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The scale-mosaic hypothesis: A framework for heterogeneous scale selection in geomorphometry and DEM-based terrain analysis

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Abstract. Scale is among the most consequential issues in geomorphometry and terrain analysis. Land-surface parameters (LSP) derived from digital elevation models (DEMs) are scale dependent because they are either defined over a neighbourhood or affected by the topographic detail retained in a DEM. The dominant multiscale workflow generates dense stacks of homogeneously scaled LSP predictors and then applies feature-selection or dimensionality-reduction procedures to retain a subset of scales. Although this approach has proven useful, it assumes that selected scales can be imposed uniformly across space. That assumption is difficult to justify in heterogeneous terrain, where landforms are nested, process domains overlap, and characteristic scales vary locally.

This paper formalizes the scale-mosaic hypothesis: land-surface parameter scale mosaics based on locally optimized scale-selection criteria can provide terrain representations and model predictors with greater scale-space information density, improved correspondence with spatially heterogeneous process scales, and consequently equal or improved modelling performance relative to homogeneous multiscale alternatives.

The paper defines the principal concepts underlying the hypothesis, including scale signatures, characteristic scales, key-scale rasters, scale-space partitions, and scale mosaics. It distinguishes heterogeneous scale selection from conventional homogeneous multiscale feature selection, clarifies the relationship with scale-space theory and automatic scale selection, and identifies why a scale mosaic is not merely a visualization of a multiscale stack but a different way of collapsing scale-space. Scale mosaicking is therefore not simply another scale-selection method, but a distinct mode of scale-space reduction in which scale itself becomes a mapped property of the terrain representation.

The hypothesis is developed as a set of linked and falsifiable claims concerning information density, process-scale representation, and predictive performance. Existing evidence is reviewed according to these claims. This evidence includes scale-signature analysis, DEV_{max} and key-scale mapping, scale-optimized roughness and anisotropy, Gaussian scale-space optimization of derivative-based land-surface parameters, digital soil mapping, wetland prediction, information-density analysis, and emerging terrain-classification applications. Together, these studies indicate that characteristic scales are spatially structured, that heterogeneous scale representation is applicable across multiple parameter families, that scale mosaics can preserve information from more of the sampled scale domain than any sparse homogeneous subset, and that terrain-driven local scale optimization can match or exceed model-optimized homogeneous scale selection. The framework therefore repositions scale from a fixed analytical parameter to a spatially distributed property of terrain representation.

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1 Introduction

Scale has long been recognized as a central problem in geomorphometry and related terrain analysis applications because the extraction of topographic information from DEMs depends, either directly or indirectly, on the scale at which the surface is represented (Pike et al., 2009; Florinsky, 2017). In practice, however, the problem is still most often addressed by selecting one or several scales that are then applied uniformly throughout a study area. The practical success of this approach has reinforced the view that multiscale representation is mainly a matter of sampling the scale domain and then identifying an optimal subset from within it. The premise of this paper is that such a view is incomplete.

The issue is not whether multiscale analysis is useful. It clearly is. Nor is the issue whether homogeneous scale stacks can improve modelling relative to the naïve practice of relying on a single scale dictated by DEM grid resolution. They often do (Behrens et al., 2010; Miller et al., 2015). The problem is that the dominant workflow continues to assume that the relevant scales of terrain representation can be selected globally and then imposed everywhere. In complex landscapes this assumption is difficult to maintain. Landforms are superimposed, process domains vary across space, and local topographic context changes over short distances. Under these conditions there is little reason to expect one global scale, or even a small set of them, to be equally representative of all sites (Wood, 2009; Goodchild, 2011).

An alternative perspective has emerged through work on surface curvature, local topographic position, roughness, Gaussian scale-space optimization, and more recent multiscale elevation residual analysis (Wood, 1996, 2009; Lindsay et al., 2015, 2019; Newman et al., 2022b; Lindsay et al., 2025). The common idea is that characteristic scale should be allowed to vary spatially and that scale selection should be tied to the local topographic setting rather than imposed globally. When the value of a land-surface parameter (LSP) is measured at a site-specific key scale and these values are assembled for all grid cells, the result is a scale mosaic. In this framework, the geography of characteristic scale is not treated as a nuisance or a hidden dimension of the problem; it becomes part of the representation itself.

Although the methods underlying this perspective have already been described and applied, the broader conceptual proposition that unites them has not been articulated in a dedicated paper. There is therefore no single citable source that defines the scale-mosaic hypothesis, distinguishes it from homogeneous multiscale analysis, sets out its corollaries, and identifies the basis upon which it should be tested. The purpose of this paper is to address that gap. It is intended as a conceptual synthesis rather than a new methods article. The aim is to formalize the scale-mosaic hypothesis, define the principal terms and distinctions needed to interpret it properly, summarize the evidence currently available in support of it, and outline the research agenda required to test it more rigorously.

1.1 Terminology

For clarity, the following terms used in this paper are defined below:

- **Land-surface parameter**: one of a large number of metrics that are extracted from DEMs to characterize the spatial distribution of a topographic property, such as slope, curvature, relative position, or roughness.

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- **Scale-space**: a set of land-surface parameter representations sampled over a sequence of scales.
- **Scale signature**: the variation of a land-surface parameter value with scale for a given grid cell.
- **Key scale/characteristic scale**: the scale selected for a grid cell according to a specified local optimization criterion.
- **Key-scale raster**: the raster storing the selected key scale for each grid cell.
- **Scale mosaic**: a raster created by collapsing a land-surface parameter scale-space using the key scale selected for each grid cell.
- **Homogeneous scale selection**: any approach in which one or more globally selected scales are applied uniformly across space.
- **Heterogeneous scale selection**: any approach in which the represented scale is allowed to vary spatially.

2 Scale and the problem of homogeneous representation

Scale enters geomorphometry and terrain analysis in more than one way. Some variables, such as measures of local topographic position, roughness, relief, and related elevation residual attributes, are inherently scale dependent because they are measured over a local neighbourhood (Gallant and Wilson, 2000; Lindsay et al., 2015). Their values are therefore defined in relation to the support of the neighbourhood from which they are calculated. Other variables, such as slope and the curvatures, may be treated conceptually as local surface derivatives, yet their values still depend on the scale of topographic detail retained in the DEM (Deng et al., 2007; Newman et al., 2022b). This dependence may be explored either by changing the support of the measurement itself or by suppressing shorter-wavelength topographic structure prior to calculation. The latter method can be achieved either by coarsening the DEM grid resolution or through application of a smoothing filter (Grohmann et al., 2010; Grohmann, 2015).

