A Crown-Following Approach to the Automatic Delineation of Individual Tree Crowns in High Spatial Resolution Aerial Images

François A. Gougeon
Natural Resources Canada
Canadian Forest Service
Petawawa National Forestry Institute
P.O. Box 2000, Chalk River, Ontario, K0J 1J0
email: fgougeon@pnfi.forestry.ca

Résumé

La disponibilité d'images numériques multispectrales aériennes géoréférencées de haute résolution spatiale, telles qu'obtenues par le MEIS-II, pourrait conduire à de nouvelles façons d'acquérir les inventaires d'aménagement forestier. Le potentiel d'une interprétation humaine assistée par ordinateur et faite à l'écran est un bon exemple des bénéfices possibles d'une telle technologie. Une utilisation encore plus judicieuse de la nature numérique de ce genre de données est possible en obtenant des inventaires forestiers précis d'une manière presque complètement automatique. Pour réaliser ce but tout en quantifiant adéquatement la composition en espèce des peuplements forestiers, nous croyons qu'une délinéation des couronnes d'arbres suivie d'une identification individuelle de leurs espèces et d'un regroupement subséquent sont requis. Cet article décrit la première étape de ce projet, une approche à la délinéation automatique des couronnes d'arbres qui produit des contours détaillés pour chaque couronne et un dénombrement assez exact de celles-ci. Cette approche consiste premièrement à isoler les couronnes les unes des autres et de la végétation sous-jacente, en utilisant un programme de traitement d'images qui suit les vallées de matériel ombragé existant entre les couronnes. Par la suite, ces couronnes sont séparées et délinéées de manière plus précise par un programme à base de règles. Testée sur une image MEIS-II de plantations conifériennes d'une résolution de 31 cm/pixel, cette méthode a produit un dénombrement de couronnes à 7.7% près du dénombrement fait au sol, alors que le dénombrement fait par photo-interprétation était à seulement 18.1% près. Un examen des erreurs d'omission et de commission révèle qu'en général 81% des couronnes sont les mêmes que celles qui sont obtenues par une interprétation visuelle de l'image.

Summary

The availability of quality georeferenced high spatial resolution aerial multispectral digital images, such as those obtained with the MEIS-II, could lead to new ways of obtaining forest management inventories. The potential for computer-assisted on-screen human interpretation of colour enhanced images is a good example of the possible benefits of such technology. A fuller use of the digital nature of this type of data is also possible by getting precise forest inventories in an almost completely automatic way. To reach this goal, while still quantifying adequately the species composition of forest

• Manuscript submitted February 1995 to the Canadian Journal of Remote Sensing for a special issue on Aerial Optical Remote Sensing to be published in October1995. Corrected as per reviews in May 1995.

stands, it is believed that individual tree crown delineation followed by crown species identification and regrouping is required. This paper describes the first step in this endeavour, an approach to the automatic delineation of tree crowns which can lead to detailed crown outlines and accurate crown counts. The approach consists of first isolating crowns from the background vegetation and from each other using an image processing program that follows valleys of shaded material between crowns. These crowns are subsequently delineated more precisely and further separated using a rule-based program. Tested on a MEIS-II image of coniferous plantations at 31 cm/pixel, this method led to crown counts that are within 7.7% of ground counts, compared to 18.1% using photointerpretation. Examination of the errors of omission and commission shows that, in general, 81% of the crowns are the same as those obtained by the visual interpretation of the imagery.

Introduction

In Canada, forest management inventories are produced primarily from the interpretation of aerial photographs confirmed by sample field verification (Gillis and Leckie, 1993). On the other hand, satellite digital imagery is mostly used for remote, less intensively managed areas or for inventory updates (Beaubien, 1994; Leckie, 1990) because its species differentiation capabilities and spatial resolution are very limited. Nevertheless, digital multispectral imagery has numerous advantages over conventional photographs. For example, its multispectral nature leads to powerful image enhancement capabilities. In addition, its digital nature allows geometric corrections, making such imagery (and its interpretation or analysis) directly compatible with the geographic information systems on which most inventories now reside. Radiometric corrections can also be performed to compensate for illumination and view angles, and atmospheric path radiance effects. All of these advantages as well as good spatial resolution can now be obtained with MEIS-II (Multi-detector Electro-optical Imaging Sensor) aerial images (McColl *et al*., 1983). This opens the possibility for on-screen interpretation of colour-enhanced MEIS-II images to replace conventional methods of conducting forest management inventories. It could lead to a more efficient production of such inventories (Leckie, 1990; 1993). However, the big pay-off for such digital data will come when most of the interpretation process is automated.

