Aerial Photography: A Rapidly Evolving Tool for Ecological Management

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Ecological monitoring and management require detailed information over broad spatial scales. Historically, such information was often acquired through manual interpretation of aerial photographs. As traditional methods of analyzing aerial photographs can be time-consuming, subjective, and can require well-trained interpreters (who are currently in short supply), new approaches must be explored for collecting this ecological information. First, we discuss the benefits and challenges of using aerial photographs for ecological management. We then examine the eight fundamental characteristics used in photograph interpretation and discuss their ecological relevance. Third, we investigate the feasibility of digital-analysis methods (often used for analysis of satellite imagery) for providing more objective, consistent, and cost-effective results. We end with several examples of how the unique information from aerial photographs can aid in solutions to emerging challenges in ecological research and management, and how they may be further used with supplementary data sets.

Keywords: ecosystem management, historical information, high spatial-resolution imagery, digital image analysis and interpretation, remote sensing

The use of aerial photography to assess and map landscape change is a crucial element of ecosystem management. Aerial photographs are ideal for mapping small ecosystems and fine-scale landscape features, such as riparian areas or individual trees (Fensham and Fairfax 2002, Tuominen and Pekkarinen 2005), because they often possess a high level of spatial and radiometric (tonal) detail. Aerial photographs also provide the longest-available, temporally continuous, and spatially complete record of landscape change, dating from the early 1930s in some cases. As a result, aerial photographs are a source of valuable historical information on vegetation cover and condition (Cohen et al. 1996, Fensham and Fairfax 2002). Aerial photographs can reduce costs involved in mapping, inventorying, and planning (Paine and Kiser 2003), and, as such, are used for applications ranging from forest inventories, disturbance mapping, productivity estimates, and wildlife management (Avery and Berlin 1992). Thus, many important management decisions are routinely made on the basis of maps derived from aerial photographs (Cohen et al. 1996, Paine and Kiser 2003).

Proliferation of satellite imagery over the past few decades has influenced the use and perceived utility of aerial photography in several contrasting ways (table 1). Satellite imagery, with its broad spatial coverage and regular revisitation frequency, has provided researchers and managers with a cost-effective alternative to aerial photography. This alternative has contributed to a shift in emphasis of university curricula, and the training of spatial analysts, away from aerial photographs (Sader and Vermillion 2000) and more toward digital platforms. However, a lack of long-term satellite imagery (prior to the 1970s) limits the use of satellite data in change-detection analyses to the past three decades, underscoring the value of longer-term aerial photographs. In addition, the spatial resolution of the most widely available and free satellite imagery is generally coarser than that of aerial photographs (Tuominen and Pekkarinen 2004). One important development associated with the recent emphasis on satellite imagery, however, has been the advent of a wide range of digital image analysis techniques. While many of these techniques were originally developed for satellite imagery, they have also expanded upon the range of analysis techniques now available for aerial photographs.

Despite the many advantages of aerial photographs, there are specific challenges for using them, especially with respect to manual aerial photograph interpretation. Although manual interpretation by highly trained individuals remains one of the most effective and commonly used approaches for classification of aerial photographs (Wulder 1998), this technique relies greatly on the personal experience, knowledge, and expectations of the interpreter for a given location. Thus,

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Table 1. Comparative advantages and disadvantages associated with traditional film-based aerial photography, digital aerial photographs, and satellite imagery.

Type of photography	Advantages	Disadvantages
Aerial photography	Long time series (1930s and onward) Often high spatial resolution Primary basis for many maps used by agencies Stereoscopic view capturing height and topography Comparatively easy to capture Can be collected at any time or place Easy to tailor to specific needs (photograph scale, spatial, spectral, and temporal characteristics, etc.) Less atmospheric interference (due to lower altitude)	Individual photographs have limited spatial coverage Large time effort required for processing (film development and orthorectification) Photographs often variable among flight lines (environmental and positional variability) Difficulty in standardizing image contrast and rectification Manual interpretation can be subjective Spatial coverage dependent on needs of original project Quality of photograph dependent upon weather Spatial coverage dependent on needs of original project Limited or inconsistent metadata (mainly historic photographs)
Aerial digital photography	Easy to tailor to specific needs (photograph scale, spatial, spectral, and temporal characteristics, etc.) Image access is immediate (viewable during flight) Exposure conditions can be optimized in flight Digital storage is reusable (memory devices) Can be copied repeatedly without loss of data Radiometric calibration procedures are extensive Many digital cameras record positional data (global positioning system)	Shorter time series (1990s and onward) Individual photographs have limited spatial coverage Quality of image dependent upon weather Spatial coverage dependent on needs of original project Often have coarser resolution than film-based photographs Large amount of digital space required to store high-resolution images
Satellite imagery	High temporal frequency Systematic collection Broad spatial coverage Easily accessible (many images are free) Many image analysis methods developed Broader spectral range Typically have more rigorous radiometric calibration Metadata precise and easily obtained Current high resolution data provides continuous land cover data (facilitates comparison to historic photos)	Shorter time series (1970s and onward) Often have coarser resolution than film-based photographs Higher spatial resolution data are expensive Large amount of digital space required to store high resolution images Atmospheric correction usually needed (weather) Sensors are not serviceable (due to their location in space) Greater atmospheric influence (captured outside atmosphere)

human interpretations are subjective, and are vulnerable to inconsistency and error. In addition, resource management agencies are beginning to face a shortage of well-trained interpreters, especially those whose skills have ideally been combined with years spent in the field. As a result, there is a need for new approaches to reduce or eliminate these difficulties associated with traditional aerial photograph analysis to help foster its continued and evolving use.

Motivated by the unique information available from aerial photographs, by recent developments in digital analysis techniques, and by what we believe is a need to reinvigorate training and research in ecological management using aerial photography, we review and develop several important themes. First we provide an overview of aerial photographs, along with a generalized discussion of the challenges inherent with their use, and highlight the ecological importance of the eight essential characteristics used in traditional, manual interpretation. Second, we examine how digitized aerial photographs may be analyzed using alternative analysis techniques to provide more consistent information using more efficient means. We end with several examples of emerging ecological management questions that may be best addressed through the use of aerial photographs. Our overall aim is to highlight the unique value that aerial photographs hold for ecosystem management, and explore possible synergies between new technologies and traditional approaches for using aerial photographs.

