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Estimating stand basal area from forest panoramas

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ABSTRACT

A common forest inventory technique involves making 360° visual scans within forests and selecting a sample of trees by assessing the horizontal angle subtended by their trunks. These samples allow quick and accurate estimates of forest stand basal area. All of the information required to complete such estimates can be obtained from high-resolution panoramic photographs of forest interiors. Stand basal area in an Alaskan birch forest was measured and the result compared to estimates of basal area made using a traditional Bitterlich visual scan in the field and an equivalent protocol performed on gigapixel images captured with a GigaPan imager. The image-based method has great precision and acceptable accuracy when tree trunks are not obscured by other trees or shrubs, when stitching is error free, and when adequate depth of field provides well focused images. This technique may have application using panoramas taken for other purposes, including historical photographs.

Keywords

basal area, Bitterlich, forestry, gigapan, photography, plotless sampling, timber cruising, timber inventory

INTRODUCTION

A primary responsibility of professional foresters is to inventory standing trees in forested tracts to determine the quantity of merchantable timber available. This requires travelling on foot and making measurements at systematically or randomly selected sampling sites, and then extrapolating to a standard unit of land area. This process is commonly referred to as timber cruising. A standard index of tree size is the cross-sectional area near the base of the trunk, known as basal area. A common unit of timber quantity within a landscape is basal area per land area, for example square meters per hectare (m^2/ha).

Tens of thousands of forested hectares are inventoried every year, potentially involving the establishment of many sampling plots and the measurement of myriad tree trunks. This immense task was forever changed in 1948 when an Austrian forester, Walter Bitterlich, published a paper describing an ingenious method which did not require laying out study plots or even measuring trees. Today, timber cruising relies heavily on Bitterlich's insight.

The Bitterlich insight

For more than a decade in the 1930s and 1940s, Bitterlich grappled with the idea that viewing trees from a single observation point might provide meaningful information about the quantity of timber in a forested stand. He knew that large tree trunks at a distance subtended the same horizontal angle of view as small trees nearby. The larger trees, dispersed farther from the observer, individually contributed more to stand basal area but were scattered across a larger area than the smaller, nearby trees. In 1947 he attended a performance of Mozart's opera "Cosi fan tutte" and later credited the impeccable logic of the music with opening his mind to the solution. Five months later he published a paper (Bitterlich, 1948) demonstrating that if he used a small angle of view as a threshold criterion for selecting trees observed from a single point, he would have a sample of trees that possessed an astonishing property.

Walter Bitterlich 1908-2008

By standing at one location in a forest, rotating 360°, and selecting all the tree trunks that subtend an angle of at least, for example, 2° (e.g., hold your thumb at arm's length, spin around, and select those trees that appear wider than your thumb), an observer will typically select all the trees that are very close, only large trees that are, for example, 10 m away, and probably no trees that are more than 30 m away. In effect, every tree selected is being sampled in a circular plot with a radius that is a function of the tree's

diameter. For example, with a 2° threshold angle, trees with a diameter of 5 cm will be selected only if they are within 1.43 m (in a circular plot of radius 1.43 m with the observer at the plot's center), all 20 cm trees will be selected only if they are in a plot of radius 5.73 m, and all 60 cm trees will be selected in a plot of radius 17.19 m. Because a tree's diameter determines its basal area, and the plot radius determines the sampling area for that tree, the contribution of each selected tree to total stand basal area can be determined. Bitterlich's intellectual leap was to recognize that for such a sample of trees there is a constant relationship between tree diameter and effective sampling area, and therefore each tree selected represents exactly the same contribution to the basal area of the forest stand (3.05 m^2/ha in the above example). In order to estimate the total stand basal area, the only computation required is to multiply this special tree count by a constant. The constant is determined solely by the threshold angle of view; no measurements must be made. This insight revolutionized timber cruising and spectacularly increased the amount of time that foresters stand in one place and spin.

The GigaPan connection

There is an obvious similarity between a forester turning in a circle while looking at trees and a GigaPan imager capturing photos in a forest. The Bitterlich method calls for a 360° sweep around a discreet point. A 360° stitched panorama from a rotating camera can record all the information a forester needs to complete the tally. The forester's protocol includes repeated decisions about the apparent diameter of trees relative to a threshold angle of view. These decisions can be made at a later time using a completed panorama. That panorama must include information which allows an angle of view from the camera's perspective to be equated with a horizontal distance on the image. This is straightforward when the panorama includes the full 360° view or when targets were placed in the view for calibration.