Although uniform single species stands can probably be assessed at medium (1-10 meters/pixel) or even low (10-100 meters/pixel) spatial resolutions, we believe that in order to convey adequately the species composition levels needed in today’s typical forest management inventories of natural stands, high spatial resolution aerial imagery (30-70 cm/pixel) and individual tree-based species recognition capabilities are required. Indeed, what better way is there to establish precisely stand composition (to unprecedented levels of precision) than to know the species of each one of its components? Additionally, with data on individual tree’s species, height, and crown area, precise wood volume information will be at hand (using well established tables). In the context of existing forest inventory practices, individual tree data would rarely be needed after amalgamation into stand parameters. It can thus be viewed only as an intermediate step needed by the computer to produce detailed information. However, in the context managing forest for multiple uses via complex computerized management systems, such specific data may gather importance over time.

The first step towards an inventory based on individual tree crowns is, of course, crown delineation, and preferably, automatic crown delineation. Researchers interested in individual tree-based damage assessment and/or species recognition have used a manual delineation approach (Leckie *et al*., 1992; Murtha and Fournier, 1992) or relatively simple automatic methods of crown multispectral content acquisition based on finding the tree tops or crown centres and estimating crown radii (Gougeon and Moore, 1989; Pinz 1991). Others plan on modelling the bidirectional reflectance distribution function (BRDF) of certain tree shapes under specific measurement conditions and using image template matching to estimate crown positions (Woodham and Pollack, pers. comm.). Although detailed crown outlines are not essential for crown area assessments from which other forestry parameters are typically derived, they are needed if crown boundary structure analysis is to be part of the species identification process (in addition to multispectral, textural and structural crown analysis, and contextual information). With additional processes, such as the extraction of individual tree heights from stereo image pairs and the regrouping of crown based information into forest stands, individual tree crown delineation followed by species recognition may lead to precise semi-automatic forest management inventories (Gougeon, 1993; 1995).

This paper describes a new and precise two-stage automatic crown delineation process. First, the crowns are partially separated from the background vegetation and from each other by a valley-following program which makes use of the darker shaded pixels that generally exist between crowns. Second, the crowns are delineated and separated more precisely one by one using a rule-based approach to follow and complete each crown boundary. This automatic delineation process is tested on a high spatial resolution MEIS-II image of coniferous stands and its performance is assessed for its crown separation capabilities. This is done by verifying the accuracy of crown counts in different forest stands and by checking the errors of commission and omission. Finally, following a discussion of the results, ideas are put forward about further developments and testing of this process.

MEIS-II Data and Study Area

The airborne Multi-detector Electro-optical Imaging Sensor is capable of acquiring medium to high spatial resolution multispectral images in up to eight spectral bands, two of which are typically used with mirrors to acquire fore and aft stereo pairs. The simultaneous acquisition of precise navigational information permits the geometric correction of the images using sophisticated post-flight ground processing (Gibson *et al*., 1993). To test the automatic delineation process, a section (433 lines by 636 pixels) of a high resolution MEIS-II image (31 cm/pixel) was used covering part of the Hudson Plantation at the Petawawa National Forestry Institute, Chalk River, Ontario (Figure 1). The image was acquired at 12:25 hr EST, Nov. 22, 1982, from an altitude of 1440 ft., following a 273° flight line heading and positioned at 46°00’ latitude and 77°23’ longitude. At that time, the sun’s azimuth was 188°, with an elevation of 23°. The forested area under scrutiny consisted almost exclusively of coniferous trees organized in plantations of red pine, red spruce, white spruce and Norway spruce, and combinations thereof. To better examine the results of the automatic crown delineation process, the area was divided into compartments generally associated with the uniform forest stands (Figure 2).

Although necessary for the individual tree crown species classification (Gougeon, 1995) meant to follow the automatic crown delineation approach described here, this study does not make use of the multispectral nature of the data. Only one grey-level image is needed as input to the delineation process. Preliminary trials have indicated that for this MEIS-II image, the process actually performed better on a slightly smoothed version (i.e., means of 3x3 windows) of the near-infrared image.

An Individual Tree Crown Delineation Approach

The basis of this approach is conveniently described by an analogy with topographic data. In a grey-level image seen in three dimensions, where the pixel values are mapped to the third dimension (i.e., elevation), bright tree crowns look like mountains relative to the darker shaded background vegetation. Similarly, zones of darker shaded tree material that typically help human interpreters separate crowns from each other appear as valleys between these mountains. By first eliminating the large areas of shaded background vegetation from contention and proceeding from such shaded areas to others via the valleys, it is possible to separate the tree crowns in the image. This is accomplished by the first step of the automatic delineation process: the valley-following program. Unfortunately, this is not quite sufficient to completely separate most crowns. So a second step, a program using a rule-based approach, outlines precisely the boundaries of each crown, one crown at a time, and in the process continues the separation of the tree crowns. The program uses rules that generally favour clockwise moves to follow pixel by pixel one specific crown boundary at a time, often bridging small gaps in the process. These two consecutive steps form the basis of my approach to the automatic delineation of tree crowns in high resolution aerial images and are described in detail below.