Aerial photography basics

Aerial photography is the collection of photographs using an airborne camera. Photographs are essentially a representation of the reflectance characteristics (relative brightness) of features recorded onto photographic film. More specifically, reflectance is recorded by the film's emulsion, which is a layer of light-sensitive silver halide crystals on backing material (for black and white photographs), or a series of emulsions (for color photographs; Wolf and Dewitt 2000, Lillesand et al. 2004). Filters also play an important role in determining the type of information recorded by the camera, and consist of a layer of dyes that selectively absorb and transmit target wavelengths. As in any camera, the film is protected until briefly exposed to light through a lens and filter, during which the silver halide crystals (and dyes) react based on the degree of reflectance from features on the ground that fall within the camera's frame, or field of view (Lillesand et al. 2004). Aerial photographs are captured most commonly as panchromatic (black and white), color, or false-color infrared; however, various types of electromagnetic radiation can also be recorded onto photographic film with the use of different emulsions and filters (Cohen et al. 1996).

Obtaining a photograph with an appropriate amount of contrast, or tonal variation, is paramount for accurate analysis or interpretation. Photographic contrast, or the range of values within the photograph, is a product of the film's emulsion type, the degree of exposure to light, and the film development conditions (Wolf and Dewitt 2000). Contrast is also directly related to radiometric resolution, which is defined as the smallest detectable difference in exposure, or measurable difference in reflectance levels (Lillesand et al. 2004). Generally, when exposure and development conditions are ideal, any decreases in radiometric resolution (smaller detectable differences in tone) will result in greater contrast within the photograph.

Of fundamental importance to the quality of aerial photographs is the camera used to obtain the images. Two broad types of airborne cameras are used: film-based and digital cameras (table 1). The most common type of camera used in aerial photography is film-based, single-lens frame cameras, with lenses of high geometric quality to minimize distortion (Wolf and Dewitt 2000). Aerial cameras must take photographs of features from great distances; therefore, the focal length of the lens (the distance from the lens to the film) is fixed to focus reflectance from effectively infinite distances away (Wolf and Dewitt 2000, Lillesand et al. 2004). The most common focal length for aerial cameras is 152 millimeters, but longer focal lengths may be used to capture imagery from higher altitudes, which are used primarily for aerial mosaics. Aerial digital cameras are quite similar in structure; however, reflectance is recorded with electronic sensors and stored digitally instead of on film. Although images captured by airborne digital cameras are not technically photographs, such imagery will be referred to as digital photography in this article.

The scale of an aerial photograph is a function of camera focal length and the flying height of the aircraft (Cohen et al. 1996), and most often refers to the conversion between a unit distance represented on the photograph and the number of equivalent units on the ground. Scale can also refer to the finest or highest spatial unit of resolution (grain), as well as the size of the entire scene (extent). The finest unit of resolution on a film-based photograph is not represented by uniform pixels (the smallest spatial unit of resolution within an image), as is the case with airborne digital imagery or satellite imagery, but is instead dependent upon the clusters of silver halide grains within the emulsion, which tend to be irregularly sized and unevenly distributed (Lillesand et al. 2004). As silver halide grains are smaller than most digital detectors, film-camera resolution is often finer than digital-camera resolution (Paine and Kiser 2003). However, the resolution of some current digital cameras can be comparable to film resolutions for systems with similar formatting and scale (Lillesand et al. 2004). Also of relevance to scale is consideration of the minimum mapping unit (MMU), which represents the size of the smallest entity to be mapped. However, this is often established as part of the classification system; both the scale of the photographs and the grain will influence definition of the MMU (table 2).

Photographs can be grouped according to their geometry as either vertical or oblique. Vertical photographs are taken parallel to the ground, with the optical axis of the camera situated directly downward. Because of the variable conditions during photograph collection (wind, turbulence, etc.), true vertical orientation is rarely achieved, and photographs almost always contain some degree of tilt. Tilted images are obtained on an angle, meaning that the optical axis of the camera diverges more than 3 degrees from the vertical (Jensen 2000), shifting the normally central focus of a photograph to another location, and thereby shifting the positions of certain features (Avery and Berlin 1992). In contrast, oblique photographs are acquired with a deliberate deviation from a vertical orientation. Although oblique landscape photographs can predate aerial photographs by decades (acquired from high points on the landscape such as land surveys or airborne) and can often provide rare historical information, they are more challenging to analyze systematically. Therefore, our discussion is limited to the use of vertical aerial photographs.

Two closely related disciplines with distinct end goals are involved in aerial photography: photogrammetry and aerial photograph interpretation. Photogrammetry (also called metric photogrammetry) is concerned with obtaining exceptionally precise quantitative measurements from aerial photographs, whereas photographic interpretation (or interpretive photogrammetry) focuses more on the recognition, identification, and significance of features on photographs (Wolf and Dewitt 2000, Paine and Kiser 2003). Photogrammetric methods are highly precise, and much of this discipline evolves around techniques to address and correct photographic errors. Interpretation methods have also been extensively developed and are relevant for understanding the types of ecological information, which can be derived from

Table 2. Common minimum mapping units and the general uses of photographs taken at different scales (Lillesand et. al 2004).

Uses and mapping units	1:40,000	1:20,000–1:4800	1:2400–1:1200
Common minimum mapping units	General land cover; 2 to 4 hectares	Forest stand polygons, vegetation communities, habitat patches, natural disturbances (e.g., landslides)	Individual trees, stream reaches
Common uses	General resource assessment and planning over large areas	Mapping of tree species, agricultural crops, vegetation communities, and soil surveys. Historical photographs were often taken at these scales.	Intensive mapping and monitoring of specific entities, such as damage surveys

aerial photographs. Principles of both disciplines are addressed here, but we focus primarily on photograph interpretation and classification.

