond (1964) characterization is the most regionalized, as would be expected from a semi-quantitative, manually constructed, non-digital approach. The Hammond (1964) physiographic regions are represented as relatively large and homogenous polygon regions, as opposed to the Sayre et al. (2014) approach in which increased terrain feature granularity and heterogeneity is observed, but where the original sense of general physiographic regionalization is lacking. The Morgan and Lesh (2005) model provides a greater sense of regionalization, and the regions are generally visually consistent with the original Hammond (1964) regions.

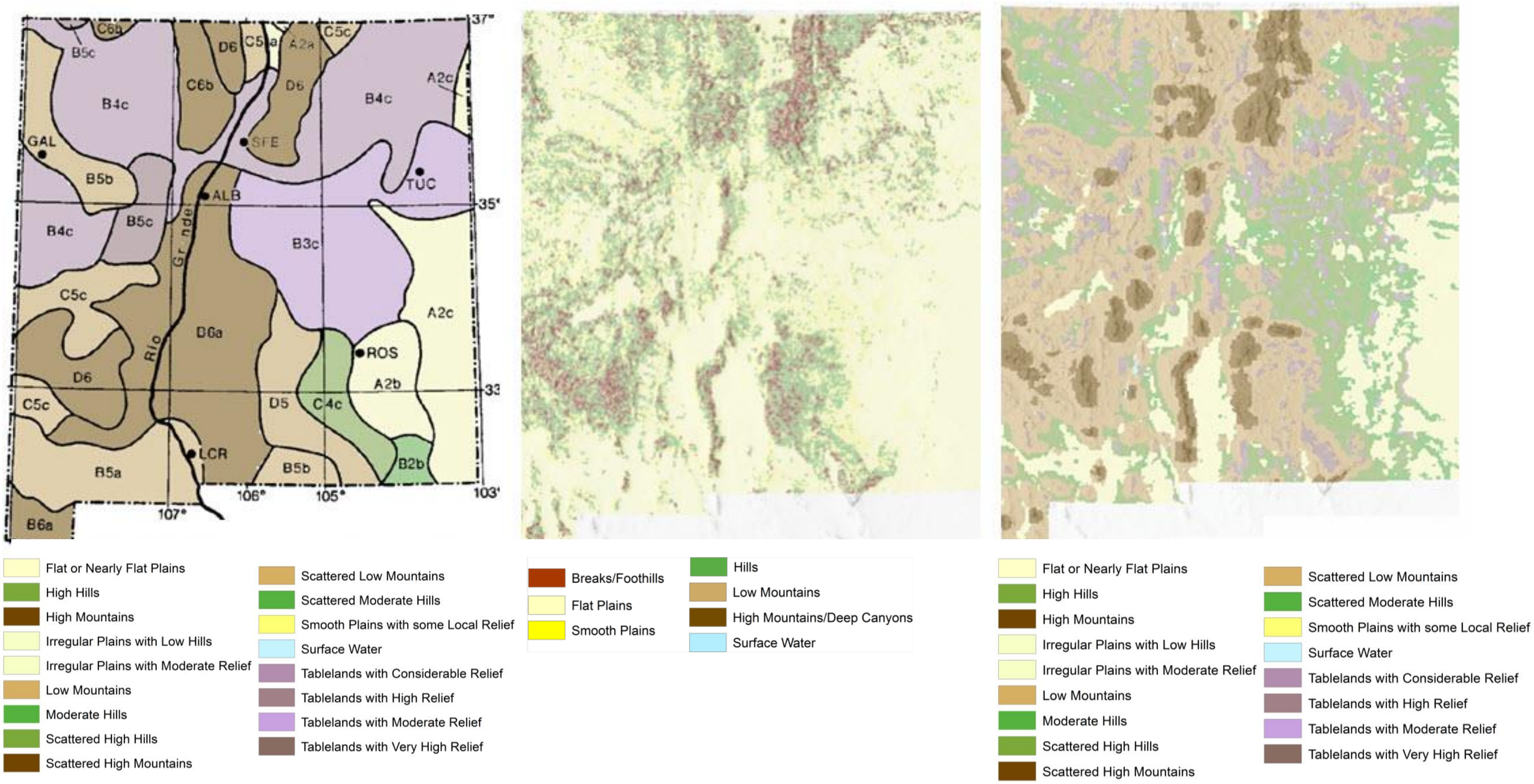

Figure 10 Left Map represents Hammond (1964), middle map represents USGS (2014) and right map represents Improved Hammond Landform classification map (this study). This is the comparison of results in New Mexico.