a) Initial Tree Crown Isolation - The Valley-Following Program

The isolation and delineation of individual tree crowns implies the ability to first separate them from the background vegetation and other non-forested areas, and second, from each other within forest stands. When stands are dense and sun elevation is low (as is the case with the test image), a simple thresholding of the input grey-level image may be sufficient to accomplish the first objective. This capability was thus built into the valley-following program. For more complex images than the one under consideration, a simple *a priori* multispectral unsupervised classification can be used instead. With either approach, the idea is to mask areas devoid of significant tree crowns, leaving only forest stands in which tree crowns are separated by narrow bands of shaded tree material for further analysis. Within these remaining areas, local minima are found. They typically correspond to the darkest points in the shaded material left between the tree crowns. Continuing the topographic analogy, they would correspond to places where water would accumulate as lakes or potholes. Then, from these local minima, irregular lines are grown in various directions until they reach another local minima or a non-forested area, or until progress is deemed impossible. The line-growing criteria are such that they are equivalent to following up or down V-shaped valleys in our analogy. The details of the valley-following algorithm are outlined below.

I - Initialization:

- The input image is read into a two-dimensional array. An array for the output binary (or thematic) image is also defined.

II - Classification and search of local minima:

- Scanning the input image pixel by pixel, a simple threshold (in this version) is used to separate the forested areas from the non-forested (and shaded) areas. The pixels assessed as non-forested areas are marked (pixel = 1) in the output image array.
- The input image array is then scanned with a 3x3 moving window to find local minima in the forested areas. The center pixel of the 3x3 window is only considered a local minimum if all of the pixels surrounding it have higher values. The locations of these local minima are marked in the output image.

III - Valley-following:

- An image scan is initiated from the top left corner of the image, going down and right.
  - The scan is interrupted when a marked pixel is found in the output image. That location corresponds to a local minimum, the border of one of the marked shaded or non-forested areas, or an existing "valley pixel" (n.b., there is no "valley pixel" if this is the first image scan).
  - Using reflectance data from a 5x5 window around that pixel's position (X), its four immediate neighbours (Os) in the scan direction (initially, down and right)

    (i.e.: • • • • •
    • • • • •
    • • X O •
    • O O O •
    • • • • •)

    are examined to find a pixel flanked on both sides by pixels of higher values. If found, such a pixel is flagged as a "valley pixel" in the output image array.
  - Similarly, two- and three-pixel-wide valleys are also considered.
  - The image scan is then resumed. The above operations are repeated for the full image.
- Next, another full image scan (similar to the above scan) is performed, but from the bottom-right of the image going up and left, while detecting valley elements by looking in these same directions.
- A third full image scan is performed, but now from the top-right of the image going down and left, detecting valley elements by looking in these directions.
- Finally, a fourth full image scan is performed from the bottom-left of the image going up and right, detecting valley elements by looking in these directions.
- These four directional valley-following scans are repeated many times until no additional valley elements are found.

IV - Output stage:

- The output thematic (binary) image array is written out to a file to be used by the crown delineation rule-based program.

The valley-following algorithm was run on the high spatial resolution MEIS-II image of the Hudson plantation (Figure 1). Figure 3 illustrates the results obtained from different phases of the valley-following program. Figure 3a shows a representative section of a smoothed version of the MEIS-II image in Figure 1. The smoothing was done by scanning the image with a 3x3 moving window and replacing the center pixel by the average intensity value in that window. Figure 3b shows, for the same section. the non-forested areas and the local minima thematic pixels. Figure 3c shows the thematic information resulting of the first valley-following scan of the image (i.e., scanning from upper left to lower right). Figure 3d shows the final resulting thematic information. Notice the general tendency in Figure 3c for valleys to go mostly down and right, and how this situation is alleviated in Figure 3d by the use of consecutive directional image scans in the algorithm.

The results of the valley-following program (partially shown in Figure 3d) appear realistic. However, closer examination of the full image reveals that a sizeable number of crowns are not completely surrounded by valleys and non-forested areas and, thus, are not fully delineated. This can be partially explained by the fact that any branch sticking out of a crown may cause a specific valley-following to abort in what would otherwise be a perfectly good valley. Although possible, no effort is made to jump such obstacles in this version of the program. Rather, the completion of the delineation process is left to a rule-based program which, because of its more general nature, can also finish the delineation of crowns that did not complete due to other causes, and even sometimes, separate crowns forming very thigh clusters. The program will use rules dealing with local situations in collaboration or in competition with other rules that have a more global view of the situation at hand.

b) Complete Tree Crown Delineation - The Rule-based Program

Given that numerous crown outlines are incomplete and that various outlines actually encompass more than one crown (see Figure 3d), it was decided to complete the delineation process using a rule-based program. The present version of the program works essentially at a thematic level (i.e., using the output of the valley-following program with no reference to the multispectral data). Its goal is to follow and augment, using numerous specific rules, the boundaries of the roughly delineated crowns to obtain their closure. Later, with rules using a more global perspective and access to the multispectral data, it should be made better able to detect and separate multiple crowns previously considered a single crown (or vice-versa).

This rule-based program improves crown delineation by following step by step (often, pixel by pixel) one specific crown boundary at a time in an essentially clockwise fashion. Five hierarchical levels of highly localized rules deal with increasingly difficult deviations from this "generally" clock-wise path.