Digitization of aerial photographs

Film-based photographs may be converted into digital format through scanning (Wolf and Dewitt 2000). Photogrammetric scanners convert analog images (or continuous tone photographs) into digital files represented as pixels (Wolf and Dewitt 2000). The cost of the highest quality scanners can be considerable, from $25,000 to $100,000 (Aronoff 2005); however, scanners under $10,000 can still produce digital products suitable for most interpretation needs, with the exception of precise photogrammetric work. An inherent drawback of scanning photographs is a potential loss of radiometric or tonal variation and spatial resolution from the photograph (Warner et al. 1996), and as a result, second- or third-generation products will not have the level of detail found in the original. Thus, it is crucial that the scanning resolution (both spatial and radiometric) is sufficient to create a geometrically and visually accurate representation of the original aerial photograph. It is primarily the physical characteristics of the film and the scale of the aerial photograph that will limit the resolvable scanning resolution (dots per inch, table 3; Jensen 2000); however, other factors, such as atmospheric clarity and scene contrast, can also affect resolution of photographs. Scanning at a resolution too low will result in loss of information, whereas a needlessly high scanning resolution will lead to digital files of enormous size and storage requirements. Scanning has the advantage that any subsequent interpretation can be assisted by software capable of providing systematic analyses (Fensham and Fairfax 2002).

Overview of basic photographic errors

Despite the great utility of aerial photographs, it is important to note that errors often occur during the collection and digitization of photographs that can limit their use (Cohen et al. 1996, Tuominen and Pekkarinen 2004). While these inaccuracies rarely render aerial photographs useless (provided appropriate precautions were taken during photographic acquisition, storage, and digitization), an understanding of the major sources of error is crucial for accurate analysis. Typically, for many ecological management purposes, geometric errors and radiometric errors are most relevant, as they may inaccurately represent photographic features. Therefore, we examine the major sources and types of photographic errors in four main categories. Errors can be classified as either geometric or radiometric in origin, and either systematic or random in form (table 4).

Geometric errors (or positional errors) alter the perceived location and size of features on a photograph. Geometric errors can occur due to problems with the equipment used to capture the photographs (Wolf and Dewitt 2000), stability of the airborne platform, flying and shutter speeds (Paine and Kiser 2003), and the location being photographed. Relief displacement, in particular, results in features at higher elevations appearing larger than similarly sized features located at lower elevations (Aronoff 2005). However, relief displacement is also what enables three-dimensional viewing of overlapping stereo pairs (called parallax), which aids manual photograph interpretation by allowing visualization of topographic relief (Jensen 2000, Paine and Kiser 2003, Aronoff 2005). A stereo pair is defined as two adjacent photographs from the same flight line that possess some amount of image overlap, usually 60% (Paine and Kiser 2003). While geometric distortion is utilized in the manual interpretation process, geometric errors are often problematic for digital analyses.

Radiometric errors (errors in tone or color) can be caused by the vantage point, condition, and calibration of the camera, as well as the types of filter and film emulsion (Jensen 2000). Environmental sources of radiometric variability include the hour and season of image capture (which affects the angle of the sun), which can cause shadow or glare. Atmospheric interference as a result of clouds and haze can also cause radiometric errors (Cohen et al. 1996). In addition, the geometry of the airborne platform (camera) can cause variability in brightness values, which can be further confounded by sun angle, platform position, and topographic variation (Cohen et al. 1996, Paine and Kiser 2003). Next, we present some basic methods for addressing the most relevant geometric and radiometric errors, recognizing that additional errors can also affect aerial photographs (table 4).

Table 3. Relationship between scanner resolution and ground resolution for multiple scales of aerial photography. Adapted from Jensen (2000).

Digitizer detector IFOV (scanner resolution: spot size)		Pixel ground resolution as a function of photographic scale (meters)					
Dots per inch	Micrometers	1:40,000	1:20,000	1:9600	1:4800	1:2400	1:1200
200	127.00	5.08	2.54	1.22	0.61	0.30	0.15
600	42.34	1.69	0.85	0.41	0.20	0.10	0.05
800	31.75	1.27	0.64	0.30	0.15	0.08	0.04
1200	21.17	0.85	0.42	0.20	0.10	0.05	0.03
1500	16.94	0.67	0.34	0.16	0.08	0.04	0.02
2000	12.70	0.51	0.25	0.12	0.06	0.03	0.02

Note: IFOV, instantaneous field of view.

Table 4. Common errors associated with the use of aerial photographs. Source: Adapted from Paine and Kiser (2003).

Type of error	Systematic	Random
Geometric		
Distortion	Lens distortion (more common on old photographs)[a] Image motion compensation (typically occurs on high spatial resolution photographs)	Film or print shrinkage (occurs on historic photographs or film)[a] Atmospheric refraction of light[a]
Displacement	Earth curvature[a]	Topographic/relief displacement (more obvious in mountainous areas) Tilt displacement (especially problematic for oblique photographs) Detector error (roll, crab/yaw, pitch)[a] Typically affects older aerial photographs
Radiometric		
Sensor	Exposure falloff Sensing geometry	Bidirectional reflectance (e.g., hot spot effects and mutual shadowing)
Environment	Atmospheric (haze)	Clouds Sun angle (worse for photographs taken off solar noon)

a. Errors generally considered to be negligible or accounted for during processing.

Error correction

For most digital classification and mapping purposes, it is necessary to use orthorectification procedures to correct for geometric displacement errors and provide spatial reference. Orthorectification involves the spatial manipulation of a digitized or digital photograph into an orthophoto, by adding vertical map (*x, y,* and *z*) coordinates to accurately represent distances, angles, and areas (Lillesand et al. 2004). This process is different than georeferencing, which solely assigns horizontal map (*x, y*) coordinates to an image. The most basic need for correcting these geometric errors is a reference data set, or a set of reference coordinates, which is commonly derived from existing topographic maps, GIS (geographic information system) data sets, satellite imagery, orthophotos, or orthophoto mosaics. Highly accurate reference and control data are critical because the spatial accuracy of the corrected product is dependent upon the geometric quality of the reference layer. Reference data are used to orientate the photograph to its true position through the selection of ground control points (GCPs)—locations or features easily identifiable on both the reference data and uncorrected photograph, ideally distributed evenly throughout the entire scene. The target aerial photograph (lacking spatial reference) is shifted or warped to its true spatial position by resampling the data using the GCPs as a guide. Various resampling algorithms exist—most common are the nearest neighbor (simplest and fastest), bilinear interpolation, and cubic convolution (yields the smoothest image, yet is computationally intensive), and these are available within most standard orthorectification software. It is important to note that orthorectification and georeferencing are time consuming, particularly for large sets of aerial photographs. Geometric correction of historic photographs can be particularly challenging, because changes in land cover and feature position over time can make GCP identification difficult. In addition, orthorectification procedures can distort spectral data, therefore spatial referencing is commonly applied postclassification.