Within several years of its invention, the Bitterlich method was introduced to America (Grosenbaugh 1952). A minor industry quickly emerged to develop optical devices that assess tree size from a distance (Bitterlich 1984, Clark et al. 2000). Although there was early recognition that photographs could provide the information required to apply Bitterlich's technique (DeCourt 1956), little progress was made because performing the analyses on photographic prints is cumbersome. Recently, however, Adam Dick has developed a protocol for estimating basal area from digital panoramas (Dick et al. *in preparation*) and has also pioneered a technique for mapping trees using digital panoramas (Dick et al. 2010). The current study follows Dick's innovations and describes the application of gigapixel forest panoramas made with GigaPan technology to the determination of stand basal area.

METHODS

Study site

The Bonanza Creek Experimental Forest is in the Tanana Valley State Forest approximately 20 km southwest of Fairbanks, Alaska. It includes 5053 ha of boreal forest including floodplain forests along the Tanana River and upland forests on deeply loess-covered hills north of the floodplain. In 1987 the Bonanza Creek (BNZ) Long-Term Ecological Research site (LTER) was established there as part of a nationwide network of research sites sponsored by the National Science Foundation.

In June, 2010, I established a single study plot in an upland forest (elevation 300 m) between permanent study sites UP2B and UP2C, which are maintained by the BNZ LTER. The study stand has one overstory species, Alaskan birch (*Betula neoalaskana*), and a few understory white spruce (*Picea glauca*). The forest established after a stand-replacing wildfire around 1915, and all birch are similar in age (70-80 years). The understory is dominated by shrubs (*Viburnum edule, Rosa acicularis*) and herbs (*Epilobium angustifolium, Calamagrostis canadensis*), most of which were conveniently shorter than 1 m.

Figure 1. Trees were assessed in the field for inclusion in the Bitterlich sample by viewing the lateral displacement by a calibrated glass prism held over the sample/photo point.

Study plot

A rectangular plot, 42 m x 38 m, was located in an undisturbed area that was flat and almost level. Plot boundaries were surveyed and measured with compass and tape, and corners were marked with steel conduit pipes.

Tree measurements

Basal area of the stand of birch was measured in the field and also estimated in the field using a Bitterlich sampling method. The circumference of each live birch tree in the rectangular plot was measured with a tape which converts to diameter. This complete survey allows the computation of the actual basal area in the plot. Centered within the plot, three sample/photo points were established forming an equilateral triangle 17 m on a side and marked with conduit. At each sample/photo point, a basal area prism (Bruce 1955) was used to select live trees that met a size threshold (Figures 1 and 2). The standard cruising prism used (basal area factor = 10) offsets the image by 1.736°, facilitating the selection of trees that subtend at least that angle. This angle allows the resulting tree count to be multiplied by 10 to estimate the stand basal area in ft^2/acre. The prism was held directly over the conduit as a 360° scan was made. The number of trees meeting the size criteria was recorded at each point.

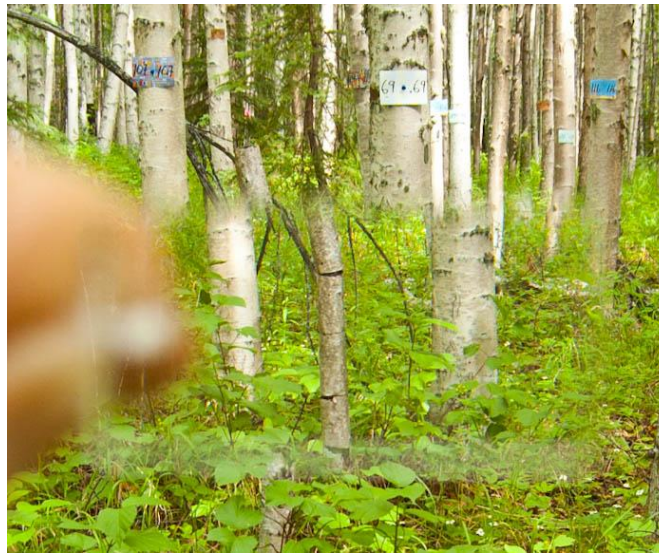

Figure 2. Here the prism displaces the image to the right 1.736° (center of photo). The diameter of tree 69 (center) is ≥ the displacement, and it was therefore included in the sample. The diameter of tree 107 (left) is ≤ the displacement so it was not included.