I - Initialization:

- Read in the thematic (or binary) image produced by the valley-following program (e.g., Figure 3d). It is essentially a binary image representing crown matter (pixel = 0) partially separated into individual crowns by what will be referred to as valley-following or VF matter (pixel = 1).

- Create a buffer box of VF matter (two-pixel wide) enclosing the full image so that the crown boundary following rules do not stray outside the image boundaries.

II - Initial Crown Localisation:

- Scan the image pixel by pixel, left to right, and down, line by line.
- Find a significant blob of tree crown matter. Here, a significant blob corresponds to an area of roughly one square meter (i.e., 3x3 pixels), centred on the current pixel, and that is devoid of any VF matter.
- Find the left side of this potential tree crown by going left, pixel by pixel, until a VF pixel is encountered.
- From there, use the rules defined below to follow step by step the crown boundary in a "generally" clockwise fashion. Consider the initial direction to be up and make the present direction (IDIR) equal to 1 (see Figure 4a). For each step, the rules are organised and tested for applicability in a sequential order, but are grouped into an hierarchy that presently spans five major levels. The first rule for which conditions are met is activated. The control is then passed to the crown delineation termination assessment module (section IV).

III - Crown Boundary Following:

Level 1 Rules

Level 1 rules assume that the crown can be followed by using exclusively clockwise displacements. The crown is assumed essentially round (but may be somewhat squarish locally) with no discontinuity, no inlet into the crown, and no branches sticking out.

- From the present position in the image (on VF matter at a potential crown boundary), check all directions (eight directions over 360°, as per Figure 4a) and make a list of possible directions (named IPDIR) for following the crown boundary using a generally clockwise strategy. That is, find other VF pixels connected to the present boundary pixel with a crown matter pixel (pixel=0) on their right-hand side. This list is also used by the other levels of rules.
- Make a sublist containing only the Level 1 allowable clockwise directions (i.e., 0° and 45° clockwise from the present direction). That is, using the present direction (IDIR), keep only the moves implying directions IDIR or IDIR+1 (see two examples of such situations in Figure 4b).
- If that sublist is empty, it is not a Level 1 case. Go to Level 2 rules.
- From that sublist of allowable directions, find the most clockwise direction (i.e., IDIR+1 has precedence over IDIR if both are sublist members).
- Make the VF pixel in that direction the next boundary pixel, update the ongoing direction (IDIR), and continue the boundary following (i.e., go to section IV).

Level 2 Rules

Level 2 rules deal with minor breaches of the generally clockwise strategy. Specifically, they deal with the 45° counter-clockwise (CCW) turns that may occur while following a crown boundary (see example in Fig. 4c). Keep in mind that the list of possible directions was first examined by the Level 1 rules before getting to this second level of rules.

- Check the list of possible directions (IPDIR). If one is IDIR-1 (a slight CCW move), then make the VF pixel in that direction the next boundary pixel, update the ongoing direction (IDIR), and continue the boundary following.
- If the present situation does not qualify as Level 2, go to the next level of rules.

Level 3 Rules

Level 3 rules deal with 90° CCW turns, appearing either as square CCW corners or as single contour pixel inlets into the crown (see examples in Fig. 4d). However, before making such a turn, they check whether there is VF matter within a pixel's length in three general directions commensurate with not making this turn. Essentially, the rules decide whether such a turn is just a normal part of the crown outline or if it is an indication of a gap in the outline that should be filled to continue the boundary following in a more CW direction.

- Check the list of possible directions for 90° CCW turns from the present direction. If no 90° CCW turn is found, go to Level 4 rules.
- For the 90° CCW turn found, check whether there is VF matter within one pixel's length of the outside of the turn (i.e., inside the crown, on the right-hand side, shown as dashed pixels in Fig. 4d).
- If there is no VF matter, make the turn, update the ongoing direction, and continue the boundary following.
- If there is some VF matter, recheck more precisely the neighborhood (three pixel wide) in three directions commensurate with not making that turn, checking the most clockwise direction first, to decide how to best fill this one-pixel gap to the VF matter. These three directions are respectively: a) at 180° from the potential turn direction, b) at 135° CW from the potential turn direction, and c) in the present direction. Fill the gap with VF matter and consider that pixel the next crown boundary pixel, update the ongoing direction, and continue the boundary following from there.

Level 4 Rules

Level 4 rules deal with 135° CCW turns. They can represent small anomalies in crown boundaries but, more often then not, such drastic turns are indicative of a separation between two crowns. So, similarly to Level 3, the turn is only taken if there is no potential move in a more CW direction that can be made by filling a gap to other VF matter on the outside of the turn. Also, since these 135° CCW turns are often found at the end of a long inlet into a crown and usually indicate the separation of two crowns, the presence of VF matter outside the turn is checked gradually from 1 to 3 pixel lengths away, and gaps up to 3 pixels wide can be filled (see Figure 4e).