The improved global Hammond landforms dataset has sixteen classes, as opposed to six landform classes modeled by Sayre et al. (2014). To facilitate a comparison of these two resources, all classes for each dataset were aggregated into one of four classes: plains, hills, low mountains, and high mountains (Table 7).

Table 7 Landform classes used Within the Four Major Landform Class Groups.

	World Landforms (Sayre, et al. 2014)	Improved Hammond Global Landform Classification Map
Plains	Flat or Nearly Flat Plains Smooth Plains with Some Local Relief	Flat or Nearly Flat Plains Smooth Plains with Some Local Relief
Hills	High hills Moderate Hills Low Hills	High Hills Moderate Hills Scattered High Hills Scattered Moderate Hills Irregular Plains with Low Hills Irregular Plains with Moderate Relief Tablelands with Moderate Relief Tablelands with Considerable Relief Tablelands with High Relief Tablelands with very High Relief
Low Mountains	Low Mountains	Low Mountains Scattered Low Mountains
High Mountains	High Mountains	High Mountains Scattered High Mountains

Figure 11 shows the comparison of total area of each of the four generalized landform regions (plains, hills, low mountains, and high mountains) for the two datasets. These results are consistent with the assertion that the Sayre et al. (2014) product over-represented plains at the expense of the other relief classes. The improved global Hammond landforms map identified considerably less area in plains than the Sayre et al. (2014) map and a corresponding increase in low and high mountains. The improved global Hammond landforms map therefore resulted in a more balanced distribution of general landform classes, and reduced what had been noted by the authors as an overabundance of plains features.

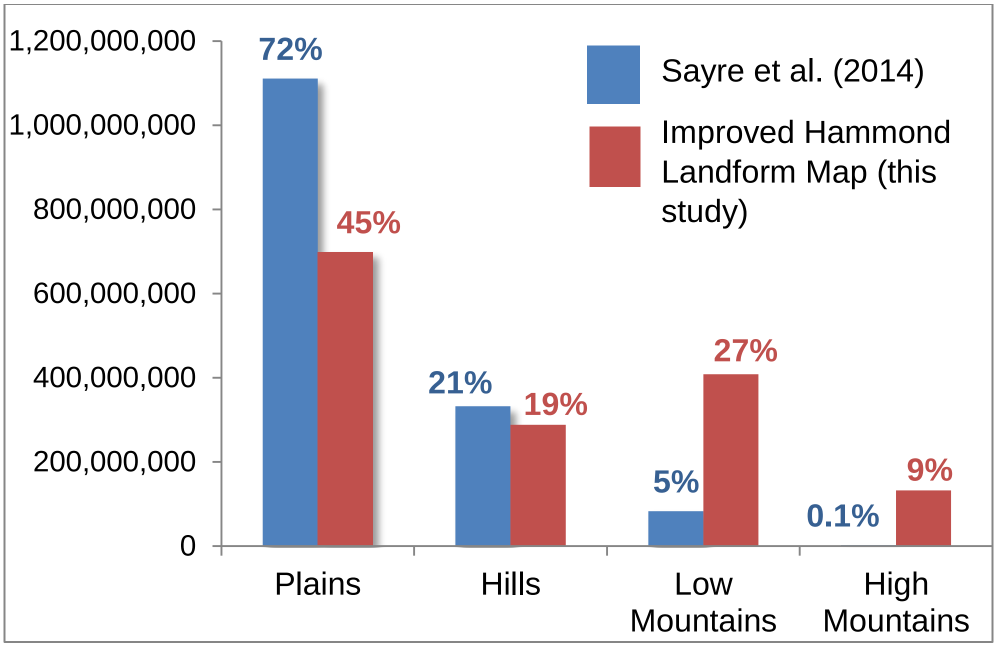

Figure 11 Comparison of major landform classes between the Sayre et al. (2014) map and Improved Hammond Landform Map (this study).

