Should You Use a Digital Camera in Your Research?

Vince Gutschick, Dept. of Biology, 3AF, New Mexico State University, Las Cruces, NM 88003.
vince@nmsu.edu

Digital cameras offer some significant advantages for researchers over traditional cameras performing silver-based photography. Several come to mind immediately to most people. One is the ability to incorporate images into documents rapidly. Another is the in-the-field assurance that those field photos that are so expensive or impossible to retake are recorded properly. Prices of digicams, as we may term them, have come down sharply every year, and performance has increased by many measures. Promoters of digicams highlight their advantages, but there are downsides. The balance of pros and cons in one's own research may be hard to strike before one undertakes a major expense. I offer the following comparisons to help in this judgment.

Spatial resolution and its cost-effectiveness

Background: Details in an image are resolved as differences between pixels separated by a given distance. To account for differences in sizes of subjects, it is useful to measure resolution as the total number of line pairs that can be distinguished across an image. Consider completely contrasting features, such as alternating black and white lines. No imaging system (lens plus film or digital charge-coupled device) will preserve all the contrast, but retention of detail above some minimum allows distinction. (Whether or not quantitative measures, such as vegetative cover, can be usefully composed with degraded contrast is another matter.) A human observer, using brightness as a cue, can distinguish lines differing by as little as 2% in luminance (Hecht 1924). A picture element, or pixel, has other attributes for discrimination - namely, (1) hue, loosely what we call color; we can distinguish about 1000 hues, and (2) saturation, or the purity of hue; desaturation is addition of white, which is equal amounts of red, green, and blue (R, G, B) primary colors. Hue, saturation, and brightness or value (H, S, V) have quantitative definitions when one can measure R, G, and B (Myler and Weeks 1993; see also my Web site, http://biology-web.nmsu.edu/vince/course.on.color.pdf). Light that is not too bright or too dim (Klinker 1993, p. 38) optimizes our ability to discriminate colors (H, S, V or equivalent R, G, B combinations), to about 20,000 different colors.

Lines are quoted directly for digicams, as in 2048 x 1536 pixels in a typical 3-megapixel (MP) camera. (Recall that a true *mega*byte is 2^{10} or 1,048,576 bytes; the same meaning of *mega* applies in digital photography.) Silver-based films vary in resolution, up to about 80 line-pairs per mm (2880 lines across the 36-mm long dimension of a 35-mm frame). This is not a simple measure. Contrast (and resolution, therefore) degrades not suddenly at one fine scale, but continuously as one progresses from comparing widely-spaced to comparing closely-spaced pixels. Effective resolution in silver-based films is commonly quoted down to the separation where contrast is down to about 10%. The imaging area in a digicam is a charge-coupled device, or CCD, which inherently is composed of discrete pixels. This does not guarantee anything near 100% contrast between adjacent pixels. Some light is scattered between CCD pixels, and high light in one pixel also "blooms" electronically into nearby pixels (Klinker 1993; Beynon and Lamb 1980; it is also discussed in popular magazines as an issue of quality among different digicams). A quick rule of thumb is that modest-speed silver film in 35-mm format has an effective resolution of about 2500 x 1700 pixels. Some films are finer-grained with higher resolution, sometimes remarkably so (Kolonia 2001). Silver-based films have simple and effective optical engineering to avoid light scattering among adjacent areas, called halation. Commonly, extra dyes absorb excess light and are removed in film processing.