The dominant practical response to this scale-dependency problem has been the construction of homogeneous scale-spaces. A predictor is calculated over many scales, producing a stack of raster representations, and some method is then used to identify a smaller subset of scales for further analysis (Fig. 1A). In environmental modelling, the selected subset is often determined by feature-selection procedures, collinearity reduction, or optimization of some measure of predictive performance (Behrens et al., 2010; Drăguţ et al., 2011; Miller et al., 2015). Such approaches have become standard because they are intuitive, operationally convenient, and often effective. They acknowledge the scale sensitivity of topographic predictors without fundamentally altering the structure of the predictor set.

Yet the limitation of this framework is also clear. Once selected, each retained scale applies everywhere in the study area. The multiscale approach therefore remains homogeneous in its final representation. Even if several scales are retained, each is still spatially stationary. The predictor set may be multiscaled, but the selected scales are global. This becomes problematic in heterogeneous terrain and extensive study sites because it assumes that a relatively small set of globally selected scales can stand in for the local scale behaviour of the entire landscape (Wood, 2009; Goodchild, 2011).

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There is also a second limitation. Homogeneous multiscale feature selection tends to treat scale primarily as an empirical tuning parameter. Scales are chosen because of their statistical relation with a dependent variable or because they satisfy a dimensionality-reduction criterion. While such strategies may be useful for prediction, they do not address whether the selected representation is itself the most meaningful one from the perspective of the terrain. In that sense, scale selection under the homogeneous framework is often more strongly tied to model optimization than to the nature of topographic representation.

3 Scale signatures, characteristic scales, and scale mosaics

The heterogeneous alternative (Fig. 1B) begins with the observation that the multiscale behaviour of an individual site can itself be informative. When the value of an LSP is tracked through a sequence of scales for a given grid cell, the resulting curve is referred to as the scale signature (Wood, 2009) of that site (Fig. 2). Scale signatures provide a direct expression of how local topographic context varies with scale and therefore offer a basis for identifying the scales at which topographic properties are most strongly expressed (Wood, 2009; Newman et al., 2022b).

Characteristic scales may be identified in different ways depending on the nature of the variable and the purpose of the analysis. For topographic position metrics, the key scale may correspond to the scale at which a site is most deviated relative to its surroundings (Lindsay et al., 2015). For roughness measures, it may be the scale of maximum local complexity (Lindsay et al., 2019). For derivative-based variables derived in Gaussian scale-space, it may be the scale at which the scale-standardized response is maximal (Newman et al., 2022b). The operational details vary, but the common point is that scale selection is performed site by site rather than globally.

Once a key scale has been identified for each grid cell, the corresponding value of the parameter can be extracted from the scale-space and inserted into an output raster. Repeating this operation throughout the DEM collapses the scale-space into a single map in which neighbouring cells may be represented at different characteristic scales. This output is the scale mosaic. The associated key-scale raster records the selected scale for each cell and is itself informative because it reveals how characteristic scales are distributed across the landscape.

The contrast with the homogeneous framework is fundamental. A scale stack retains several spatially stationary representations and leaves the problem of local scale mismatch unresolved. A scale mosaic expresses a single representation, but it is heterogeneous in the sense that the represented scale varies with the local topographic setting. This is not simply a different visualization of multiscale information. It is a different way of collapsing the scale dimension.

Object-based image analysis (OBIA), or segmentation-based approaches (Drăguţ et al., 2011), also allow scale to vary spatially by partitioning space into discrete, uneven-sized units. Unlike OBIA, however, the scale-mosaic framework retains a continuous raster structure while allowing scale to vary locally.

It is also worth emphasizing that the full possible scale-space of a DEM need not be collapsed into one mosaic. In many situations broad scale partitions are preferable (Fig. 1B). Local and broad scale ranges may correspond more naturally to different landforms or process domains and may reduce discontinuities in the final representation (Lindsay et al., 2015, 2019). This point has proven especially important for elevation residual metrics because a site may be elevated at one scale and low-lying

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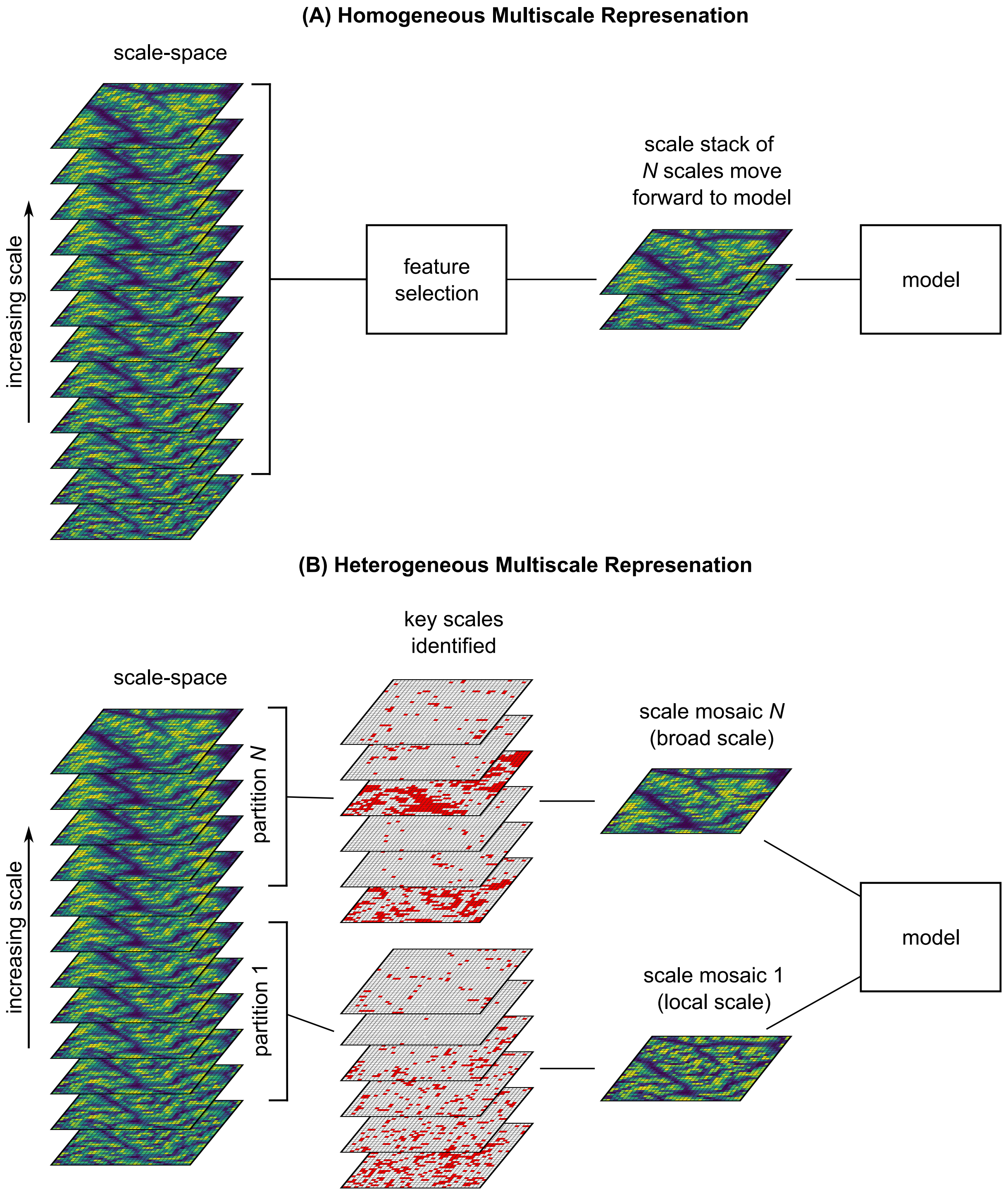