While these four aggregated classes are useful for both comparing different landform models and for aggregating ecologically meaningful areas by physiography, the improved classification resolution in the new landform models is also welcome. The new model characterizes 16 classes using a rigorous assessment of the three determinants: slope, local relief, and profile type. The overall allocation of classifier attributes into final landform classes is summarized in a master parameter combination diagram below (Figure 12). In this figure, all landform classes are presented as composites of the values of the three parameters.

3.2 Final Landform Classes from Parameter Combinations

Figure 12 composites all three parameters to show how they relate to produce the final landform classifications. There are two vertical axes on the diagram. The left shows local relief classes. The right vertical axis shows profile classes within each relief class. The horizontal axis indicates slope classes. The upper right portion of the table describes occurrences of higher slopes combined with higher relief, resulting in high and low mountains. Hills result when the relief is lower (150-300m) but the slope is still high. The lower left area in the table shows situations of low slope and low relief, yielding the plains classes. The upper left portion represents tablelands, occurring when the profile parameter is high (3-4). This figure also shows the impact of the plains feature override, which split dual classes such as plains with low mountains into separate regions for plains and low mountains. The plains features added in the later stages of the process affected the upper left portion of the diagram and corresponded with tablelands, where the profile parameter values were 0, 1, and 2.

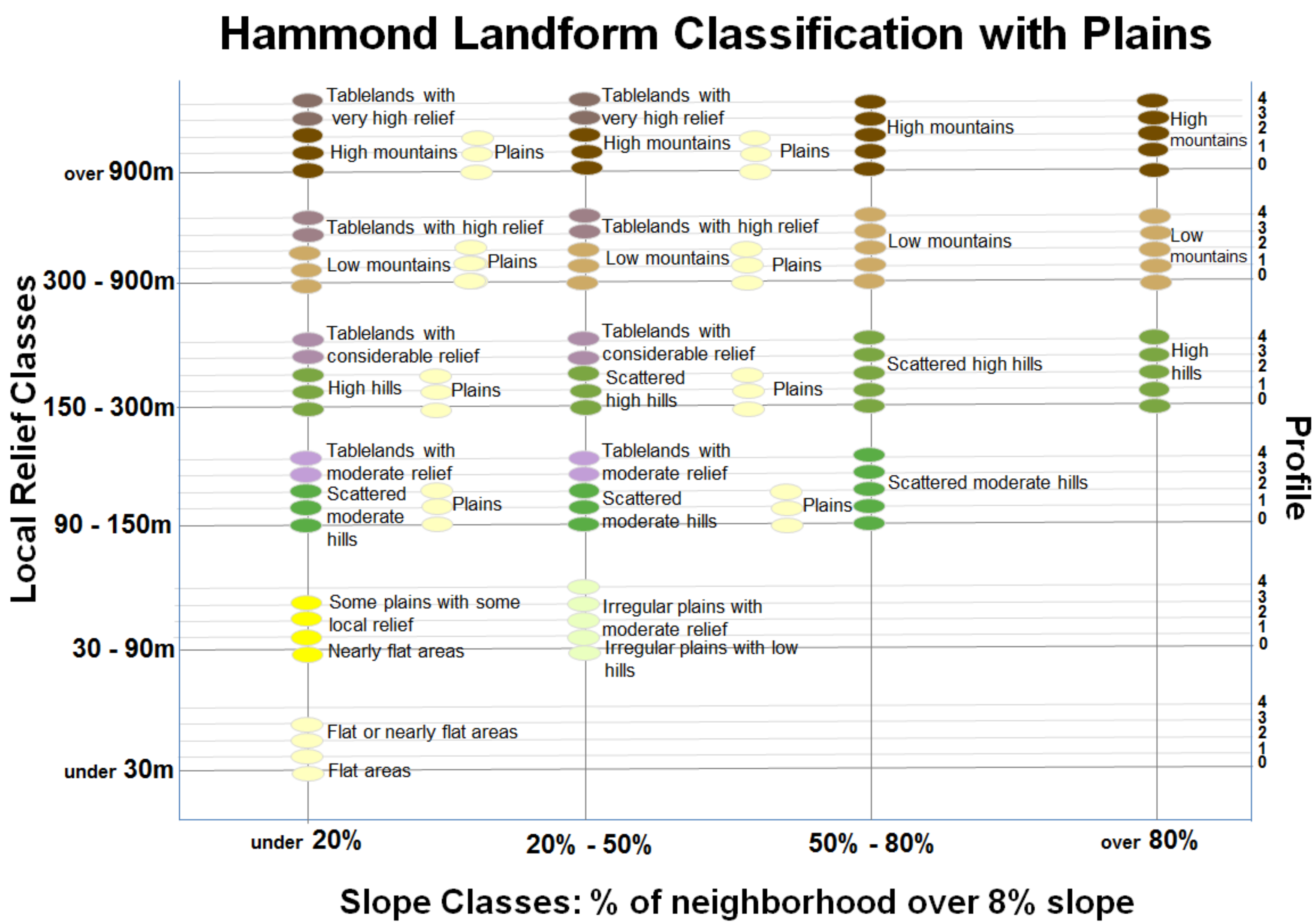

Figure 12 Diagram of how landform classes are produced from the slope, local relief, and profile parameters, and how the additional plains features impacted these combinations.

4 Conclusions and Future Work

This study implemented the latest GIS-based articulation of Hammond's model (Morgan and Lesh, 2005) as an ArcGIS geoprocessing script tool, with the script written in the Python programming language. This implementation used the Global Multi-resolution Terrain Elevation Data (GMTED) 2010, a 250-meter resolution DEM. To our knowledge, this is the first successful automated implementation of Hammond's complete landform classification on a global DEM. The result shows that this method produces landform classes consistent with the earlier work of Hammond (1964) and Dikau et al.,(1995).

The regional landform classes produced in this work describe landscape morphology in a fashion sufficient to support characterization and definition of ecosystems and ecological land units. Additionally, the work to refine the neighborhood window sizes, and to subsequently override the dual class regions with plains, addressed one of Dikau et al.'s (1995) suggestions for future work. That suggestion questioned the value of regions with dual classes.