The most common radiometric procedures applied to digitized aerial photographs typically involve manipulation of the image histogram (distribution of the tonal and radiometric values for the entire photograph or image). Contrast, or histogram stretching, is often used to improve the visual appearance of aerial photographs, and alters the frequency distribution of original pixel values to allow for better differentiation among unclear or hazy regions. Contrast enhancement includes procedures such as image dodging (equalizes dark and light areas across an image for a monochromatically balanced product), saturation, and sharpening. Photographs acquired at various times within the day are particularly problematic, as radiometric response is highly dependent upon sun angle and atmospheric conditions. Normalization techniques are available that work to identify similar land-cover types across photographs taken under various conditions and resample problematic photographs based on the tonal distributions of photographs with more ideal contrast. Histogram manipulation can be achieved using a variety of software such as Adobe Photoshop and most standard image processing and analysis programs.

Aerial photograph interpretation

Traditionally, information has been obtained from aerial photographs through manual interpretation (table 5). Over the years, manual interpretation has evolved from plastic overlays on hard-copy images to soft-copy systems and digitized photographs (Avery and Berlin 1992, Wolf and Dewitt 2000). Regardless of the approach, manual interpretation typically involves delineation of polygon boundaries (areas with similar properties) on a stereo pair and the subsequent classification of those polygons by a trained specialist. A variety of key characteristics are used to delineate and classify polygons, including tone or color, shape, size, pattern, texture, shadows, site, and context (figure 1; Avery and Berlin 1992, Lillesand et al. 2004). Interestingly, these characteristics can help identify important ecological features and can also be linked to various concepts in ecology (table 6). Although we discuss these eight characteristics separately, manual interpretation often requires some combination of these characteristics for feature identification.

Tone or color. Variation and relative differences in tone or color on photographs (radiometric properties) are the primary characteristics enabling feature identification. For example, foliage of deciduous tree species often reflects more light

Table 5. Comparative advantages and disadvantages of manual aerial photograph interpretation, conventional pixel-based analysis, and object-based classification techniques.

Type	Advantages	Disadvantages
Manual interpretation	Can be fairly accurate Limited image preparation required Commonly used to make resource management maps Comprehensive, uses human knowledge to make logical decisions Well-developed discipline (in some regions)	Subjective Time consuming Inconsistent among interpreters Expensive Dependent upon interpreters' experience Shortage of well-trained and experienced interpreters Accuracy standards vary widely
Pixel-based classifiers	Systematic Consistent Repeatable Many well-developed and affordable software packages are available Pixel-based accuracy assessment techniques are well developed	Arbitrary analysis unit (pixel) Tend to use only spectral information Less suited to analysis of high spatial resolution imagery Can produce speckled "salt and pepper" results
Object-based classifiers	Systematic Consistent Repeatable Ability to incorporate multiple scales Better mimics human perception of objects Integrates attributes important to landscape analysis (tone, shape, size, texture, context)	Object creation is difficult and can produce unexpected results Less availability and affordability of software Better suited to high spatial resolution imagery Object-based accuracy assessment procedures less developed

and appears brighter than coniferous species, which are darker because they reflect less light (figure 1). Tone or color can also be used to make inferences related to the state or the condition of certain features. Surficial deposits with dark tones may suggest poor drainage (water absorbs and transmits energy) and high organic-matter content, in comparison to lightly colored deposits that are reflective and usually indicate well-drained materials such as sand or gravel (Keser 1979). Technically, both tone and color relate to the intensity of light reflected by an object or feature; with tone used to describe grayscale variation on black and white (panchromatic) photographs, and color referring to the hue characteristics of color photographs (Avery and Berlin 1992). A result of complex interactions between the sun's radiation and the Earth's surface, tone and color are greatly influenced by conditions during photograph acquisition and digitization (Avery and Berlin 1992). Therefore, it is important to compare photographic tone and color and land-cover relationships between adjacent photographs or among all photographs used in a project.

Size. The relative and absolute size of objects or features is important not only for identifying both cultural and natural features but also for making ecological inferences about the features being identified. Size is particularly significant because of its direct connection to spatial scale, a fundamental component of understanding ecological patterns and processes. In ecological applications, scale is often used to describe the size, or spatial unit, of a focal entity or phenomenon. Analyses can focus on multiple spatial scales, such as at the scale of individual tree crowns, where the sizes of individual trees differ according to age class (figure 1); or at broader scales, where the relative sizes of habitat patches can provide indicators of suitability for different species (Turner et al. 1989). The absolute size of various features may also have important ecological implications. Riparian vegetation width is an illustration of this point, because riparian size is important for quantifying local protection afforded to a stream, such as in highly modified watersheds (Roth et al. 1996). Furthermore, spatial characteristics such as the distribution of canopy gaps and other forest structural properties can be identified from high spatial-resolution aerial photographs, which are important parameters relevant for many wildlife species (Fox et al. 2000).

Shape. Shape is particularly useful for identifying cultural features, which usually have a specific geometry and obvious edges, as well as many other natural features with distinctive forms (Avery and Berlin 1992). In particular, shape can be used to identify various geomorphic features such as fluvial landforms (e.g., fans or oxbow lakes), glacial landforms (e.g., drumlins or cirques), or organic landforms (e.g., swamps or fens), and disturbances such as landslides (Keser 1979). A relevant characteristic over a wide range of spatial scales, shape results from the contrast between the border of a specific feature or patch and the surrounding environment. At fine scales, aerial photograph interpreters look for recognizable shapes to classify features, such as crown shape to identify tree species, or geometry to identify anthropogenic features (e.g., the long, linear characteristics of roads; figure 1). At broader scales, patch shape can be used to distinguish between anthropogenic land use (logged stands or agriculture) and natural disturbances (fire or insect damage), and can provide indicators of landscape complexity. Interestingly, patch edges influence many important ecosystem and landscape processes such as habitat quality (Ries et al. 2004); edge characteristics such as shape therefore play an important role in understanding the interaction between landscape structure and ecological processes.