- Check the list of possible directions for a 135° CCW turn from the present direction. If no 135° CCW turn is found, go to Level 5 rules.
- For the 135° CCW turn found, gradually check that there is no VF matter within 1 to 3 pixel lengths in the general direction (i.e., +/- 1 pixel) of the two potential directions implied by the turn. These two directions are, respectively, a) 180° from the potential turn direction, and b) in the present direction.
- If there is no VF matter in any of these directions, make the turn, update the ongoing direction, and continue the boundary following.
- If there is some VF matter, fill the gap to that VF matter. Go to the last "gap-filling pixel" (now considered VF matter and part of the crown boundary), update the ongoing direction, and continue the boundary following from there.

Level 5 Rules

Level 5 rules deal with cases of direction reversals, that is, when the only possible direction is back to where one came from (see Figure 4f). This is often encountered at the end of a long inlet into a potential big crown and usually signifies the presence of two crowns that were not fully separated by the valley-following algorithm. Consequently, similar to Level 3 and Level 4 rules, potential gaps are sought and filled when VF matter is found within 1 to 3 pixel lengths from the present boundary pixel. If such VF matter is not found, the boundary pixel, and potentially the whole inlet, is erased and thus considered crown matter from then on.

- Check the list of possible directions for a 180° turn from the present direction. If no 180° turn is found, record the fact that additional rule levels (not implemented yet) are needed for this case.
- Check gradually for a 1 to 3 pixel gap to fill by looking for VF matter in the general direction (i.e., +/- one pixel) of the last move (i.e., the present on-going direction (IDIR)).
- If VF matter is found, fill the gap and go to the last "gap-filling pixel", update the ongoing direction, and continue the boundary following from there.
- If no VF matter is found, start to backtrack, erasing the present boundary pixel (VF matter) by making it crown matter (pixel=0). Go to the previous boundary pixel, change the ongoing direction to the previous ongoing direction as if the boundary pixel just erased was never there, and continue the boundary following from there.

IV - Crown delineation termination assessment

After having used at least one rule from a given position on the boundary of a potential tree crown (and thus having made one new step along this boundary), the control is always returned to the crown delineation termination module to test whether the crown has been fully delineated. This is done by checking three situations:

a) whether there has been a return to the point of departure (i.e., to the left of the original blob of crown matter);

b) whether the present position was previously visited, thus forming a closed loop; or,

c) whether there has been more than 250 steps, meaning an unusually long contour that would definitively not be a single crown (i.e., a huge crown with a 10 m diameter would imply roughly a hundred 30 cm steps).

In cases (a) and (b) a crown has been successfully delineated and the area inside the closed contour is filled in an output thematic image. In all three cases, the area is also filled in the input image to remove that area from further analysis. The program continues by finding new blobs of crown material (i.e., section II). If none of the above terminating conditions are met, the program simply continues its rule-based boundary following activities from the present boundary pixel position (i.e., section III).

V - Repeating cycles and output

Once the image has been completely analysed, the process is repeated several times (typically three times) to delineate tree crowns that can only be isolated after other adjacent crowns have been ascertained. Such situations are consequences of the left to right and top to bottom direction of the image analysis process and of the clockwise approach to crown delineation. This re-analysis is accomplished by making available over and over again the areas that were filled in case (c) above. The task is judged completed when no further progress is made (i.e., no further crown is detected). The final thematic image and overall statistics, such as the number of well delineated crowns and their size parameters, are output.

Results

The results of the combined valley-following isolation and rule-based delineation processes applied to the Hudson plantation are shown in Figures 5a and 5b. A quick visual assessment informs us that, in general, a large number of crowns were properly isolated and delineated. Some areas, such as the line of well illuminated red pine trees (compartment 3 in Figure 2) and the hardwood trees, still pose obvious difficulties for the combined processes. In the former case, the system fails to separate most of the crowns properly. However, given the same image, humans have the same problems. In the latter case, the system creates too many crowns. However, the hardwood trees are without foliage since the image was acquired in November and are thus not representative of a typical inventory situation. The big Norway spruce trees, generally not a problem for human interpreters, are also broken down into too many crowns. Auxiliary tests reveal that this problem disappears at other spatial resolutions (i.e., 70 cm/pixel) or with further smoothing. A more quantitative evaluation of the performance of the overall crown delineation process follows.

Table 1 compares by compartment the crown counts resulting from the automatic delineation process with counts done in the field and other interpretative counts. The total crown count, a total count without compartment 5 (the troublesome Norway spruce compartment), and the percentage of difference from the ground count are also given for each method.

The "ground counts" were acquired by sequentially enclosing adjacent corridor-like areas within a given compartment and counting the trees within each corridor. Potential sources of error are that : a) the ground counts were conducted in 1993, many years after the images (MEIS-II and aerial) were acquired, so that trees may have died and/or fallen to the ground, and, b) it is often necessary to account for suppressed crowns not visible on the image. In the first case, it was assumed that such trees had not been removed from the area. We thus assessed the age of dead and fallen trees to decide whether or not to include them in the counts. In the second case, because we were dealing with uniform even-aged stands, decision about suppressed trees were fairly straightforward. The total ground count was 1327 crowns and 1288 crowns without compartment 5.