Resolution is not only determined by the imaging medium. The lens commonly limits resolution in less-expensive cameras, to as little as 1000 line pairs across a frame or less. Resolution inevitably degrades toward the edges of any image: a number of aberrations occur in all lenses (Williams and Becklund 1972). For any given lens, a wider aperture, such as one needs to gather more light in low light conditions, displays more of its optical aberrations that degrade resolution. Overall, medium- to high-priced cameras of either digital or silver-based types show lens-limitations to resolution only at larger apertures. Very small apertures can also be highly deleterious to resolution. Light diffracts around the edges of the aperture. The well-known diffraction formula variously developed by Newton, Young, and Airy, describes the radius about a point (on the film or CCD) into which intensity "spills" when a lens is used at numerical aperture *F*:

$$r_0 = 1.22\ \lambda\ F$$

Apertures are quoted as fractions of lens focal length - e.g., f/4 denotes an aperture that is 1/4 the focal length. At the same relative aperture, lenses of different focal length are equally effective in exposing film (or recording on a CCD) at a chosen shutter speed. For a 35-mm camera with a lens of 'normal' focal length (50 mm) used with an aperture of f/22, diffraction limits the resolved angles in an image to about 0.015 mm. This is coarser than a silver-based film image (about 0.006 mm). In a digicam, the CCD is commonly smaller than 35-mm film. If it is 2/3 as large, the lens focal length is 2/3 as long and the diffraction radius is 1.5 times larger. Not only is diffraction over a larger area, but each distance on the focal plane covers 1.5 times as many pixels as on 35-mm film. Thus, degradation occurs over 2.25 times as many pixels in each linear dimension.

A concise critical discussion of limitations in digital imaging and the best use of digital imagery may be found in Chieco *et al*. (1994).

Pro: A 4-MP digital camera is approximately equivalent in resolution to a good-quality camera using silver-based film. For comparable number of optical features, the traditional camera is still cheaper (about $500 vs. $800), but the price differential will likely disappear or reverse within several years. There are additional costs of operation (media, film, printing) that differ between digital and film-based cameras; these will be discussed shortly.

Timely verification of image quality

Pro: All but the very cheapest digicams have liquid-crystal displays (LCDs) that can be used to verify each image. One not only avoids the horror of finding that film is absent or has not wound; one can also verify that exposure and composition are acceptable.

Con: Lower-end digicams, and most mid-range ones, use rangefinders to present the scene to your eye. When the subject is close, an optical offset or parallax occurs. This can be detected after the fact on the LCD display, but it means retaking the image. Higher-end digicams present a viewfinder image that is either taken directly from the CCD imager, or that is a direct view through the lens generated by a splitting prism. Cameras with through-the-lens viewing are called SLRs (single-lens reflexes), similarly to common silver-based cameras, or, sometimes, ZLRs (zoom-lens reflexes, because almost all digicams have a fixed lens that cannot be swapped for one of another focal length; a zoom is the only way to get variable focal lengths).

Critical focus is harder to verify. Autofocus does not always choose the portion of the subject you wish to choose. Also, it may be important to you to control the depth of field (range of distances in focus). You may wish this to be large, to record all of a scene in acceptable focus, or you may wish it to be small to isolate a single flower, for example. Most digicams have imaging areas (their CCDs) that are smaller than the equivalent film-based camera. Correspondingly, they use lenses of shorter focal length that have inherently greater depth of field at any given exposure (f-stop). This is an advantage, unless one wants to deliberately restrict depth of field in order to emphasize the principal subject against a background. Depth of field is readily previewed in a film-based SLR. Low- to medium-priced digicams typically lack depth-of-field preview, in which the aperture is closed down to show the scene as it will actually be recorded. One can view the final image, after the fact, which adds some time to composing the image and perhaps re-shooting it. In most digicams, preview is on LCD displays that are too grainy (at most, 170,000 pixels) to judge critical focus. Higher-end digicams have either optical through-the-lens finders, or with an LCD display one can zoom in the EVF (electronic viewfinder) to verify focus. One temporarily loses the sense of composition.