Figure 1. Conceptual contrast between homogeneous scale selection (A), in which a sparse subset of N globally selected scales is retained, and heterogeneous scale selection (B), in which locally selected characteristic scales are expressed within N scale mosaics created by collapsing N partitions of scale-space.

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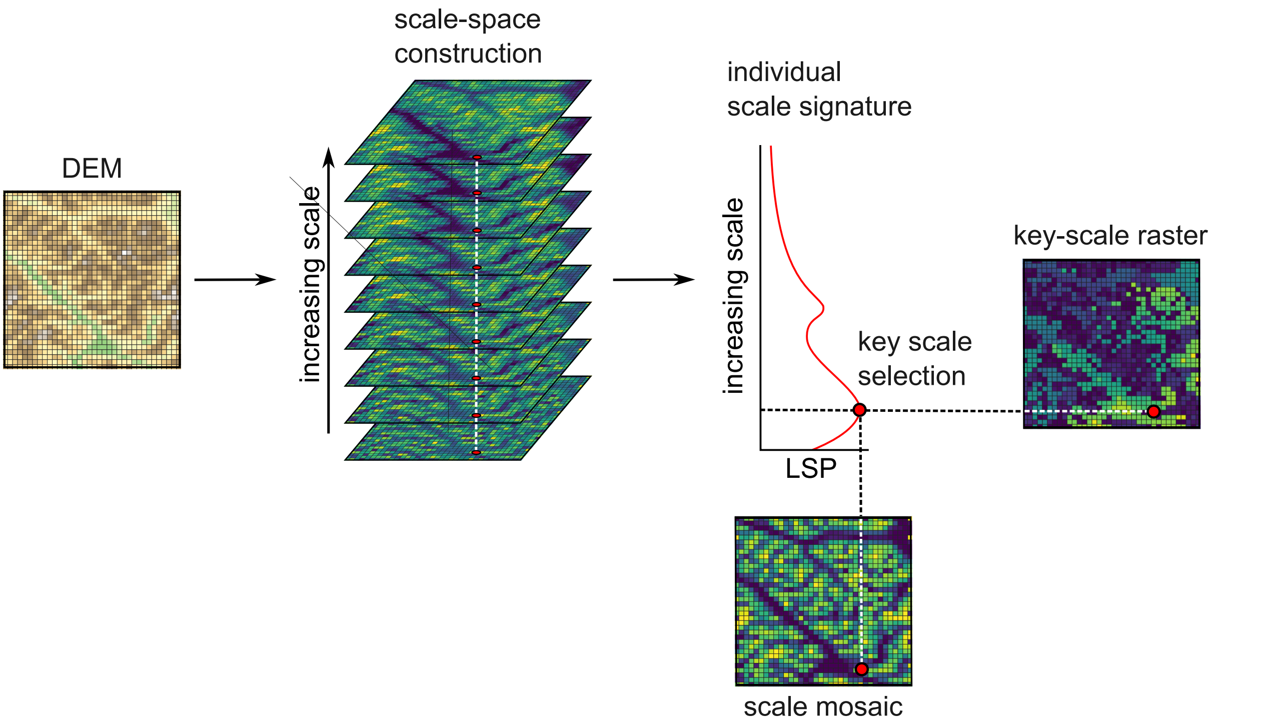

Figure 2. Conceptual workflow for the generation of a scale mosaic from a DEM-derived land-surface parameter (LSP), through scale-space construction, site scale signatures, and key-scale selection.

at another. In such cases, partitioning the scale-space avoids forcing incompatible scale expressions into one signed variable. That is, scale partitions allow for the representation of multiple characteristic scales for a single site. Lindsay et al. (2015) showed how a 3-partition scheme (local/meso/broad) can be used to create a scale colour composite for terrain visualization.

4 Relation to scale-space theory and automatic scale selection

The concept of identifying characteristic scales from multiscale representations has a well-established foundation in scale-space theory, particularly in the work of Lindeberg (1999, 2017, 2018a, b), who formalized principles for automatic scale selection based on extrema of scale-normalized responses. In that framework, meaningful structures are detected at scales where appropriately normalized differential operators attain maxima over scale. Several developments in geomorphometry, including Gaussian scale-space optimization of LSPs, draw directly on this lineage (Newman et al., 2018a, e.g.), and therefore share a conceptual basis with automatic scale selection in computer vision.

Despite this shared foundation, the scale-mosaic framework departs from classical automatic scale selection in a fundamental way. In Lindeberg's formulation, scale selection is primarily feature-centric: characteristic scales are associated with detected image structures (e.g., edges, blobs, or spatio-temporal events), and the scale estimates are treated as attributes of those

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structures. By contrast, the scale-mosaic framework is representation-centric. Rather than identifying scales only for discrete features, it assigns a locally optimal scale to every grid cell and uses these selections to construct a spatial field in which the represented scale varies continuously across the landscape. The resulting scale mosaic is therefore not simply a set of detected features with associated scales, but a reconstruction of an LSP field under spatially heterogeneous scale selection.

This difference may be understood in terms of how scale-space is collapsed. Classical automatic scale selection identifies extrema within scale-space and retains them as descriptors of local structure, leaving the underlying signal unchanged. In contrast, the scale-mosaic approach collapses scale-space into a single spatial representation by selecting, for each location, the parameter value at its locally determined characteristic scale. In this sense, scale mosaics provide a fundamentally different mechanism for reducing scale-space: one that produces a spatially heterogeneous field rather than a set of multiscale feature descriptors.