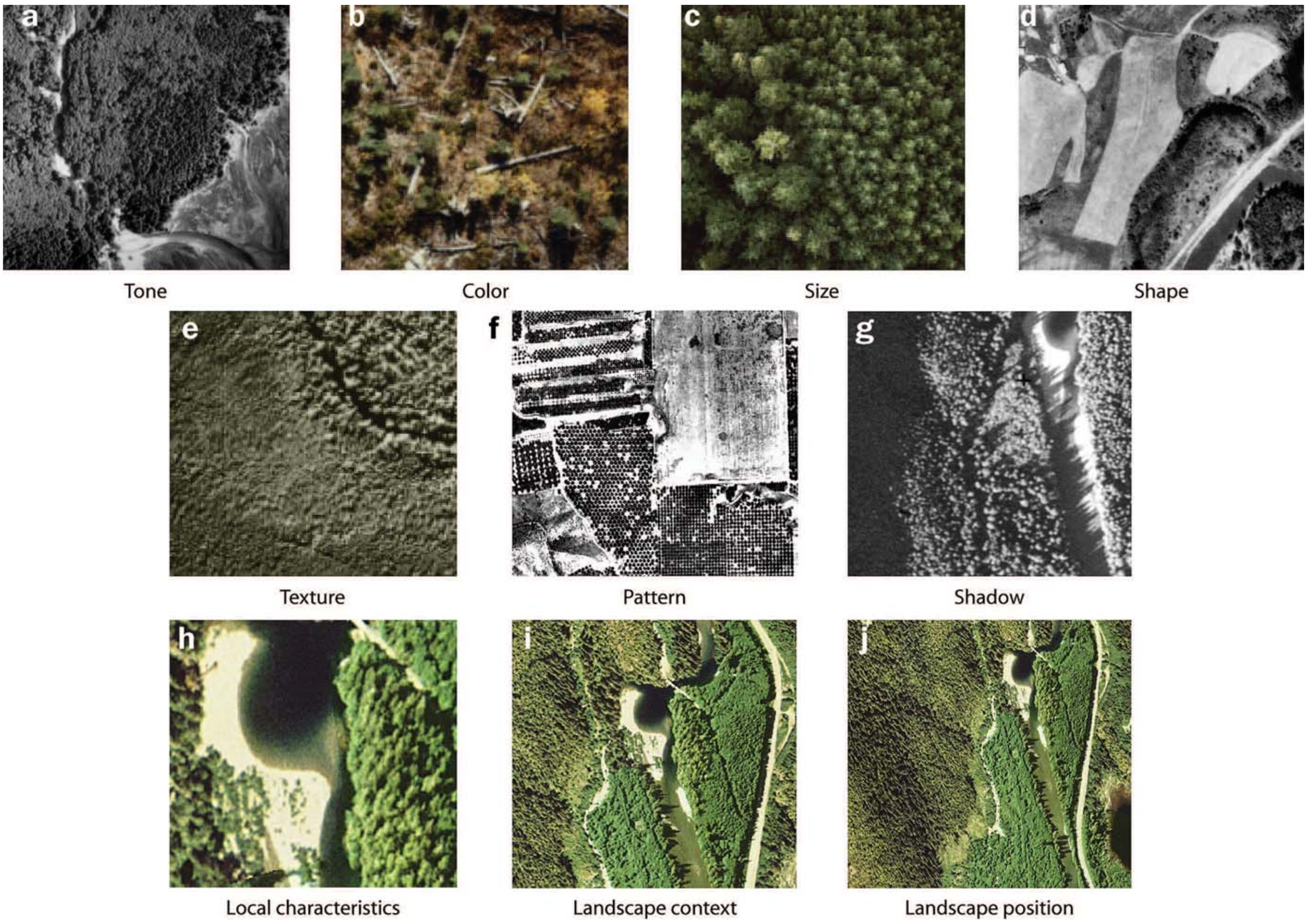

*Figure 1. (a) Darker tree species near water are coniferous (***Tsuga heterophylla***); lighter tree species are deciduous (***Alnus rubra***). (b) Yellow trees are trembling aspen (***Populus tremuloides***); green trees are Sitka spruce (***Picea sitchensis***). (c) Larger trees on left side of photograph are mature western hemlock (***T. heterophylla***); on right side of photograph trees are smaller, immature western hemlock (***T. heterophylla***). (d) The long, linear object is a road and the irregular geometric patches are cultivated areas. (e) The rough texture in the top right corner of the photograph is indicative of a mature stand with high stand complexity; the smooth textured stands at the bottom are more uniform in height, indicating a younger stand. (f) Various patterns indicating different agricultural uses (crops, vineyards, etc.). (g) Tree shadows cast on the river help species identification (***T. heterophylla** and* **Thuja plicata***). (h) Lighter color of trees suggests presence of deciduous vegetation. (i) Presence of river indicates riparian area. (j) Shadow on left side of photograph suggests decrease in elevation toward the right side of photograph.*

Texture. Image texture is particularly useful for landform and land-cover classification, and is related to variation in biophysical parameters, landscape heterogeneity, and forest structural characteristics (Wulder 1998). It can also be helpful for prediction of species distribution and biodiversity patterns (St-Louis et al. 2006, Fischer et al. 2008). Aerial photograph interpreters describe texture in terms of smoothness and roughness, and the relative variation of this attribute can be used to distinguish between features (Avery and Berlin 1992). For example, the textures of different forested stands provide visual indicators of stand complexity, age, and crown closure (figure 1). Texture is commonly used to help differentiate between tree species (Trichon 2001) and other features that may otherwise have similar reflectance and dimensional characteristics (Avery and Berlin 1992, Lillesand et al. 2004). Texture is also useful for identifying soil types, rangeland vegetation, various hydrologic characteristics, and agricultural crops (Lillesand et al. 2004). Texture generally focuses on fine-scale variation (the pixel level) in particular by emphasizing the spatial arrangement and frequency of variation in image tone (Paine and Kiser 2003, Lillesand et al. 2004). However, texture is directly related to spatial scale, meaning textural characteristics will change as the scale of the photograph changes (Avery and Berlin 1992), although textures generally appear smoother as scale increases, or as the altitude of the aircraft increases.