Cost of recording media and need to carry different media

Pro: Memory media of high capacity (say, 32 MB to 1 GB) are offered for the great majority of digicams. A 3-megapixel (3-MP) camera that uses 24-bit (3-byte) color per pixel has a raw image size of 9 MB, but JPEG image compression commonly reduces storage greatly, to the order of 1.2 MB (at high quality; commonly as little as 0.1 MB at low quality). JPEG compression is "lossy," in that some details of high spatial frequency (close spacing) are lost (Netravali and Haskell 1995). This loss is virtually unnoticeable in most applications. Thus, one expects that in most applications a 64 MB card (under $50) will suffice for about 53 high-quality JPEG images with 3 megapixels. (All cost estimates in this article are based on prices in ads of major mail-order retailers in their own literature or in photography magazines.) Memory media can be erased and reused. Slide film and processing for 200 images would cost about $100 but these are not reusable, and failed images cannot be erased with reuse of storage.

Con: Physical media (compact flash RAM, memory sticks, etc.) do go obsolete (floppy disks are nearly there). This may be late in the useful life of a digicam (say, 10 years, rather shorter than the lifetime of a film-based camera). A medium lost by accident means the loss of many images; loss of a large-capacity medium is also expensive (up to $500). It is prudent to download images to a laptop or other mass-storage device, even in the field. When image accuracy in individual pixels is important, as in images my group analyzes to get leaf area index, uncompressed images should be used, reducing storage capacity dramatically and correspondingly raising the needed investment in storage media (100 images would need a 1 GB microdrive for $300, if one's digicam accepts it, or two 512 MB media such as compact flash RAM for about $350).

Microdrives don't function at extremes; they depend on air to float the head, which (at least as of last year) limited them to altitudes of 3,500 m (12,000 ft) or so. In the field, compact flash RAM or memory sticks are more reliable. And, speaking of field conditions, cold will significantly increase battery needs.

In the lowest light, using silver-based films is still advantageous. CCD imaging cannot achieve as high "speeds" (ASA or ISO indices) as the fastest silver-based films. CCDs top out at about 1600 ASA in the high-end, while many films can be pushed to 3200. (The new Fuji Provia 400F slide film retains very high resolution when pushed to ASA 1600; Kolonia 2001.) In low light, electronic or Johnson noise degrades CCD images; noise-removal software is improving, we note. Both limitations are inherent, arising from the lower ability of silicon to absorb light than the corresponding ability of sensitizing dyes used in silver photography.

Silver-based films do show some color biases ("warm," "magenta," etc.: see, various popular photographic magazines, e.g., Anon. 2001) but CCDs are not neutral. They tend to a slight blue tinge, again based on the absorption or action spectrum of silicon; many digicams allow adjustment of the white balance, which is recommended. CCDs also record off-axis light (at the edges of a scene) differently than on-axis light; the same effect in silver-based films has been largely engineered out (see above). Some high-end digicams, notably the Olympus E-10 and E-20, direct the light perpendicular to the CCD to avoid this problem.

The cost of using electronic imaging is large power consumption, mostly for the LCD viewfinder and/or LCD monitor. A high-resolution digicam taken on an expedition might demand a high-capacity rechargeable lithium-ion battery pack costing about $400. While not very portable, a relatively inexpensive car or marine battery can be used; the maximum input voltage to the digicam should not be exceeded, so that a simple voltage regulator may be needed.

The cost of hard-drive space to store digital images on a desktop computer is admittedly low. It is heading toward $2 per GB, or about $0.03 per 5-MP image in uncompressed TIFF. A new drive to handle many images still represents a modest capital investment and some time to install it. The maintenance cost of large drives, as in scans for viruses or defragmentation, can be substantial in time, adding hours per scan.