Where scale-mosaic implementations employ Gaussian scale-space with scale-standardized responses, the connection to Lindeberg's theory becomes especially direct. In such cases, characteristic scales correspond to extrema of normalized responses across scale, closely paralleling the criteria used in automatic scale selection. The distinction, however, remains in how these scales are used: not only to detect salient structures, but to define the scale at which each location is represented in the final map.

The scale-mosaic framework may therefore be viewed as an extension of scale-selection principles into the domain of spatial representation. It retains the core insight that meaningful structure can be revealed through extrema over scale but applies that insight to the construction of spatially heterogeneous fields rather than to the detection of discrete features.

5 Formal statement of the scale-mosaic hypothesis

The scale-mosaic hypothesis (Lindsay, 2023; Lindsay et al., 2025) is stated here as follows: land-surface parameter scale mosaics based on locally optimized scale-selection criteria can provide terrain representations and model predictors with greater scale-space information density, improved correspondence with spatially heterogeneous landscape process scales, and consequently equal or improved modelling performance relative to homogeneous multiscale alternatives.

This statement contains three linked claims. First, scale mosaics can provide information-dense representations because many sampled scales may, in principle, be expressed somewhere in the final output. A homogeneous raster represents one scale everywhere. A sparse homogeneous stack represents several scales that survive feature selection everywhere. A scale mosaic represents one value per cell but may draw those values from many scales according to the local scale signature. The key-scale raster identifies which scales are actually represented.

Second, the represented scale is selected from local topographic context. If topography is an expression of geomorphic process, then local topographic scale signatures may act as proxies for the scales at which relevant processes or landforms are expressed. This does not guarantee process-scale correspondence, but it provides a physically grounded basis for scale selection that is independent of the response variable used in subsequent modelling, unlike the homogeneous scale-stack approach.

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Third, if scale mosaics preserve more relevant scale-space information and better match local process scales, then they may improve modelling performance or at least match homogeneous alternatives while being more compact and internally consistent. This claim is deliberately stated with some caution. The hypothesis does not assert that every heterogeneous implementation will outperform every homogeneous stack. Nor does it imply that all LSPs will benefit equally from scale mosaicking. Instead, it asserts that locally optimized heterogeneous representations can confer advantages under identifiable conditions, especially in topographically heterogeneous terrain and in applications where process scale matters.

The hypothesis also differs from the narrower idea that local scale optimization is simply another feature-selection technique. Feature selection, in its most common modelling form, chooses variables from an already constructed candidate set. The scale-mosaic framework changes the construction of the variables themselves. The question is not merely which scales should be selected from a homogeneous stack, but whether the represented scale should be permitted to vary spatially in the first place. This is a distinction in representation rather than only in variable selection.

Scale mosaicking should therefore be understood as more than a procedure for selecting scales. It is a representation framework in which scale is promoted from an externally imposed analytical setting to a spatially distributed attribute of the terrain model. The scale mosaic itself stores the parameter values, while the associated key-scale raster stores the geography of representation scale. Together, these rasters express both terrain form and the scale at which that form is locally most characteristic. In many applications the key-scale raster has been treated as ancillary. Under the present framework, however, it is better regarded as a substantive map of the distribution of characteristic scales. It therefore provides information on the scale structure of the landscape and may yield direct insight into the geography of process domains and topographic organization.

6 Corollaries and falsifiable predictions

Five corollaries follow directly from the hypothesis (Table 1). 1) If landscapes are characterized by spatially heterogeneous characteristic scales, then key-scale rasters should display meaningful spatial structure rather than random patterns. 2) If scale mosaics preserve more geomorphometrically relevant scale-space information than individual homogeneous rasters, then they should often exhibit greater information density, whether measured statistically, structurally, or in terms of represented landform expression. 3) If predictor values are more appropriately matched to local scale context, then heterogeneous predictor sets should often match or exceed homogeneous multiscale stacks in environmental modelling applications, especially when compared against strong baselines. 4) If the principal value of scale mosaics lies in their ability to address heterogeneous terrain, then the strongest advantages should be expected in landscapes with marked spatial variability in scale structure. 5) Finally, if unrestricted scale ranges can combine incompatible topographic expressions, broad process-relevant scale-space partitions should often improve interpretability and modelling performance relative to unrestricted mosaics.

These corollaries render the hypothesis testable. It would be weakened if repeated, well-designed comparisons were to show that key-scale rasters contain little interpretable spatial pattern, that scale mosaics do not differ from homogeneous alternatives in information density under robust measures, or that heterogeneous predictor sets consistently underperform homogeneous

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scale stacks across diverse landscapes and applications. The hypothesis would also be weakened if any observed gains proved attributable merely to increased predictor number or model flexibility rather than to heterogeneous scale representation itself.

At the same time, evidence against one implementation of scale mosaicking would not, by itself, falsify the broader framework. Heterogeneous scale representation is not a single algorithm. Different LSPs, key-scale criteria, scaling frameworks, and scale-range partitions may all affect outcomes. The proper tests are therefore comparative and multi-contextual. They must ask not whether one particular implementation succeeds or fails, but whether locally optimized scale representation, applied coherently, provides advantages relative to strong homogeneous baselines.

The purpose of Table 1 is to make explicit that the scale-mosaic hypothesis is presented here as a falsifiable proposition rather than as a descriptive label for an existing group of methods.

7 Existing evidence in support of the hypothesis

Support for the scale-mosaic hypothesis has developed progressively through conceptual work on scale signatures, methodological advances in efficient scale-space sampling, extensions to multiple LSP families, and applied modelling studies. The evidence is best evaluated according to the claims of the hypothesis rather than simply as a chronology. The following subsections therefore review evidence for spatially heterogeneous characteristic scales, generality across LSPs, information density, environmental modelling performance, and terrain-classification applications. The evidence reviewed below includes peer-reviewed studies, conference contributions, and manuscripts currently in preparation. Where results derive from unpublished manuscripts, they are identified as emerging evidence and are used to motivate testable predictions rather than to establish settled conclusions.

7.1 Conceptual origins: scale signatures and characteristic scales

The conceptual origin of the framework lies in multiscale geomorphometry and the idea of the scale signature. The roots of scale signatures predate the term itself. Pike (1988) introduced the broader notion of a geometric signature: a diagnostic set of topographic measurements capable of distinguishing geomorphically different landscapes. Wood (1996) extended this logic into an explicitly multiscale and location-specific framework, showing that morphometric parameters and feature classes vary with window size at individual DEM grid cells and that this variation can be represented as a feature membership function or landform signature. Fisher et al. (2004) subsequently interpreted such multiscale class variation as the basis for fuzzy morphometric membership, while Schmidt and Andrew (2005) developed local scale behaviour diagrams and dominant scale ranges (i.e. characteristic scales) from polynomial surface approximations.