The "photo counts" were done by an experienced photointerpreter using stereo pairs of normal colour aerial images acquired in June 1982 at a scale of 1:2000. The process consisted in ticking off the interpreted tree crown on a mylar sheet covering the aerial photo. Although mature trees, depending on the species, can sometimes be difficult to separate due to crown overlap, the uniformly planted stands under consideration sometimes minimized this effect. Nevertheless, the interpreter felt less confident about these counts than the ones obtained from interpreting the MEIS-II image. (**Footnote**: According to the interpreter, this was mostly due to the zooming capabilities available when displaying MEIS-II imagery and the presence of a cursor which preserved crown position.). This is reflected in the counts which totaled (without compartment 5) 1055 crowns, 18.1% less than the ground counts.

The two "screen counts" were obtained by two interpreters visually estimating the extent of individual tree crowns and counting them on a computer screen displaying the multispectral MEIS-II image in a colour-infrared emulation mode. Powerful continuous zooming and panning capabilities were available, as was the possibility of looking at the individual spectral bands. The procedure consisted of writing a line through the crowns as the interpretation and counting progressed to avoid counting anything twice. These counts were done independently by an experienced MEIS-II interpreter (A) and by one with little experience (B). The former arrived at a total count (without compartment 5) of 1179 crowns, only 8.5% less than the ground count, while the latter arrived at 1046 crowns, 18.8% off. Both interpreters appeared to systematically undercount relative to the ground truth, more so if less experienced. Interestingly, the counts of the experienced interpreter are closer to reality with the MEIS-II on-screen image than with the aerial photographs.

The "delineation counts" quantify the performance of the automatic individual tree crown delineation process. These counts were computed by a program examining the resulting thematic image (Figure 5a). The program’s primary goal is to extract the multispectral data contained within each crown and feed it to a species recognition system, but it can also be used to produce crown counts and average crown dimensions for each of the compartments used here. The total crown count (without compartment 5) was 1189, 7.7% below the ground count. It is significantly better than the counts obtained from aerial photos and marginally better than the best MEIS-II image screen count.

Another way to quantify the performance of the automatic crown delineation process is to examine its errors. The procedure consisted of displaying the thematic results of the automatic delineation process (seen in Figure 5a) on top of the colour-infrared emulation MEIS-II image (seen in Figure 1) and of assessing and counting both the interpreted and delineated crowns by switching repetitively between the overlaid thematic display and the bare MEIS-II image. The compartments were broken down into small, easily handled areas (similar to the ground counting operation) to facilitate this procedure. The assessment kept track of the various errors of commission and omission of the automatic delineation process. Again, the "continuous zoom" feature of the image display sub-system was very useful. Table 2 gives the detailed breakdown by compartment of the errors of commission and omission.

In Table 2, the first line indicates various combinations of the number of automatically delineated crowns versus the number of interpreted crowns, while the lines below show how often such combinations were encountered in the corresponding compartments. For example, for compartment 1, there were 44 instances where the automatic delineation process detected one tree crown but the interpreter judged that there were two. As before, compartments 5 (not shown) and 3 are atypical, as they correspond to the troublesome Norway spruce stand and the line of brightly illuminated red pine trees, both of which gave the present system difficulty. In the other compartments (1, 2, 4, and 6), the automatic delineation process attained good crown separation performance with an overall accuracy of 81% (77, 78, 83, and 85%, respectively, see Table 3). The most common omission errors were due to the amalgamation of two crowns into one. On average, this affected 15.3% of the crowns. The amalgamation of more than two crowns into one occurs more rarely. On average, it affected 3.8% of the crowns. Commission errors are of the order of 4%.

Discussion, limitations, and future directions

This first application of the automatic crown delineation process to a high resolution MEIS-II image succeeded in delineating reasonable tree crowns (compare Figure 1 and 5) and in producing fairly accurate crown counts. A first quantitative estimation of its performance, a comparison with ground counts (Table 1) indicates a difference of only 7.7%, better than the counts made using aerial photo and MEIS-II image on-screen interpretations. However, this result does not take into consideration the possible cancelling effects of errors of commission and omission. A second estimation addressing more specifically this issue (Table 2 and 3) reveals that the automatic crown delineation is generally 81% accurate when compared with a human interpretation of the same image. This comparison also has its weaknesses since the interpretation process is also subject to errors (as seen in Table 1). On the other hand, in this comparison, the interpreter had the added benefit (or drawback) of seeing the computer’s crown separation results while making his own assessment of a given situation. From Table 2, it appears that the bulk of the improvements needed is in separating pairs of intertwined crowns. Indeed, 8.2% of the crowns found by the delineation process (or 15.3% of the interpreted crowns) need this type of further separation. This is probably due to the fact that, in such situations, the indicators used by interpreters to assess the presence of two crowns are of a rather subtle nature. In certain cases, they may depend more on global perception (e.g., general roundness) than on detailed analysis of particular elements indicating separation. These circumstances and their appropriate remedies are the subject of ongoing research.