Compared to Hammond's (1964) work, which produced a small scale U.S. map of landforms, and Dikau et al.'s (1995) work produced a similar scale map of New Mexico, this work produced more detailed results. This is due, at least in part, to the use of satellite derived DEMs instead of DEMs based on topographic maps. The increased detail produces many smaller regions of tablelands, hills, and mountains. Thus, one suggestion for future work is to develop a set of minimum mapping units for each type of regional landform class, which might reduce the micro-level detail of the product and further increase regionalization.

This work is an improvement over previous Hammond-related landform regionalization for two reasons. First, and primarily, the elimination of the dual classes reduces the overall number of classes, making the result easier to understand and to incorporate into other GIS analyses and models. Second, separately calculating plains with a smaller neighborhood analysis window and overriding the initial result with these plains produced results that match expectations when comparing the landforms data with a hillshade.

Due to the relatively complicated series of steps required to calculate the profile type parameter, it was necessary to investigate the output of each step to understand what was produced. Doing so at several study area locations (Grand Canyon Region) provided the necessary insight to identify tablelands. One insight gained was that escarpment features are located at the edges of some tablelands. For this work, we considered escarpments as features, rather than regional landform classes, and thus, did not pursue classifying them. We determined that escarpments may be found by calculating slope and relief in a 1-km neighborhood window and then looking at very steep and very high relief areas within tablelands or mountains.

Given the availability of global 30-meter DEMs, potential future work could include a higher spatial resolution implementation of the model, which might identify additional features such as terraces, escarpments, badlands, and canyons. A higher spatial resolution input DEM, however, would likely change the approach to an identification of microscale, local landform features (cliffs, toeslopes, ridges, etc) rather than mesoscale physiographic regions. The classification of regions versus features does not, however, need to be mutually exclusive. Harris et al. (2014) mapped the geomorphology of the seafloor by first characterizing four general physiographic regions, and then overlaying on these regions discrete landform features such as seamounts and submarine canyons. Such an approach could be adopted for the land masses of the planet as well, mapping mesoscale Hammond landform regions first, and then overlaying local terrain features onto the Hammond regional landform complexes.