The term scale signature was later used by Wood (2009) to describe how surface parameters vary with analysis scale at individual locations and how characteristic scales can be identified from peaks, troughs, and other salient features of these signatures. This work established that local scale behaviour is itself interpretable and that characteristic scales may vary spatially. To the author's knowledge, Wood (2009) was the first published use of the term "scale signature" in this geomorphometric sense, although the underlying concept was already present in Wood's 1996 doctoral thesis.

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Table 1. Formal predictions and potential falsifiers of the scale-mosaic hypothesis.

Prediction	Rationale	Expected supporting observations	Important falsifier
Key-scale rasters should show meaningful spatial structure.	If characteristic scales vary spatially, the selected scales should map coherent terrain organization rather than random patterning.	Spatial correspondence with landforms, process domains, or topographic transitions.	Noise-like key-scale patterns with no interpretable spatial organization across repeated case studies.
Scale mosaics should often be more information dense than single uniform-scale rasters.	A mosaic permits many sampled scales to be represented in one output rather than reducing representation to one global scale.	Higher feature counts, greater represented landform area, or lower redundancy.	No evidence of increased represented terrain structure relative to homogeneous baselines.
Heterogeneous predictor sets should often match or exceed homogeneous scale stacks in modelling.	Locally selected scales should better match terrain context than globally selected scales.	Comparable or improved performance across multiple applications and landscapes.	Consistent underperformance relative to strong homogeneous multiscale baselines.
Heterogeneous predictor sets should offer greater advantage in topographically complex landscapes.	Complex landscapes exhibit landforms superimposed across scales.	Degree of improvement in modelling performance relative to homogeneous baseline is larger in more topographically complex landscapes.	No evidence of landscape dependency in heterogeneous improvement over homogeneous baseline.
Broad process-relevant scale partitions should often strengthen heterogeneous scaling.	Very wide scale ranges may combine incompatible topographic expressions; partitioning may improve interpretability and representation.	Improved performance or clearer patterning for local/meso/broad mosaics relative to unrestricted full-range mosaics.	No difference between partitioned and unrestricted heterogeneous approaches across repeated tests.

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The scale-mosaic hypothesis is, however, not simply the claim that characteristic scales exist and can be determined from the scale signature function. That claim is already well established. The hypothesis concerns the consequences of constructing terrain representations from spatially heterogeneous characteristic scales. The distinction is important: scale signatures provide the evidence of local scale behaviour, whereas scale mosaics use that behaviour to build LSP rasters.

7.2 Operational evidence: DEV_{max} and key-scale mapping

Lindsay et al. (2015) provided the first operational implementation of this logic for dense multiscale topographic position analysis. The integral image method made it possible to evaluate deviation from mean elevation (DEV) across wide and densely sampled scale ranges. DEV_{max} retained the signed LSP value at the scale of maximum absolute deviation for each cell, while r_{max} mapped the selected key scale.

This work demonstrated several foundational points. First, scale signatures for local topographic position can contain multiple peaks and troughs, indicating that different landforms and process domains are expressed at different scales. Second, key-scale rasters contain coherent spatial structure. Third, partitioning scale-space into local, meso, and broad ranges can reveal different levels of topographic organization, i.e., the possibility that a site may have more than one meaningful characteristic scale. Finally, the resulting mosaics and multiscale topographic position colour composites contained visual and analytical information that could not be captured by a single homogeneous scale.

Viewed retrospectively, DEV_{max} was an early scale mosaic before the broader hypothesis had been formalized. It showed that local scale optimization was computationally feasible and geomorphically meaningful.

7.3 Methodological consolidation and generality across LSPs

Subsequent studies extended heterogeneous scale representation beyond DEV. Newman et al. (2018a) evaluated metrics of local topographic position and found that DEV, calculated using integral images, provided a suitable balance of robustness and computational efficiency for hyperscale applications. This established a stronger methodological basis for dense local topographic position scale-space analysis.

Newman et al. (2018b) extended the logic to topographic anisotropy. Anisotropy scale signatures revealed nested and multimodal structures, and the spatial distribution of maximum anisotropy and its associated scale co-located with anisotropic landforms such as dunes, drumlins, valleys, and outcrops. This work demonstrated that local scale optimization could represent not only elevation residual magnitude but also directional landscape texture.

Lindsay et al. (2019) extended the framework to surface roughness and complexity. Roughness scale signatures differed among land-cover and landform contexts, and key-scale rasters showed that peak roughness occurred at highly variable scales across the landscape. This was an important generalization because it showed that scale mosaicking was applicable to surface texture and not only local topographic position.

Newman et al. (2022a) evaluated scaling frameworks for multiscale geomorphometry and identified fast Gaussian scale-space as a favourable general approach. Gaussian scale-space preserves spatial resolution, has a continuous scale parameter, and can be implemented efficiently. Newman et al. (2022b) then used scale-standardized Gaussian scale-space to optimize

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derivative-based LSPs, including slope and curvature. This was a major conceptual expansion because it showed that local characteristic scales could be identified for variables not defined originally as neighbourhood residuals. Together, these studies indicate that heterogeneous scale representation is a general strategy rather than a technique restricted to one parameter family.

7.4 Evidence for increased information density

The information-density component of the hypothesis has both a structural and an empirical aspect. Structurally, a scale mosaic can, at least theoretically, draw information from every scale within the scale-space; these sampled scales will be represented in the key-scale raster. Therefore, if the key-scale raster contains values across much of the sampled scale domain, the mosaic necessarily contains scale-space information absent from any sparse homogeneous subset. In that strict sense, a homogeneous subset cannot reproduce the same representation unless it includes all represented scales and their spatial allocation. Lindsay et al. (2019) demonstrated that key-scale rasters do commonly contain a widely ranging sample of the sampled scales within scale-space.

The empirical question is whether this additional scale-space information improves representation in meaningful ways. In a manuscript currently in preparation for submission, Coric and Lindsay evaluate this directly by comparing scale mosaics with the homogeneous-scale rasters from which they were built. The results indicate that information density is multidimensional. Marginal entropy is sensitive to distribution shape, clipping, and discretization, and therefore does not provide a universal test. In contrast, scale mosaics consistently maximized root-mean-square contrast and total mapped outlier-feature area, while feature count results were more nuanced because fine homogeneous scales often create many fragmented objects. These findings refine the hypothesis: scale mosaics should not be described as universal maximizers of every information metric, but they can preserve greater value differentiation and broader spatial expression of strong terrain positions than any individual homogeneous raster.