Pattern. In contrast to texture, which focuses on tonal variation at a fine scale (the pixel level), pattern is concerned with the spatial arrangement of features or patches over coarser scales (Paine and Kiser 2003). Spatial pattern can be random or systematic (Jensen 2000) and is often very distinctive for many anthropogenic and natural features (Avery and Berlin 1992). For instance, trees in an orchard have a systematic pattern (figure 1), whereas the distribution of gaps in old-growth forests may have a more random pattern. In this regard, spatial patterns of features in a photograph can provide important clues for identification of land use, forest structural characteristics, and disturbance types—all important to understand in terms of ecosystem management. In addition, patterns of different habitat or land-cover patches can influence movement of organisms and materials across the landscape (Gergel and Turner 2002). The comprehensive approach of aerial photograph interpretation can also be particularly useful for gaining an understanding of the connections and interactions between spatial patterns of natural features and landscape structure. One such case used aerial photograph interpretation aided by information collected in the field to describe the connection between the spatial patterns of ribbon forests and the structure, lithology, and topography of the landscape in Glacier National Park, Montana (Butler et al. 2003).

Shadow. Shadows may either help feature identification, by providing information about an object or feature's height, shape, and orientation, or hinder classification, by obscuring parts of the landscape. Shadows provide profiles or silhouettes of certain objects (Tsai 2006) and are particularly useful for small feature identification, topographic enhancement, or features otherwise lacking tonal contrast (Avery and Berlin 1992, Aronoff 2005). The shadows cast by the crowns of different trees on a contrasting background can be helpful for species identification (figure 1); however, excessive shadows can obscure features (Jensen 2000) and distort tone, color, and shape (Tsai 2006). Modern aerial data are typically collected within two hours of solar noon (Jensen 2000), thus limiting the extent of shadows; however, shadows are often problematic on historic aerial photographs.

Site and context. Site and context (sometimes termed association or location) are used in manual interpretation, yet are often defined using overlapping and closely related concepts (Avery and Berlin 1992, Wolf and Dewitt 2000, Paine and Kiser 2003). Despite the confusion surrounding these characteristics, they relate quite well to three very distinct yet fundamental ecological concepts: patch characteristics, landscape context (Pearson 1993), and landscape position (Swanson et al. 1988). Because these concepts are widely recognized as important in ecological planning and management, we propose refining the ideas around site, context, and association to these three ecologically relevant and well-defined concepts. Local characteristics (at the feature or patch level) are important because they reflect fine-scale, microclimatic conditions (Chen et al. 1999). In contrast, landscape context (conditions surrounding the feature or patch) is essential because the properties of neighboring patches can affect a wide range of ecological phenomena, such as prediction of species for conservation planning (Mazerolle and Villard 1999). In the specific case of identifying high-quality bird habitat, characteristics of the landscape surrounding a patch can even have more influence on patch occupancy than any characteristic within the patch itself (Pearson 1993). Finally, landscape position (the location of the feature or patch in relation to topography) is critical because characteristics such as slope, aspect, and moisture gradients affect processes such as vegetation patterns and natural disturbance events (Swanson et al. 1988, Dorner et al. 2002).

Local characteristics, landscape context, and landscape position are often used in tandem by an interpreter to identify various features. For instance, the identification of riparian forests could be facilitated by the presence of deciduous vegetation (patch characteristic), its adjacency to a river (landscape context), or the fact that riparian forests occur in areas of lower relative elevation than upland forests (landscape position; figure 1). Classification of bog types in higher latitudes can also be aided by using local traits, such as vegetation type and vegetation presence or absence; contextual attributes, such as collapse scars and water pools; and positional traits, including relative height (indicating permafrost thickness) and hummocks (Vitt et al. 1994).

New approaches for aerial photograph analysis

Recently developed automated methods of image enhancement and classification (typically applied to satellite imagery) are potentially quite useful for aerial photographs, and may help address some of the problems with traditional photo interpretation (table 4). Automated analysis of digital imagery has evolved over time into two main approaches (table 5). Conventional automated image analysis has been conducted on a per-pixel basis, whereby enhancement and classification algorithms are applied to individual pixels. While "pixel-based" approaches are relatively easy to implement, the representation of landscape elements with pixels may be less relevant for nonrectangular features. A contrasting approach is that of object-based analysis (Hay et al. 2003). The basic premise of the most common object-based approaches is that neighboring pixels of similar properties are merged to form objects (using a process termed segmentation) before analysis (Blaschke 2004). The resulting objects can then be classified using quantitative characteristics such as tone and color, size, shape, texture, and contextual relationships (Hay et al. 2003), similar to the approach used by manual interpreters. This method is particularly promising because it can create objects over multiple target scales and sizes to represent the hierarchical nature of ecosystems.

One of the advantages of automated digital techniques is the ability to analyze explicitly and separately the individual characteristics of photographs. Digital-edge enhancement is one technique that can help identify shape characteristics by emphasizing abrupt changes in brightness values between pixels to identify edges (table 6). Edge-detection techniques have been useful for identifying fine-scale features from aerial photographs with distinctive shapes such as roads (Rowe and Grewe 2001), and linear geologic features such as faults, joints, and folds (Karniele et al. 1996). Edge-detection techniques allow researchers to extract geologic features with results comparable to that of manual interpretation, and improve upon manual interpretation for identification of linear features larger in size (Karniele et al. 1996). Similarly, texture information is often incorporated by calculating separate texture layers (such as homogeneity or variance) on the basis of the gray-level co-occurrence matrix (table 6), and has been helpful for improving the accuracy of vegetation classifications (Franklin et al. 2000, Jauhiainen et al. 2007). Textural derivatives of this nature can extract various components of image texture (beyond the smooth-rough scale used by manual interpreters) and were useful for exploring drainage-driven vegetation dynamics in various mire sites using recent and historic aerial photography (Jauhiainen et al. 2007). Variogram analysis, which identifies autocorrelation over space (table 6), is another useful tool that can help identify spatial ranges (sizes) of ecological features or processes, such as disease influence in potato crops (Johnson et al. 2003).