Ability to view, edit, and send images in timely fashion

Pro: Images can be downloaded to existing computers with little or no additional equipment. Perhaps a $15 memory-medium reader is needed; software for viewing and a variety of common image manipulations is usually included with a digicam. The software also allows conversions among common file formats, such as JPEG, GIF, and TIFF. In contrast, a silver-based photo must first be scanned. This takes time, and the hardware, while coming down in price, is still a significant investment (about $400 for a scanner capable of 2500 dots per inch or more). Some information is degraded during scanning. Consider two adjacent pixels, one of green leaves with some soil, and another of light-colored soil. Their respective (red, green, blue) = (RGB) values might be (35, 55, 50) and (100, 100, 100). A linear measure, such as albedo, is unchanged by averaging the pixels. However, a nonlinear index such as I = (G-R)/(G+R), similar to the normalized-difference vegetation index (Huete *et al*. 1994), is distorted. Pixel 1 has I = 20/80 = 0.25, pixel 2 has I = 0, and the averaged pixel has I = (77.5 - 67.5)/(77.5+67.5) = 0.07, which is far less than the average I = 0.125.

As part of this direct availability, digital images are readily pasted into documents. Often, they can be sent with only modest delay from locations of field research; one might, for example, email images from a nearby town at night after a day of remote field work. Problems that show up only after processing images might be caught during a field campaign. Duplicate images are readily sent to collaborators, as digital files. Once on the hard drive, images may be sorted in viewing software. Pictures on film are readily sorted, too, but must be scanned first, a lengthy process.

Con: Almost no one has a computer monitor that can show the full resolution of a moderate-quality digital image, either an image captured directly digitally with a digicam or a silver-based image that has been scanned. The highest resolution monitors in common use are 2048 x 1536 pixels, and this only at 21"; smaller monitors have correspondingly lower resolution). This is notably less than the approximately (2500 to 3000) x (1700 to 2000) lines in a quality image. One can zoom in on the image in the viewing software, but one loses the sense of the image as a whole. To see a digital image in full, one must print it, which is slow and somewhat expensive for ink and paper (as much as $1 per 8" x 10" = 203 mm x 254 mm print). This cost exceeds that of film and processing for a typical 35-mm slide (about $0.50). One can print a digital image onto a slide, with somewhat costly hardware (about $4000 for a film recorder, somewhat less for a lower resolution "slidemaker" of lower color accuracy), but this gives up many advantages of digital imagery. Furthermore, the range of brightnesses that one can distinguish in a print by reflection is only about 15 to 1, which is equivalent to about 4 bits of resolution (per primary color). In a slide, it is about 50 to 1, or about 6 bits equivalent. A full description of distinctions by the human eye may be found in Nelson (1966). (This discussion points out that imaging or scanning in 10, 12, or 16 bits per color rather than the current *de facto* standard of 8 bits is absurd "featurism," invisible to users.)

Bringing up a high-resolution image on a computer monitor can be slow, tens of seconds for a 12 MB image. It is slow, inconvenient, or, on older computers and monitors, effectively impossible to compare many digital images side-by-side on a monitor, while ordinary slides or prints can be compared by spreading them on a light table. Software such as ACDSee allows a monitor to act as the equivalent of a light table, though images must be opened at full resolution to assess quality.

Flexibility of composition and exposure of images

Background: This is a very broad topic that has generated voluminous discussion in the popular literature, as well as the great diversity of cameras. Nonetheless, some clear distinctions exist silver-based and digital cameras. My discussion here focuses on field use, while many researchers also image subjects in a microscope. Both digital and silver-based cameras are offered with adapters for use on a microscope, with more or less convenience.

Con, part 1: *choices of focal length*: One difference is that digicams, other than a few that are built on traditional cameras and that are extremely expensive ($5,000 and more), have a single lens permanently affixed. This is typically a zoom lens with an optical zoom ratio of 2.5- to 4-fold. (One Olympus model, the C-2100UZ, has a 10x optical zoom and stabilized lens, albeit with only low to moderate resolution of 1.92 megapixels.) Digital zooming is available, but with great image degradation; digital zooming by 3-fold fills 9 pixels with the contents of 1 pixel, leading to pronounced jaggedness or pixellation in an image. The optical zoom range, which I would claim as the only useful range for full-frame views, does not match the ranges available in demountable SLR lenses (from 7.5 mm fisheye lenses to 800 mm super- telephotos; the 'affordable' range is easily 28 mm to 300 mm). Some digicams can use supplemental lenses; these are typically higher-priced cameras. Zoom ability may be limited by vignetting with these screw-on lenses. Specialized lenses, such as fisheye, are not available except for very expensive true SLR digicams. Some digicams, such as the Nikon Cool[pix series, have good macro capability, in native mode and more so with supplemental lenses.