7.5 Evidence from environmental modelling

The strongest published applied evidence currently comes from digital soil mapping. Newman et al. (2023) compared unscaled, homogeneous multiscale, and heterogeneous scale-mosaic predictor sets for multiple soil properties and depths. Unscaled predictors performed worst, confirming that DEM-resolution terrain attributes are usually inadequate. Homogeneous and heterogeneous multiscale strategies were broadly comparable, but the partitioned heterogeneous strategy consistently performed best or near best across accuracy, uncertainty, and error metrics. This finding is important because the heterogeneous representation was constructed from topographic scale signatures rather than by selecting scales to maximize model performance against the soil response.

A manuscript in preparation by Coric et al. extends this modelling evidence using prairie pothole wetland prediction as a controlled terrain-dependent task. Its contribution is not that it provides the first modelling support for the hypothesis, but that it evaluates heterogeneous scale mosaics against an especially strong homogeneous baseline: wrapper-selected scale stacks optimized for random forest performance. In that comparison, partitioned scale mosaics matched or exceeded the corresponding

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homogeneous stacks in most paired comparisons, strengthening the inference that terrain-driven local scale optimization can be competitive with response-optimized homogeneous scale selection.

This distinction is central to the scale-mosaic hypothesis. If predictors whose scales are selected only from local topographic context can match or outperform predictors whose scales are selected through model-performance optimization, then local topography is carrying information about appropriate representation scale. The most parsimonious explanation is that scale mosaics better match the scale of terrain representation to the spatially heterogeneous process scales expressed in the landscape. The result is also practically important because scale mosaics can be generated directly once the LSP, scale range, and scale interval are specified. Wrapper-based homogeneous selection, by comparison, requires dense stack generation, repeated model fitting, feature selection, and storage or management of many intermediate rasters. Scale mosaicking is generally a relatively simpler workflow.

7.6 Evidence from elevation residual analysis and terrain classification

Recent elevation residual work (Lindsay et al., 2025) has extended the framework by separating elevated and low-lying expressions into multiscale elevated and low-lying indices (MsEI and MsLLI). This addresses a limitation of signed mosaics such as DEV_{max} and elevation percentile mosaics, where a site may be low-lying at one scale and elevated at another. By separating minima and maxima of scale signatures, MsEI and MsLLI reduce discontinuities and provide clearer maps of upland and bottomland positions across broad scale ranges. Case studies in glaciated and fluvial landscapes show that these indices can represent landforms of widely varying scales and that key-scale maps adapt to local hillslope length and landform size.

A manuscript in preparation by Wang et al. develops a multiscale topographic position classification (MSTP-Class) framework, illustrating one possible extension of the scale-mosaic concept from continuous LSP fields to categorical landform classification. The MSTP-Class framework combines local and broad DEV_{max} mosaics, classifies each into ternary position classes, and forms a nine-class local-by-broad terrain classification. Although this work remains under evaluation, it illustrates how heterogeneous scale representation can support landscape partitioning and operational landform classification.

7.7 Synthesis of the evidence

The evidence base remains incomplete, but already includes both established and emerging support for the scale-mosaic hypothesis. Published work provides strong evidence that characteristic scales are spatially structured, that heterogeneous scale representation is feasible across several LSP families, and that heterogeneous predictor sets can be competitive with homogeneous multiscale alternatives in environmental modelling. In particular, Newman et al. (2023) showed in a digital soil mapping context that partitioned heterogeneous scale-mosaic predictors performed best or near best across multiple evaluation criteria, despite being constructed from terrain scale signatures rather than selected directly to optimize the soil-response models. Emerging manuscript evidence extends this foundation. Coric and Lindsay directly evaluate the information-density claim, while Coric et al. provide a more demanding modelling comparison in which scale mosaics are tested against wrapper-selected homogeneous scale stacks optimized for random forest performance. These unpublished studies are therefore treated here as provisional extensions of an already published evidence base, not as the sole basis for the modelling-performance claim.

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These findings do not prove that scale mosaics will always outperform homogeneous stacks. They do, however, provide converging support for the central proposition that scale is spatially heterogeneous and that terrain representation should be allowed to reflect that heterogeneity.

8 Boundary conditions and limitations

Formalizing the hypothesis also requires clarity regarding its likely limits. Not all LSPs are expected to benefit equally from heterogeneous scale representation. Parameters for which scale dependence is explicit in the variable definition, such as topographic position and roughness measures, may be especially well suited to scale mosaicking. Other variables may show weaker, more subtle, or more application-dependent gains.

The hypothesis is also inherently landscape contingent. In terrain where characteristic scales vary little across space, homogeneous representations may perform nearly as well as heterogeneous ones. The principal benefits of the framework should therefore be expected in topographically heterogeneous landscapes, characterized by scale superposition and overlapping process domains, or in applications where the phenomena of interest are themselves strongly scale dependent. It should be noted that these conditions are more likely to occur at larger spatial extents.

The operational details of scale selection matter as well. Key scales may be defined using maxima, minima, absolute departures, standardized extrema, or other salient characteristics of scale signatures. These are not interchangeable definitions, and no single criterion will be appropriate in all cases. Similarly, analyses conducted across very broad neighbourhood ranges may be affected by edge effects and by divergence between nominal and effective support near DEM margins. Such issues are not unique to heterogeneous approaches, but they deserve explicit consideration because they may influence the shape and interpretation of scale signatures. Defining classes of scale-signature shape (e.g. monotonic, single extremum, multiple extrema, and oscillatory) may provide an additional means for interpreting characteristic scale patterns in landscapes.

Although, given the well-established link between process and form, characteristic scales derived from scale signatures are likely to correspond to process-relevant scales, this correspondence is not guaranteed and should be treated as a testable hypothesis rather than an assumption. The correspondence should be evaluated where possible through comparison with mapped landforms, process domains, field observations, or modelling outcomes.

Lastly, the relation between improved topographic representation and improved model performance is not expected to be one-to-one. Environmental models often include non-topographic covariates, spatially variable data quality, and multiple sources of uncertainty. Consequently, the gains associated with scale mosaics may be amplified, muted, or obscured depending on the broader modelling context. The hypothesis should therefore be interpreted as a proposition about representation effects, not as a guarantee of universal predictive superiority.