Gigapans

At each of the three sample/photo points, a 360° multi-image panorama was taken with a Nikon D40 (6.1 megapixels) and Nikkor PC 105 mm f/2.5 lens (35 mm equivalent is 160 mm) mounted on a GigaPan Epic 100 imager. The tripod was adjusted so the imager was level and the entrance pupil of the lens was 1.3 m above the ground. Each panorama included 504 photos (12 rows, 42 columns) and included a vertical field of view of about 80°; approximately half above and half below the horizon. The photos were captured in camera raw format, converted to full quality jpegs in Adobe Lightroom *v*. 3.0, and stitched with GigaPan Stitch *v*. 1.1.0963 using the default projection setting (spherical). Final panoramas were approximately 86,500 x 18,500 pixels or 1.6 gigapixels. The gigapans from all three apices of the triangle can be viewed online.

Analysis

The cross sectional area of each birch tree was calculated from measured diameters, summed, divided by the plot area (42 m x 38 m = 1596 m^2), and scaled to m^2/ha to establish the actual basal area of birch in the study plot. Tree counts from the prism method at each sample/photo point were multiplied by 10, and the result converted from ft^2/acre to m^2/ha.

Stitched gigapans were exported as Photoshop RAW format and opened in Adobe Photoshop CS3. In each image, the locations of the photo points at the other two apices of the triangle were visible, and were used as a test of the approach of substituting a horizontal pixel measurement for a horizontal angle. Interior angles of equilateral triangles are 60°, so the far photo points should be separated in the image by 1/6 (60°/360°) of the pixel width of the entire image.

Figure 3. Screen capture from Photoshop with drawn yellow rectangles which are 418 pixels in width. Tree 124 was included in the count, and more distant tree 136 was not. Trees have a numbered card for another image analysis project.

To establish a horizontal distance in the image that was equivalent to a subtending angle of 1.736° viewed from the camera location, the width of the image in pixels was divided by 360, and the result multiplied by 1.736. For each panorama, a rectangle of that pixel width was drawn and compared to the width of each tree trunk (Figure 3). Following the Bitterlich procedure, trunks as wide as or wider than the rectangle were included in the count which was multiplied by 10 and converted from ft^2/acre to m^2/ha.

RESULTS

Tree measurements

Stand basal area derived from measurements of all 205 live birch trees in the study plot was 29.96 m^2/ha (Figure 4). Stand density of live birch in the plot was 1284.5 trees/ha.

The numbers of live trees which met the size threshold using the prism method at three points ranged from 9 to 13 (Table 1). No trees were included in the sample from more than one sample/photo point (there was no sampling overlap among sample points). Basal area estimated with the prism in the field ranged from 20.66 to 29.85 m^2/ha, with a mean (±standard error) of 26.02±2.25 m^2/ha (Figure 4).

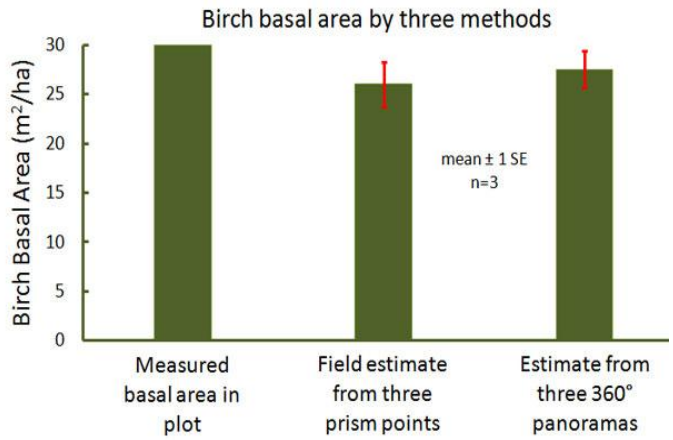

Figure 4. Basal area of birch trees in a 42 m x 38 m plot (left) and estimates of that value using 3 replicate Bitterlich prism field sample points (center) and analysis of Gigapan panoramas taken from each of those points (right).

Gigapan image analysis

The interior angles of the triangle of photo points measured from pixel distances in the panoramic images were 59.9°, 59.9°, and 59.8°. The threshold angle of 1.736° was represented by 415 to 418 pixels in the three images.