Though very encouraging, the potential of automatic crown delineation towards precise semi-automatic forest inventory from high spatial resolution digital aerial images has not yet been fully realized. The test reported here benefited from at least two favourable conditions, a) the conical shape of the exclusively coniferous tree crowns, and b) a late fall image of low sun angle providing enhanced shade-related crown separation. Mid-summer images may prove more difficult to analyse and hardwood crowns will be more difficult to separate. These two aspects will be the subject of future research endeavours.

Conclusion

Although MEIS-II digital images have numerous advantages over aerial photographs and their gradual acceptance could lead to computer-assisted on-screen interpretation in the production of forest management maps, their full potential will only be realised when most of the image analysis processes can be automated. We believe that for a semi-automated process to reach and exceed present forest stand composition requirements, the use of high spatial resolution images (30 - 70 cm/pixel) and individual tree based species recognition is required. One of the important steps towards this goal is the automatic delineation of individual tree crowns in such images.

This paper presented a new approach to the automatic delineation of tree crowns which provides detailed crown outlines and accurate crown counts. This approach consists of first isolating the tree crowns from the background vegetation and from each other using an image processing program that follows valleys of shaded material between crowns, and second, of delineating more precisely and further separating the crowns using a rule-based program. Tested on a 31 cm/pixel MEIS-II image of coniferous plantations, this system led to crown counts that were within -7.7% of those made on the ground. A good human interpretation of the same image lead to comparable results (-8.5%), while counts done by photointerpretation at the 1:2000 scale were off by -18.1%. An examination of the errors of omission and commission shows that 81% of the automatically delineated crowns are the same as those obtained by the best MEIS-II image interpretation and that the amalgamation of two crowns into one is the most common error. Further improvements to both parts of this system are possible and will provide additional accuracy. However, these initial promising results should be tempered by the fact that the system was tested only on plantations of coniferous trees and with the advantage of a low elevation sun. Future studies will examine the system's capabilities with summer images of natural coniferous stands, and later, of mixedwood stands. Crown delineation precision and crown area assessments will also be studied, as well as, the effects of using lower spatial resolution images.

Acknowledgments

The author thanks Dr. Don Leckie for his support and guidance throughout this research endeavour, as well as, for his insightful reviews of earlier manuscripts. Thanks are also due to Ed Cloney and Brian Lee for the field, photo, MEIS interpretative, and MEIS comparative counts. The critical reviews of Steve Joyce, Ed Cloney and Joe Lowe are gratefully acknowledged.

References

Beaubien, J. 1994. Landsat TM satellite images of forests: From enhancements to classification. *Can. J. Rem. Sens.* 20(1): 17-26.

Gibson, J.R.; Buchheit, M.; Hak, L. 1993. Precise geometric processing of stereo MEIS imagery. Pages 69-78 *in* Leckie, D.G.; Gillis M.D., eds. International Forum on Airborne Multispectral Scanning for Forestry and Mapping (with Emphasis on MEIS**),** April 13-16, 1992, Val-Morin, Québec. Inf. Rep. PI-X-113, Petawawa Natl. For. Inst., Chalk River, Ontario.

Gillis, M.D.; Leckie, D.G. 1993. Forest inventory mapping procedures across Canada. Inf. Rep. PI-X-114, Petawawa Natl. For. Inst., Chalk River, Ontario, 79 p.

Gougeon, F.A.; Moore, T. 1989. Classification individuelle des arbres à partir d'images à haute résolution spatiale". Pages 185-196 *in* Bernier, M., *et al*., eds. Télédétection et gestion des ressources Vol. VI - 6e congrès de L'association québécoise de télédétection. May 4-6, 1988, Sherbrooke, Québec.

Gougeon, F.A. 1993. Individual tree identification from high resolution MEIS images. Pages 117-128 *in* Leckie, D.G.; Gillis M.D., eds. International Forum on Airborne Multispectral Scanning for Forestry and Mapping (with Emphasis on MEIS**),** April 13-16, 1992, Val-Morin, Québec. Inf. Rep. PI-X-113, Petawawa Natl. For. Inst., Chalk River, Ontario.

Gougeon, F.A. 1995. Comparison of possible multispectral classification schemes for tree crowns individually delineated on high spatial resolution MEIS images. *Can. J. Rem. Sens.* 21(2):1-9.

Leckie, D.G. 1990. Advances in remote sensing technologies for forest surveys and management. *Can. J. For. Res.* 20:464-483.

Leckie, D.G.; Yuan, X.; Ostaff, D.P.; Piene, H.; MacLean, D.A. 1992. Analysis of high resolution multispectral MEIS imagery for spruce budworm damage assessment on a single tree basis. *Rem. Sens. Environ.* 40(2):125-136.