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9 Implications for geomorphometry, terrain analysis, and environmental modelling

The scale-mosaic hypothesis has implications that extend beyond one family of algorithms. Most importantly, it suggests that the prevailing treatment of scale in geomorphometry remains incomplete. Scale is commonly acknowledged as important, yet it is still most often incorporated into terrain analysis through globally selected scales. In this respect, the scale-mosaic framework challenges a longstanding operational default and proposes that spatially heterogeneous scale selection should be treated as a viable, and in some settings preferable, alternative.

This matters in two ways. The first is representational. Scale mosaics provide a mechanism for collapsing extensive scale-spaces while retaining local relevance. They therefore offer a way to reduce the redundancy of dense multiscale predictor sets without erasing the possibility that different locations require different representation scales. The second is interpretive. Key-scale rasters reveal the geography of characteristic scale and may therefore yield direct scientific insight into the organization of landforms, process domains, and topographic transitions.

The framework also encourages a closer alignment between geomorphometry and process geomorphology. If topography is understood as an expression of process, then the scales used to represent topographic properties should not be imposed globally without good reason. The scale-mosaic framework does not resolve the problem of scale matching automatically, but it does acknowledge that the problem is spatially heterogeneous. In that sense, it is as much a conceptual repositioning of scale in geomorphometry as it is a set of methods for producing predictors.

There is a broader methodological implication as well. Selecting scales by maximizing fit to a response variable has always carried some degree of logical circularity. Such methods may improve prediction, but they mean that the representation of the independent variable is determined partly by its observed relation with the dependent variable. A terrain-driven scale-selection framework offers a more internally consistent alternative because representation is grounded first in the properties of the terrain itself. The heterogeneous framework does not assume that optimal representation is defined by predictive performance alone; rather, it treats representation and modelling as related but distinct evaluation domains.

10 A research agenda for testing the hypothesis

The scale-mosaic hypothesis now requires broader and more systematic testing.

First, environmental modelling comparisons should be expanded across more domains, including vegetation and habitat modelling, landform classification, geologic mapping, hydrological modelling, erosion and landslide susceptibility, and hazard analysis. These studies should compare mosaics not only against unscaled predictors but against strong homogeneous baselines, including wrapper-selected stacks.

Second, landscape diversity must be evaluated explicitly. Tests should span glaciated lowlands, fluvial landscapes, mountainous terrain, low-relief plains, coastal settings, anthropogenic landscapes, and planetary surfaces. The hypothesis predicts that benefits should increase with scale heterogeneity, but this remains to be quantified.

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Third, key-scale rasters should be treated as scientific outputs rather than ancillary products. Future work should test whether key-scale patterns correspond to mapped landforms, process domains, lithology, land cover, soil units, drainage organization, or field-observed geomorphic transitions.

Fourth, information density should be assessed using multiple metrics. Entropy, redundancy, spatial autocorrelation, contrast, feature counts, feature area, object fragmentation, transferability, and model importance may each capture different aspects of scale-space information. No single metric is likely to be definitive.

Fifth, the structure of scale signatures deserves further study. Signature shape, multimodality, peak ratios, monotonicity, and the number of salient extrema may provide additional information about nested landforms and process superposition. Scale mosaics based on one extremum may not capture all relevant structure in complex signatures and these additional data may provide a diagnostic basis for deciding on scale partitions. Classes of signature shape in particular offer an attractive and potentially geomorphically meaningful dimension for multiscale interpretation.

Finally, scale-space partitioning should be investigated systematically. Existing evidence suggests that local/broad or local/meso/broad partitions can improve interpretation and modelling. However, methods are needed for selecting partitions in ways that are conceptually meaningful, computationally efficient, and transferable across landscapes. Here again, development of a scale-signature shape classification may provide a way forward.

11 Conclusions

This paper has formalized the scale-mosaic hypothesis as a framework for heterogeneous scale selection in geomorphometry and DEM-based terrain analysis. The argument begins from a simple observation: many LSPs are scale dependent, yet the dominant multiscale workflow still selects scales globally and applies them uniformly across space. In heterogeneous landscapes this is difficult to justify.

Scale mosaics offer a different way to collapse scale-space. Rather than retaining a sparse subset of homogeneous layers, the mosaic selects a locally optimized key scale for each grid cell and stores the LSP value measured at that scale. The associated key-scale raster records the spatial distribution of characteristic scales. This construction allows scale to vary according to local topographic context.

The scale-mosaic hypothesis proposes that such representations can provide greater scale-space information density, better correspondence with spatially heterogeneous process scales, and equal or improved modelling performance relative to homogeneous multiscale alternatives. Existing evidence supports several components of this proposition. Characteristic scales are spatially structured. Heterogeneous scale representations can be constructed for multiple LSP families. Scale mosaics contain information from more of the sampled scale domain than sparse homogeneous subsets. Partitioned mosaics appear especially promising. In environmental modelling, terrain-driven scale mosaics have matched or exceeded homogeneous scale-selection strategies that were optimized using the response variable.

The hypothesis remains open to testing and refinement. Its value does not depend on every implementation outperforming every alternative. Rather, it depends on whether spatially heterogeneous scale representation provides a more faithful and

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useful way to represent terrain in landscapes where characteristic scales vary. If the hypothesis proves robust, it may encourage a broader shift in geomorphometry: scale should no longer be treated as a uniformly applied afterthought, but as a spatially distributed property of topographic representation.

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References

Behrens, T., Zhu, A.-X., Schmidt, K., and Scholten, T.: Multi-scale digital terrain analysis and feature selection for digital soil mapping, Geoderma, 155, 175–185, https://doi.org/10.1016/j.geoderma.2009.07.010, 2010.

Coric, M. and Lindsay, J. B.: Information density of geomorphometric scale mosaics, manuscript in review, Geomorphology.

Coric, M., DeVries, B., and Lindsay, J. B.: Testing heterogeneous scale mosaics for multiscale geomorphometric modelling: A prairie pothole wetland prediction case study, manuscript in preparation.

Deng, Y., Wilson, J. P., and Bauer, B. O.: DEM resolution dependencies of terrain attributes across a landscape, International Journal of Geographical Information Science, 21, 187–213, https://doi.org/10.1080/13658810600894364, 2007.

Drăguţ, L., Eisank, C., and Strasser, T.: Local variance for multi-scale analysis in geomorphometry, Geomorphology, 130, 162–172, https://www.sciencedirect.com/science/article/pii/S0169555X11001413, 2011.

Fisher, P., Wood, J., and Cheng, T.: Where is Helvellyn? Fuzziness of multi-scale landscape morphometry, Transactions of the Institute of British Geographers, 29, 106–128, https://doi.org/10.1111/j.0020-2754.2004.00117.x, 2004.