Often, photograph- or image-analysis approaches incorporate multiple automated techniques, or use techniques that target multiple characteristics of features, to improve classification capacity or accuracy. Mapping individual tree locations is one goal that can be aided by the use of both thresholds (table 6) to target specific tone or color characteristics, and window-based operators to target specific-sized objects related to tree crowns; however, aerial photographs of high spatial resolutions are required (Uuttera et al. 1998). Similarly, wavelets use tone, size, and shape characteristics to identify patterns over multiple spatial or temporal scales (table 6), and can be used to identify vegetation distribution characteristics such as woody-plant encroachment over time (Strand et al. 2006). Object-based classification is another multiscale approach particularly promising for vegetation and landscape analysis (Blaschke 2004), and was useful for investigating shrub encroachment dynamics (Laliberte et al. 2004). Shrubs greater than 2 square meters in size were delineated from digitized aerial photographs using specific sizes (segmentation scales), and then classified using tone and contextual relationships among neighbors and over multiple spatial scales (table 6) with accuracies of 87% (Laliberte et al. 2004). Since this approach mimics manual interpretation to a certain extent, and is better suited for high spatial-resolution imagery (table 5), this tool is particularly promising for aerial photograph analysis.

The integration of digital terrain information with aerial photographs and other remotely sensed imagery can expand mapping capabilities (Florinsky 1998). Local characteristics, such as microrelief, can be obtained from highly detailed terrain information (table 6), and are useful for fine-scale applications such as individual tree identification (Leckie et al. 2003). For example, incorporation of lidar with high spatial resolution aerial photographs greatly improves the identification of individual trees and other forest parameters, which is useful for forest inventory purposes (Leckie et al. 2003). Similarly, broad-scale landscape positional information (such as slope, aspect, and moisture indices; table 6) can be particularly useful when paired with digital imagery for classifying vegetation distributions in heterogeneous environments (e.g., Hoersch et al. 2002). Overall, there is much potential for automated approaches and ancillary data sets to aid analysis and classification of digital or digitized aerial photographs.

Accuracy assessment

The value of any analysis or classification is highly dependent upon its accuracy. Thematic maps derived from the classification of remotely sensed imagery are routinely used for mapping land cover and monitoring land-cover change. However, "poor" quality or inaccurate land-cover maps can render such maps unsuitable for operational purposes (Foody 2002), and inaccuracies can lead to ineffective, costly, or even detrimental ecosystem management decisions (Gergel et al. 2007, Thompson et al. 2007). Establishing the accuracy of a classified product is one of the biggest challenges associated with classification or map production, and is largely a result of the uncertainties regarding the measurement of accuracy, and a lack of strict assessment guidelines suited to this purpose (Foody 2002). Consequently, establishing the accuracy of maps derived from either manual interpretation or automated analysis can be problematic.

Accuracy is often estimated by comparison between the classified photograph or image and reference data derived from field data or alternative thematic data sets (Foody 2002). Collecting field reference data can be problematic for remote or difficult-to-access locations, and can be expensive over large areas. Furthermore, some attributes identified on photographs may not be measurable from the field (e.g., spatial distributions of patches), and field measurements may be even less accurate than photographic mapping (e.g., canopy gaps; Fox et al. 2000). As a result, reference data collected from the field are often limited. More common is the use of previous interpretations or other thematic data sets to assess the accuracy of new classifications. However, the accuracy of such original interpretations is rarely verified beyond limited ground checking, and many forest inventory maps are irregularly updated (Thompson et al. 2007). Furthermore, the misclassification of such inventories can reach a rate as high as 60% (Thompson et al. 2007). Establishing the accuracy of historic aerial photograph classification has additional challenges, because historic reference data are often nonexistent, and subsequent land-cover changes frequently render field data collection impossible. Current stump survey data or historic land survey data such as the Public Land Survey may provide supplemental reference point data (Manies and Mladenoff 2000). However, in many cases, the accuracy of analyses from historical aerial photographs cannot be rigorously quantified. There-

Table 6. The eight primary aerial photograph characteristics used in manual interpretation, related ecological features, and examples of corresponding digital methods which may also be useful for analysis of these attributes

Characteristic	Related ecological features	Automated technique	Description
Tone or color: the relative brightness or hue of pixels	Natural and anthropogenic feature identification (vegetation, soils, urban, etc.)	Contrast manipulation	Modifies the manner in which pixel brightness values are displayed by splitting values (thresholding), grouping values together (density/level slicing), or adjusting their range of sensitivity (contrast stretching; see Cohen et al. 1996).
Size: the number of pixels that aggregate to form a group of pixels with similar characteristics	Vegetation age, structure Habitat suitability Urban features and land use	Variogram analysis	Variograms measure spatial auto-correlation by plotting the variance between pixels as a function of distance. Related to correlograms (see Johnson et al. 2003).
Shape: the manner in which related groups of pixels are arranged; the complexity of a feature or patch border	Natural feature identification (irregular shape) Anthropogenic feature identification (geometric shape)	Spatial feature manipulation	Highlights specific areas of tonal variation by emphasizing large areas of brightness change (low pass spatial filters), local detail (high pass spatial filters), abrupt changes in brightness values (edge enhancement) or components of spatial frequency (Fourier analysis; see Karniele et al. 1996, Rowe and Grewe 2001)
Texture: the frequency of change in tone among pixels; smoothness or roughness	Vegetation identification Biodiversity estimates Surface properties (natural and anthropogenic features)	GLCM (gray-level co-occurrence matrix) texture	Based on the GLCM, which summarizes the frequency distribution of various combinations of pixel brightness values. Texture images are created by applying algorithms to each pixel within an image (see Franklin et al. 2000, Jauhiainen et al. 2007).
Pattern: the spatial arrangement and repetition of features (groups of pixels) across an area	Land use Natural and anthropogenic disturbance Habitat suitability Landscape structure	Wavelets	Mathematical function that divides imagery into frequency components at multiple scales (see Strand et al. 2006).
Shadow: the combination of dark or "shadow" pixels adjacent to brighter pixels	Natural and anthropogenic feature identification Orientation (landscape, feature, etc.)	Digital terrain correction	Digital terrain/elevation information is used to standardize imagery for brightness variation caused by topography (see Sheperd and Dymond 2003).
Local characteristics: Conditions at the feature or patch level	Microclimate Local species identification Habitat suitability	Elevation models	Elevation information, particularly at high spatial resolutions, can be highly useful for classification of local features (as well as land cover over broader scales; see Dorner et al. 2002, Leckie et al. 2003).
Landscape context: Conditions adjacent to or surrounding a feature or patch	Land use Habitat suitability	Object-based analysis	Quantitative contextual rules can be used to classify objects/patches based on surrounding conditions, and conditions measured over multiple spatial scales. Also measures characteristics related to tone, size, shape, and texture (see Hay et al. 2003).
Landscape position: feature or patch location within the landscape, often in relation to topography	Topographic location Vegetation patterns Natural and anthropogenic disturbance patterns	Spatial GIS data sets	Ancillary data sets can provide a wide range of additional data, useful for image analysis (see Florinsky 1998, Hoersch et al. 2002).