Our work was framed in an empirical investigation of global landform distributions, and we found that identifying the correct algorithm, parameter choice, and neighborhood window size required careful experimentation and could vary among landform features to be classified. Although in fidelity to Hammond’s classes we did not incorporate other landforms like terraces, badlands, and canyons into our classification, we experimented with these classes and concluded that they could be feasibly identified in future work. For example, identification of canyons, which exhibit relative relief differences similar to mountains and hills, might be easily separated from these classes by inverting the DEM.

Our work demonstrates that global Hammond (1964) landform classes can be successfully modeled using a 250 m global DEM. Now that a finer spatial resolution global DEM (30m) is available it might be tempting to try to implement the model with the finer resolution data. Prior to such an effort, however, and especially given the immensity of the processing effort that would be required to model global landforms at a 30 m resolution, the overall goal would need to be clarified. If the goal is only to continue identifying the same types of landform regions, then there may be no added value in producing spatially refined boundaries between landforms regions, since these boundaries are imprecise to begin with, and related to human interpretations of terrain variation. However, if there is an interest in a more detailed delineation of landform features in regions, including the identification of additional feature classes, then pursuing a global landforms implementation with finer source data may be warranted.

Finally, while the methodological development has been presented herein, the application value or intended utility of the new global landform resource needs to be established. We are using the resource as an input to the characterization of ecologically distinct areas. Other “non-ecological” applications are envisioned as well, ranging from assessments of agricultural productivity potential to assessments of movement of disease vectors across landscapes. We welcome feedback from the global ecosystems community and other interested communities on the utility of the resource.

4 Availability

Improved Hammond Landform Classification Map and underlying data can be accessible via ArcGIS Online and Living Atlas via http://www.arcgis.com/home/item.html?id=cd817a746aa7437cbd72a6d39cdb4559

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Appendix A

Gentle Slope Calculations

1. Use the ArcGIS Desktop Spatial Analyst Extension's Slope tool to produce the percent slope with the GMTED 2010 DEM as the input data. The range of slopes produced was 0% to 742.269%.
2. Use the ArcGIS Desktop Spatial Analyst Extension's Reclassify tool with the percent slope dataset from step 1 such that values less than 8% are set to 0, and values greater than 8% slope are set to 1.
3. To calculate percent of gentle slope in the 3km neighborhood window, use the ArcGIS Desktop Spatial Analyst Extension's Focal Statistics tool. The input dataset is the output of step 2, and the neighborhood type is circular. Use the Sum option, which assigns the sum of the cells within the neighborhood to each cell in the output.
4. Reclassify the result of step 3 is the four categories defined by Hammond (1964) (Table 2).

Appendix B

The steps to assign local relief to each cell in the GMTED 2010 DEM are:

1. Use the ArcGIS Spatial Analyst Extension's Focal Statistics tool to calculate maximum elevation within 25-cell circular neighborhoods with the GMTED 2010 DEM as the input data.
2. Use the ArcGIS Spatial Analyst Extension's Focal Statistics tool to calculate minimum elevation within 25-cell circular neighborhoods with the GMTED 2010 DEM as the input data.
3. Use the ArcGIS Spatial Analyst Extension's Minus tool to subtract the output of step 1 from the output of step 2.
4. Reclassify the result of step 3 into the six categories defined by Hammond (Table 3).

Appendix C

The steps to assign profile to each cell in the GMTED 2010 DEM are:

1. Use ArcGIS Spatial Analyst Math tools to calculate the half of the local relief. To do so, divide the output of difference of maximum and minimum elevation, by 2. This represents the local point of distinction between lowlands and uplands.
2. Use the ArcGIS Spatial Analyst Focal Statistics tool with the Minimum option and a 25-cell size. Add this to the output of step 1. This represents the elevation of the local distinction between lowlands and uplands.
3. Use the ArcGIS Spatial Analyst Minus tool to subtract the output of step 2 from DEM. Because the DEM values are higher, this produces a surface where the positive values represent lowlands, and negative values represent uplands.
4. Use ArcGIS Spatial Analyst Reclassify tool to reclassify lowlands as 1, and uplands as 2.
5. Use ArcGIS Spatial Analyst Reclassify tool to set lowland areas to 1 and uplands to 0.
6. Identify gentle slopes within lowlands by multiplying the output of step 5 by the output of step 2 in slope parameter.
7. Use the output of step 6 as input to the ArcGIS Spatial Analyst Focal Statistics tool with the Sum to calculate the sum of gentle slopes in lowlands.
8. Use Map Algebra, Float tool to create a floating point of step 3 in slope parameter.
9. Divide the output of Step 7 by the output of Step 8 to create a percentage of gentle slopes in lowlands. Note: after the first iteration, we saw that Step 9 produced a result with No Data values. This was resolved by inserting steps 10 and 11.
10. Use ArcGIS Spatial Analyst Reclassify tool to reclassify the output of step 9 NoData values to 0 (zero); all other values are greater than zero and less than or equal to one.
11. With the output of Steps 9 and 10 as inputs, use ArcGIS Spatial Analyst Cell Statistics with the Minimum option.

12. Multiply the output of step 11 by the output of Step 5 to isolate gentle slopes in lowlands.
13. Use ArcGIS Spatial Analyst Focal Statistics with output of Step 12, a 25-cell circular neighborhood, and the Sum option to calculate the sum of gentle slopes.
14. Use ArcGIS Spatial Analyst Reclassify tool with the output of step 13 to reclassify percentage of gentle slopes in lowland areas (<50% = 0, 50%-75% = 2, >75% = 1) Note: Unlike the approaches of Hammond, Dikau et al., and Morgan and Lesh,we broke the percent area occupied by lowlands into three classes instead of two. Previous models did not account for areas under 50% of gentle slope in lowland areas.
15. Use ArcGIS Spatial Analyst Reclassify tool with the output of Step 4 to reclassify uplands as 1 and lowlands as 0. (1=0, 2=1)
16. Identify gentle slopes by multiplying the output of step 15 with step 2 in slope parameter.
17. Use the output of Step 16 as input to the ArcGIS Spatial Analyst Focal Statistics tool with the Sum to calculate the sum of gentle slopes in uplands.
18. Calculate the percentage of gentle slopes in uplands by dividing the output of Step 17 by the output of Step 8. Note: Similar to Step 9, we saw that Step 17 also produced a result with No Data values. This was resolved by inserting steps 19 and 20.
19. Use ArcGIS Spatial Analyst Reclassify tool to reclassify the output of step 18 to set No Data values to 0 (zero); and all other values to one.
20. With the output of Steps 18 and 19 as inputs, use ArcGIS Spatial Analyst Cell Statistics with the Minimum option.
21. Multiply the output of step 20 by the output of Step 15 to isolate gentle slopes in uplands.
22. Use ArcGIS Spatial Analyst Reclassify tool to reclassify the output of Step 21 to produce the percentage of gentle slopes in upland areas (<50% = 0, 50%-75%= 3, >75%=4)
23. Add the output of Steps 22 and 14 to get the combination of percentage of gentle slopes within lowlands and uplands.

Appendix D

Landform Combination and Classification Schema used by Morgan and Lesh (2005).