Florinsky, I. V.: An illustrated introduction to general geomorphometry, Progress in Physical Geography: Earth and Environment, 41, 723–752, https://doi.org/10.1177/0309133317733667, 2017.

Gallant, J. C. and Wilson, J. P.: Primary Topographic Attributes, in: Terrain Analysis: Principles and Applications, edited by Wilson, J. P. and Gallant, J. C., pp. 51–85, John Wiley & Sons, Inc., New York, 2000.

Goodchild, M. F.: Scale in GIS: An overview, Geomorphology, 130, 5–9, https://doi.org/10.1016/j.geomorph.2010.10.004, 2011.

Grohmann, C. H.: Effects of spatial resolution on slope and aspect derivation for regional-scale analysis, Computers & Geosciences, 77, 111–117, https://doi.org/10.1016/j.cageo.2015.02.003, 2015.

Grohmann, C. H., Smith, M. J., and Riccomini, C.: Multiscale analysis of topographic surface roughness in the Midland Valley, Scotland, IEEE Transactions on geoscience and Remote Sensing, 49, 1200–1213, https://doi.org/10.1109/TGRS.2010.2053546, 2010.

Lindeberg, T.: Temporal Scale Selection in Time-Causal Scale Space, Journal of Mathematical Imaging and Vision, 58, 57–101, https://doi.org/10.1007/s10851-016-0691-3, 2017.

Lindeberg, T.: Spatio-Temporal Scale Selection in Video Data, Journal of Mathematical Imaging and Vision, 60, 525–562, https://doi.org/10.1007/s10851-017-0766-9, 2018a.

Lindeberg, T. P.: Principles for automatic scale selection, in: Handbook of Computer Vision and Applications, Three-Volume Set, vol. 2, pp. 239–274, Academic Press, 1 edn., ISBN 978-0-08-092365-9, https://shop.elsevier.com/books/handbook-of-computer-vision-and-applications-three-volume-set/jahne/978-0-08-092365-9, 1999.

Lindeberg, T. P.: Dense Scale Selection Over Space, Time, and Space-Time, SIAM Journal on Imaging Sciences, 11, 407–441, https://doi.org/https://doi.org/10.1137/17M114892, 2018b.

Lindsay, J., Wang, Y., and Coric, M.: Elevation residual analysis with scale mosaics, Zenodo, https://doi.org/10.5281/zenodo.15306905, conference Name: Geomorphometry 2025, 2025.

Lindsay, J. B.: Keynote presentation: The case for locally scale-optimized land-surface parameters, in: Geomorphometry 2023, Iași, Romania, 2023.

Lindsay, J. B., Cockburn, J. M. H., and Russell, H. A. J.: An integral image approach to performing multi-scale topographic position analysis, Geomorphology, 245, 51–61, https://doi.org/10.1016/j.geomorph.2015.05.025, 2015.

https://doi.org/10.5194/egusphere-2026-4402
Preprint. Discussion started: 21 August 2026

Lindsay, J. B., Francioni, A., and Cockburn, J. M. H.: LiDAR DEM Smoothing and the Preservation of Drainage Features, Remote Sensing, 11, 1926, https://doi.org/10.3390/rs11161926, 2019.

Miller, B. A., Koszinski, S., Wehrhan, M., and Sommer, M.: Impact of multi-scale predictor selection for modeling soil properties, Geoderma, 239-240, 97–106, https://doi.org/10.1016/j.geoderma.2014.09.018, 2015.

Newman, D. R., Lindsay, J. B., and Cockburn, J. M. H.: Evaluating metrics of local topographic position for multiscale geomorphometric analysis, Geomorphology, 312, 40–50, https://doi.org/10.1016/j.geomorph.2018.04.003, 2018a.

Newman, D. R., Lindsay, J. B., and Cockburn, J. M. H.: Measuring Hyperscale Topographic Anisotropy as a Continuous Landscape Property, Geosciences, 8, 278, https://doi.org/10.3390/geosciences8080278, 2018b.

Newman, D. R., Cockburn, J. M. H., Drăguţ, L., and Lindsay, J. B.: Evaluating Scaling Frameworks for Multiscale Geomorphometric Analysis, Geomatics, 2, 36–51, https://doi.org/10.3390/geomatics2010003, 2022a.

Newman, D. R., Cockburn, J. M. H., Drăguţ, L., and Lindsay, J. B.: Local scale optimization of geomorphometric land surface parameters using scale-standardized Gaussian scale-space, Computers & Geosciences, 165, 105 144, https://doi.org/10.1016/j.cageo.2022.105144, 2022b.

Newman, D. R., Saurette, D. D., Cockburn, J. M. H., Dragut, L., and Lindsay, J. B.: Assessing spatially heterogeneous scale representation with applied digital soil mapping, Environmental Modelling & Software, 160, 105 612, https://doi.org/10.1016/j.envsoft.2022.105612, 2023.

Pike, R. J.: The geometric signature: Quantifying landslide-terrain types from digital elevation models, Mathematical Geology, 20, 491–511, https://doi.org/10.1007/BF00890333, 1988.

Pike, R. J., Evans, I. S., and Hengl, T.: Chapter 1 Geomorphometry: A Brief Guide, in: Geomorphometry, edited by Hengl, T. and Reuter, H. I., vol. 33 of *Developments in Soil Science*, pp. 3–30, Elsevier, https://doi.org/10.1016/S0166-2481(08)00001-9, 2009.

Schmidt, J. and Andrew, R.: Multi-scale landform characterization, Area, 37, 341–350, https://doi.org/10.1111/j.1475-4762.2005.00638.x, _eprint: https://rgs-ibg.onlinelibrary.wiley.com/doi/pdf/10.1111/j.1475-4762.2005.00638.x, 2005.

Wang, Y., Grohmann, C. H., Cockburn, J. M. H., and Lindsay, J. B.: A multiscale topographic position classification system based on scale-adaptive maximum elevation deviation, manuscript in preparation.

Wood, J.: The geomorphological characterisation of digital elevation models, PhD, University of Leicester (United Kingdom), Leicester, https://figshare.le.ac.uk/articles/thesis/The_geomorphological_characterisation_of_Digital_Elevation_Models_/10152368?file=18296414, 1996.

Wood, J.: Chapter 14 Geomorphometry in LandSerf, in: Geomorphometry, edited by Hengl, T. and Reuter, H. I., vol. 33 of *Developments in Soil Science*, pp. 333–349, Elsevier, https://doi.org/10.1016/S0166-2481(08)00014-7, 2009.