Pro, part 2: *control of shutter speed and aperture*: Digital cameras are readily programmed to choose aperture and shutter-speed combinations, or to leave them to the user, much as are ordinary silver-based cameras. The fastest effective shutter speed is higher in the more expensive digicams, as fast as 1/18,000 s in the Olympus E-20 (manufacturer's specifications). Top-of-the-line silver-based cameras are as fast as 1/8,000 s, but unlikely to become faster. The high speeds have no use or very limited uses for most people, it should be noted. However, the highest speed at which a flash can be synchronized is important. Digital cameras more readily attain high 'sync' speeds than cameras using film, or they achieve the same sync speed in lower-cost cameras.

Con: While automatic focus and aperture selection is useful, there are situations in which one wants control of aperture in order to control depth of field. This is inherently more difficult to verify in digicams, as noted earlier.

Pro, part 3: *adjustment of color quality and special effects*: Inherently, one can adjust color attributes (hue, saturation, and value or any equivalents such as R, G, B) of digital images. Adjustments to silver-based images require either special duplicating equipment and filters, or intermediate conversion to digital images with attendant cost and effort. Advanced adjustments, such as atmospheric corrections, require digital subtraction of path radiance (Kaufman 1989). Subtraction is impossible to do with multiplicative corrections afforded by optical filters. Only digital images can be so corrected, using custom software.

Con: A few very special effects, such as starbursts around specular highlights for artistic composition, are only practical in initial exposure and not in digital post-processing. This is a very rare need. Filters are available for a number of effects. In many digicams, one can alter the white balance to achieve a range of filter effects.

Pro, part 4: time-and-date tagging: Digital images are routinely tagged with time and date, and some cameras allow tagging with GPS coordinates. This is often important in research. In silver-based photography, three options exist but are only partly satisfactory. Manual records can be lost or become unsynchronized. On-image date imprinting loses part of the image. Electronic recording of date and time can be done on APS film (Advanced Photo System^{TM}) but APS is available almost exclusively on less-capable point-and-shoot cameras. It also uses a smaller negative, conferring somewhat lower resolution.

Taking images in rapid sequence

Pro: Some high-end digital cameras can take images as fast as 15 frames per second (fps). Limitations in movement of shutters, film, and reflex mirrors limit silver-based cameras to 3 fps (most SLRs) or as much as 8 fps (top-line SLRs).

Con: Digital cameras can sustain only short bursts at high speed, because data transfer to storage media occurs at a limited rate. In our own aerial photography, it is important to store at least 30 images taken about 1.2 s apart. Very few digicams can do this, and even fewer can do this in TIFF or raw modes that preserve all pixel information. A burst of only 3 or 4 images is a common limitation in cameras costing well over $1,000 (or 9 frames, in cameras above $20,000). (Useful hints on aerial imagery are available from the author.)

Archival quality of images

Pro: While silver-based color films use dyes that slowly oxidize, bits in a digital image change with extreme rarity. Carefully-stored Kodachrome slides have lasted with negligible degradation for 50 years, but early chromogenic slides (the other "chromes") became unusable in 1 to 2 years. Modern "chrome" films have an expected lifetime of about 50 to 90 y (Schwalberg 1982) in normal storage. (For information on archival storage, see Kodak 1999). A more common limitation to archival storage of silver-based images is poor processing. Most of us have been victimized at one time or another by low-quality processing that yielded rapidly-degrading images, usually from failure to use fresh stabilizers. Poor stabilization is not apparent in freshly-processed slides or negatives. If it is detected, restabilization is possible but is time-consuming.