fore, any accuracy assessment requires careful consideration of the availability and quality of reference data. Further, data requirements may differ depending on whether pixel- or object-based classification was employed.

In general, two broad types of accuracy should be considered: positional and classification accuracy. Positional accuracy relates to the location of features and their borders, and is important because even small errors in positional accuracy can have significant implications for analyses, such as the measurement of river channel movement through time (Hughes et al. 2006). Positional accuracy of manual interpretation also has important implications, yet polygon position can be highly variable, and is often dependent upon interpreter style. "Lumpers" are interpreters who tend to delineate larger polygons, thereby "lumping" areas of somewhat similar character together. In contrast, "splitters" delineate smaller polygons recognizing areas with subtle differences. Point and dot grids and line transect methods may be less problematic and subjective than manual interpretation in terms of positional accuracy; however, these approaches are often time consuming and are primarily used for spatial estimates of cover (Paine and Kiser 2003). While it is arguable that the imposition of abrupt boundaries on natural ecosystems composed of gradients is inherently inaccurate, this type of generalization is a necessary simplification for classification. Methods that do assess border accuracy generally involve rigorous field data collection (Hughes et al. 2006), and therefore, positional accuracy is rarely addressed.

Classification accuracy is related to the labeling of classes, and can vary greatly among different classes. For instance, older stands and those of pure species composition can generally be identified using photograph interpretation with higher accuracy than mixed species or second-growth stands (Thompson et al. 2007). Additionally, the accuracies of individual species identified using manual interpretation can range from complete misclassification, to near perfect (Thompson et al. 2007). While many methods of class-accuracy assessment exist, the most common form of class-accuracy representation is through the use of a confusion, or error matrix (Stehman 1997). An error matrix provides a cross-tabulation of the relationships between the reference data ("truth") and the classification data on a per-class basis for a sample of locations over the entire extent (Foody 2002). Recent work has explored the utility of alternative digital approaches for accuracy assessment including pixel- and polygon-based approaches for high spatial-resolution imagery (Thompson and Gergel 2008), as well as accuracy assessments conducted across multiple spatial scales (Gergel et al. 2007). Although a full discussion is beyond the scope of this article, accuracy assessment should suit the data type, classification technique, and classification scheme used, and must work to ensure accuracy is represented as truthfully and completely as possible (Stehman 1997, Foody 2002).

Conclusions

Routinely used for decades by resource managers (Cohen et al. 1996, Johnston and Lowell 2000), aerial photographs provide a spectrum of useful information to managers and researchers unique among types of ecological inventory information. Although ecosystem management dilemmas require a different knowledge base and skill set from aerial photograph usage, the potential for aerial photographs to help answer many current and pressing ecological questions is considerable. Reconstruction of historic ecosystem conditions from archived aerial photography can be important for characterizing the historic range of variability within ecosystems, which is useful for development of strategies aimed at managing for ecological integrity (Landres et al. 1999). Historic information from aerial photographs can also be helpful for monitoring landscape and ecosystem change (Swetnam et al. 1999), such as tracking declines in foundation species (Trichon 2001, Ellison et al. 2005). Furthermore, archival aerial photographs provide a source of spatially continuous historic information, unlike several other historical reconstruction techniques that lack precise or continuous spatial coverage (e.g., dendrochronology or pollen samples; Macdonald et al. 1991, Foster et al. 1992).

Although aerial photographs are certainly useful for a variety of purposes, it is important to emphasize that they have a distinct place within remote sensing and ecology. As discussed throughout this review, there are numerous challenges associated with aerial photograph interpretation and analysis, as is found with any other types of remotely sensed data. However, it is crucial for researchers and managers to identify the strengths and weaknesses of different remotely sensed data sets, and use this knowledge to make informed decisions regarding spatial data set selection. While aerial photographs are not suited for every mapping purpose, particularly over broader spatial scales (Nichol et al. 2006), they do offer a wealth of ecological information that may be used to answer a wide range of critical ecological questions. Our objective for this article was to highlight specific uses of aerial photographs for ecosystem research and management, and outline some possible future directions for integration of their unique benefits into ecosystem management applications involving remote sensing.

As the demands for spatially explicit data by resource managers and scientists continue to grow (Cohen et al. 1996), the use of digitized or digital aerial photographs and the development of automatic analysis techniques can improve the accuracy, consistency, and efficiency of results (Harvey and Hill 2001). Given the unique and important information available from aerial photographs, and the challenges inherent with their interpretation, further research and training with emerging image-analysis techniques will be essential to fully avail ourselves to the potential of aerial photographs to assist in ecological management. Promise in combining optical imagery such as aerial photography, with detailed terrain data and other ancillary data sets, may also be of particular importance to explore for a variety of ecosystem applications. Overall, the continuous and rapid advances in the field of remote sensing will only further our ability to use aerial photographs for ecological means.

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