Counts of trees differed between field and image methods. Counts of tree trunks meeting the size threshold using images were higher than from field methods at two of the three photo points, and lower at one photo point (Table 1). Higher tree counts from images were the result of greater precision in measuring pixel widths in high resolution images compared to using a non-magnified prism to determine a subtending angle in the field. The prism might have been just as likely to result in erroneously higher rather than lower tree counts at other sample points or with other unpracticed operators. A lower count based on one panoramic image was due to a tree being obscured by a closer tree. In this case, it was not possible to determine from the image whether the obscured tree met the size threshold, so it was not counted. In the field, I moved laterally to determine that the tree was large enough to be counted.

Table 1. Counts of birch trees subtending an angle of at least 1.736° as viewed from 3 sample /photo points, and counts using calibrated pixel counts in images from those 3 points.

Sample/photo point	S	NE	NW
Counts in field	13	9	12
Counts from images	14	11	11

Estimates of stand basal area based on image analysis ranged from 25.26 to 32.14 m^2/ha with a mean (±standard error) of 27.55±1.87 m^2/ha (Figure 4).

DISCUSSION

Efficacy of the Bitterlich method

Compared to plot measurements, basal area of birch was underestimated using field-based (by 13%) and image-based (by 9%) Bitterlich procedures. Both procedures used the same three sample/photo points, and assessed only 20-40 trees close to each point. The underestimation of density could be explained if the points were surrounded by forest with lower density than the plot average. In fact, the points were not chosen randomly, but with a bias toward making the photography more convenient, and were likely placed in more sparsely treed areas.

Error in substituting pixel counts for angle measurements probably did not contribute to underestimating basal area. The good results in confirming the interior angles of the equilateral triangle of photo points suggest that the technique was well calibrated. The large number of pixels (415 to 418) which represented the threshold angle of 1.736°, and the well-resolved tree trunks in the images allow great confidence in assessing whether each tree should be included in the count. With such resolution, focus is the limiting factor, and optimizing depth of field is a critical consideration.

Field vs. image-based methods

Using a prism to select trees in the field was less precise than the image-based method, and precision can decrease when trees are distant or lighting is poor. However, other field devices which magnify the view are available (Clark et al. 2000) and can eliminate some of the advantage of the image-based method. A primary disadvantage of the image-based method is the inaccessible information about trees obscured by nearby trunks or understory foliage. In images from the three photo points in this study, only one tree in the samples was obscured, but tree branches and understory foliage were mostly absent between 1 and 3 m above ground level. In other forests, obtaining images with a clear view of most tree trunks would be a greater challenge.

The study stand of birch is rapidly self-thinning as less successful trees die and survivors dominate the available resources. Without a view of the upper branches, trees which have died recently can be difficult to distinguish from live trees. Had I not marked live trees (which I did for another project) before photography began, at least two dead trees would have been erroneously included in the samples derived from images.

Applicability of gigapans

The traditional Bitterlich field technique allows foresters with a simple viewing device to produce reliable estimates of stand basal area with minimal training, equipment, expense, and time. The extreme efficiency of this method allows large areas to be traversed and many replicate points to be sampled. High-resolution panoramic photography has comparatively hefty requirements for training, equipment, expense, and time, and therefore offers little promise to improve the efficiency of this method. However, forest panoramas taken for other purposes may contain sufficient information to allow the estimation of stand basal area. Such panoramas may have been taken for aesthetic or general documentation purposes, or may have been taken with other quantitative objectives.

One potential application of this approach is to find old panoramic photographs from known locations with no early information about timber quantity. Basal area estimates derived from these photographs could be compared to newly acquired stand data to describe long-term changes in forest condition. The seven criteria described below can be used to evaluate the potential of existing panoramas to contain useful information about timber quantity. Of these criteria, the most critical may be that the field of view must be known precisely, making 360° panoramas the best candidates. If the exact location of an original non-360° photograph is known, it might be possible to return to the site and determine its angle of view.

It may also be possible to apply the concept of angular determination of size per sample area in other arenas.

Summary recommendations

In order to use a panorama to estimate forest basal area, certain characteristics are desirable:

1. *Selecting photo points.* To eliminate bias, sampling points for forest inventories are selected systematically or randomly. Photography within forests is a challenge, and selecting points for general or panoramic photography is almost always subjective – scenic forest photographs are typically taken from small clearings among the trees. To produce an estimate of basal area that is representative of the local forest, points should be selected randomly or systematically. The resulting photographs will usually be aesthetically deprived.
2. *Field of view.* It is not essential that the panorama include a 360° view as long as the field of view is precisely known. For example, a 180° panorama will allow sampling of variable radius semicircles, and the constant must be doubled to calculate stand basal area. The exact field of view may also be required to determine what horizontal distance on the photograph is equivalent to the threshold angle used to select trees. In a 360° panorama, a 2° angle is equivalent to 1/180 of the width of the image (e.g., in pixels). A target of known width and distance from the camera can be placed in the scene before photography begins to establish or calibrate this pixel measure. Relying on

the field of view reported by stitching software may not be sufficient. For example, Gigapan Stitch crops 360° panoramas so the horizontal coverage is exactly 360°, but if there is no overlap between the right and left sides of a panorama (i.e., if total field of view is less than 360°), Stitch computes the total field of view based on how the overlap of individual images increases above and below the imager horizon. The accuracy of this result or its consistency among panoramas has not been determined (Paul Heckbert *personal communication*).

3. *Image Distortion.* In order for a horizontal angle of view to be represented by the same horizontal distance everywhere in a panorama, distortion caused by the lens or by stitching misalignments must be eliminated. Gigapan Stitch corrects for radial distortion (which most lenses exhibit) before stitching is done, so well-stitched panoramas will have a consistent relationship between horizontal pixel count and azimuth. Error-free stitching of forest interior panoramas requires the reduction of parallax inconsistencies between adjacent photos. This is a challenge because scene details in a forest are both close to and far from the camera. To reduce parallax misalignments, the camera should be mounted so it rotates precisely on the entrance pupil of the lens. Another source of stitching misalignment can be avoided if photos are taken when there is no movement caused by wind so leaves and branches are in the same position in adjacent, overlapping photos. Fortunately for this application, moderate wind movement in the forest canopy typically does not move vegetation near the base of trees.
4. *Camera orientation.* Trees are tapered near their bases, and tree basal area is standardized by measuring trees at a constant height above the ground; typically 1.3 m. In a perfectly level, flat forest, adjusting the tripod so the imager is level and the lens is 1.3 m above the ground will allow a straight line drawn across the panorama to intersect each tree at this height. This method can also work when the forest floor is flat but not level, if the panorama is taken with the imager rotating in a plane parallel to the tilted ground. However, tilting the imager introduces an inconsistency into the relationship between horizontal pixel count and azimuth (Paul Heckbert *personal communication*); just as using a prism in the field on sloping terrain requires correction because the circular sampling "plots" become elliptical (Beers 1969). Tilting the imager in a forest will also result in an image with tilted trunks, and as always, tree diameters should be measured perpendicular to each trunk. Whether level or sloping, forest floors are rarely flat, so determining the correct height on the trunk of each tree in the panorama is not straightforward. Because trunk taper is usually slight 1-2 m above ground, some error can be tolerated; for example, foresters using the Bitterlich method in the field typically estimate from afar the height at which each tree's width is assessed. Also, the method requires only that trees be categorized as in or out of the sample, so only a few trees close to the threshold must be scrutinized closely.
5. *Depth of field.* Few photographic environments require greater depth of field than forest interiors. Poor focus can cause a tree trunk to appear larger than it is, possibly biasing the tally of trees. Choosing a short focal length and a small aperture to maximize depth of field is recommended, even though these choices will compromise overall resolution. In dark forest interiors long exposures and/or high ISO settings may also be required to accommodate small apertures. To capture the same field of view, cameras with smaller sensors require less image magnification (via either shorter focal length or greater image distance) which preserves greater depth of field (Blaker 1985, pp. 40, 95). In dense forests, focus is a more critical limiting factor than resolution, so a point and shoot camera with a small sensor and good lens may give better results than a full frame DSLR. However, more advanced cameras and imagers offer the option of focus stacking, an elegant solution which will eventually be sufficiently automated to warrant application to this pursuit.
6. *Obscured trees.* Sometimes a distant tree will be partially hidden behind a nearby tree, making it impossible to determine the tree's size and whether it should be counted. In the field, a forester can step sideways to look around the nearby tree, but this is not possible with a completed panorama. If this type of problem is anticipated, multiple panoramas could be taken from points offset from the primary sampling point. Trees may also be hidden by the foliage of shrubs or other understory vegetation, so in certain types of forest, panoramas made after leaf fall are most useful.
7. *Multiple species.* Where more than one tree species is present and of interest, separate tallies can be made for each. Including the upper parts of trees in panoramas can facilitate the identification of tree species, especially if leaves can be resolved. Although in some situations a single row of photographs can include all the information needed to estimate basal area, multi-row panoramas may improve the reliability of distinctions among species and between live and dead trees.

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