Con: Bits are rather stable but formats are not. From both format obsolescence and decay of the medium (more so for magnetic media than CD-ROMs), a digital file such as an image has a useful lifetime of about 5 to 10 years (Rothenberg 1995). One can reprocess digital images every few years, converting to the newer formats. However, if one skips several generations of upgrades, digital images may become irretrievably unreadable.

Conclusions

Neither digital nor silver-based photography has the clear advantage unless one weights the decision criteria according to one's needs. Some criteria are "must-have" and should be applied multiplicatively, even as 0 (unacceptable) or 1 (fully acceptable). Others are more nearly additive and tradeable. One can and should make a scoresheet. I hope that this article makes explicit some tradeoffs that are not widely appreciated and enables researchers to make solid and cost-effective decisions. In my own work, I use both digital and silver-based photography for different purposes.

The performance attributes of both kinds of imaging continue to change, particularly rapidly for digital imaging. One must re-evaluate the technologies frequently, at least every two years, I suggest. Reviews are given frequently in popular photographic magazines (I particularly favor *Chasseur d'Images* from France, though it is not yet offered in English) and in some distributors' catalogs, such as *Digital Photography Sourcebook* offered by B&H PhotoVideo, NY. Several Web sites offer substantial reviews and discussions of digital imaging, such as www.dpreview.com, www.steves-digicams.com, and www.dcresource.com.

Please note that mention of a product does not constitute endorsement.

Literature cited

Anon. 2001. Comparatif. Chasseur d'Images **Juin-Juillet**: 52-61.

Beynon, J. D. E., and D. R. Lamb. 1980. Charge-Coupled Devices and Their Applications. McGraw-Hill, London.

Chieco, P., A. Jonker, C. Melchiorri, G. Vanni, and C. J. F. VanNoorden. 1994. A user's guide for avoiding errors in absorbency image cytometry: a review with original experimental observations. Histochemical J. **26**: 1-19.

Hecht, S. 1924. The visual discrimination of intensity and the Weber-Fechner law. J. Gen. Physiol. **7**: 241-250.

Huete, A., C. Justice, and H. Liu. 1994. Development of vegetation and soil indices for MODIS-EOS. Remote Sensing Environ. **49**: 224-234.

Kaufman, Y. J. 1989. The atmospheric effect on remote sensing and its correction. In G. Asrar, editor. Theory and Application of Optical Remote Sensing, pp. 336-428. Wiley-Interscience, New York.

Klinker, G. J. 1993. A Physical Approach to Color Image Understanding. A. K. Peters, Wellesley, MA.

Kodak. 1999. Storage and care of Kodak photographic materials. Tech Pub E-30. Eastman Kodak, Rochester, New York. (Also posted on the Web at www.kodak.com; search archival photo storage.)

Kolonia, P. 2001. Color. Pop. Photog. **Oct**.: 20 & 184-185.

Myler, H. R., and A. R. Weeks. 1993. Computer imaging recipes in C. Prentice-Hall, Englewood Cliff, NJ.

Nelson, C. N. 1966. The theory of tone reproduction. In C. E. K. Mees and T. H. James, editors. The Theory of the Photographic Process, pp. 464-498. Macmillan, New York.

Netravali, A. N., and B. G. Haskell. 1995. Digital Pictures: Representation, Compression, and Standards, 2nd Ed. Plenum, New York.

Rothenberg, J. 1995. Ensuring the longevity of digital documents. Sci. Am. **272**: 42-47.

Schwalberg, B. 1982. Color preservation update.Pop. Photog., **January**: 81-85.

Williams, C. S., and O. A. Becklund. 1972. Optics: A Short Course for Engineers and Scientists. Wiley-Interscience, New York.