Combined Values	Morgan and Lesh (2005) Classification	Slope (hundreds)	Relief (tens)	Profile (ones)
140-141-142-143-144	Low Mountains	100	40	0-1-2-3-4
150-151-152-153-154	Low Mountains	100	50	0-1-2-3-4
160-161-162-163-164	High Mountains	100	60	0-1-2-3-4
230	Moderate Hills	200	30	0
231-232-233-234	Open Moderate Hills	200	30	1-2-3-4
240	High Hills	200	40	0
241-242-243-244	Open High Hills	200	40	1-2-3-4
250	Low Mountains	200	50	0
251-252-253-254	Open Low Mountains	200	50	1-2-3-4
260	High Mountains	200	60	0
261-262-263-264	Open High Mountains	200	60	1-2-3-4
320	Irregular Plains with Low Hills	300	20	0
321-322-323-324	Irregular Plains with Moderate Relief	300	20	1-2-3-4
330	Irregular Plains with Hills	300	30	0
331-332	Plains with Hills	300	30	1-2
333-334	Tablelands with Moderate Relief	300	30	3-4
340	Irregular Plains with High Hills	300	40	0
341-342	Plains with High Hills	300	40	1-2
343-344	Tablelands with Considerable Relief	300	40	3-4
350	Irregular Plains with Foothills	300	50	0
351-352	Plains with Low Mountains	300	50	1-2
353-354	Tablelands with High Relief	300	50	3-4
360	Irregular Plains with Spires	300	60	0
361-362	Plains with High Mountains	300	60	1-2
363-364	Tablelands with Very High Relief	300	60	3-4
410	Nearly Flat Plains	400	10	0
411-412-413-414	Flat or Nearly Flat Plains	400	10	1-2-3-4
420	Nearly Flat Plains	400	20	0
421-422-423-424	Smooth Plains with some local relief	400	20	1-2-3-4
430	Nearly Flat Plains with Hills	400	30	0
431-432	Plains with Hills	400	30	1-2
433-434	Tablelands with Moderate Relief	400	30	3-4
440	Nearly Flat Plains with High Hills	400	40	0
441-442	Plains with High Hills	400	40	1-2
443-444	Tablelands with Considerable Relief	400	40	3-4
450	Nearly Flat Plains with Low Mountains	400	50	0
451-452	Plains with Low Mountains	400	50	1-2
453-454	Tablelands with High Relief	400	50	3-4
460	Nearly Flat Plains with High Mountains	400	60	0
461-462	Plains with High Mountains	400	60	1-2
463-464	Tablelands with Very High Relief	400	60	3-4

Appendix E

The steps to calculate feature centric plains are:

1. Use the ArcGIS Desktop Spatial Analyst Extension's Slope tool to produce the percent slope with the GMTED 2010 DEM as the input data. The range of slopes produce was 0% to 742.269%.
2. Use the ArcGIS Desktop Spatial Analyst Extension's Reclassify tool with the percent slope dataset from Step 1 such that values less than 5% are set to 0, and values greater than 5% slope are set to 1.
3. Use ArcGIS Majority Filter with 8 neighborhoods use the input as the output of Step 2
4. Use ArcGIS Desktop Spatial Analyst Extension's Focal Statistics tool with the Sum option and a circular neighborhood of 4 cells (1-km), and the output of Step 3 as the input.
5. Reclassify the result of Step 4 into two categories. 0 to 20% as 1 and over 20% as No Data. Note: Slope of the neighborhood window is considered flat when more than 80% of the area in a 1-km neighborhood has slope less than 5 percent of slope, otherwise the area is considered as not flat area therefore as classified as No Data, eliminating those cells from the next steps.
6. Use the ArcGIS Spatial Analyst Extension's Focal Statistics tool to calculate maximum elevation within 4-cell circular neighborhood using the GMTED 2010 DEM as the input data.
7. Use the ArcGIS Spatial Analyst Extension's Focal Statistics tool to calculate minimum elevation within 4-cell circular neighborhoods with the GMTED 2010 DEM as the input data.
8. Use the ArcGIS Spatial Analyst Extension's Minus tool to subtract the output of step 7 from the output of Step 6

9. Reclassify the result of Step 8 into the two categories. 0-30-ms as 10 and rest is No Data. Note: Local relief is classified as very low when the difference between maximum and minimum elevation is between the ranges of 0-30-ms, otherwise the area is considered as not low relief and classified as No Data.
10. Use the ArcGIS Spatial Analyst Extension's Plus tool to add the output of step 9 to the output of step 5. The combination of slope and local relief class determines the feature centric plain areas.
11. Use the ArcGIS Spatial Analyst Extension's Reclassify tool to reclassify only plain areas to 2000. The input for this step is the output of 10.
12. Use the ArcGIS Spatial Analyst Extension's Cell Statistics maximum tool with the output of step 11 and the previous final map to override the plains features.
13. Use the ArcGIS Spatial Analyst Extension's Reclassify tool, to reclassify the output of map 12, select unique values with the Table 6. Green row indicates as the changing values. This step removes the dual-classes.
14. Use ArcGIS Spatial Analyst Extension, Cell statistics maximum tool to add surface water to the output of map 13.