Leckie, D.G. 1993. Application of airborne multispectral scanning to forest inventory mapping. Pages 86-93 *in* Leckie, D.G.; Gillis M.D., eds. International Forum on Airborne Multispectral Scanning for Forestry and Mapping (with Emphasis on MEIS**),** April 13-16, 1992, Val-Morin, Québec. Inf. Rep. PI-X-113, Petawawa Natl. For. Inst., Chalk River, Ontario.

McColl, W.D.; Neville, R.A.; Till, S.M. 1983. Multi-detector Electro-optical Imaging Scanner MEIS II. Pages 71-79 *in* 8th Can. Symp. on Remote Sensing and 4th Conf. L'association québécoise de télédétection. May 3-6, 1983, Montréal, Québec.

Murtha, P.A.; Fournier, R.A. 1992. Varying reflectance patterns influence photo interpretation of dead tree crowns. *Can. J. Rem Sens*. 18(3):167-173.

Pinz, A.J. 1991. A computer vision system for the recognition of trees in aerial photographs. Pages 111-124 *in* Tilden, T., ed. Multisource Data Integration in Remote Sensing. NASA Conf. Pub. 3099.

Table 1 - Crown or polygon counts for the compartments of Figure 2.

Compartment No.	Tree species	Ground counts	Photo counts	Screen counts A	Screen counts B	Delineation counts
1	White spruce	467	385	402	347	415
2&3	Red pine	218	186	201	180	194
4	Red spruce	235	227	230	222	247
5	Norway spruce	39	39	39	40	138
6	R. pine & W. spruce	368	257	346	297	333
Total		1327	1094	1218	1086	1327
Total without compartment 5		1288	1055	1179	1046	1189
% difference from ground counts (without compartment 5)		0	-18.1	-8.5	-18.8	-7.7

Table 2 - Automatically delineated crowns *vs.* interpreted crowns
Errors of commission and omission

	Delineated crowns : Interpreted crowns							
Compartment	1:0	0:1	1:1	1:2	1:3	1:4	1:5	1:6
1	17	1	357	44	4	1	0	0
2	0	0	166	20	2	0	0	0
3	0	0	16	7	2	1	0	1
4	19	0	220	15	2	0	2	0
6	16	1	311	21	4	0	0	0

Table 3 - Automatically delineated tree crown accuracy by compartments

Compartment	1	2	3	4	6
Accuracy (%)	77	78	35	83	85

Compartments 1, 2, 4, and 6 average accuracy = 81%

Compartments 1, 2, 4, and 6 overall accuracy = 81%

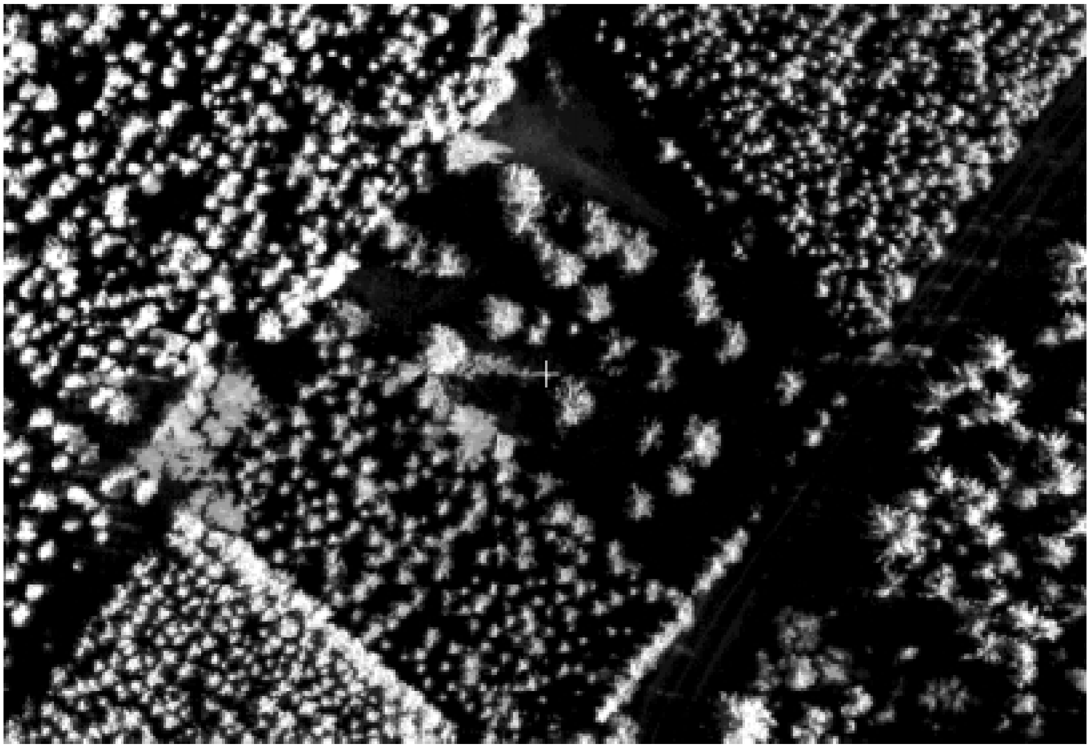
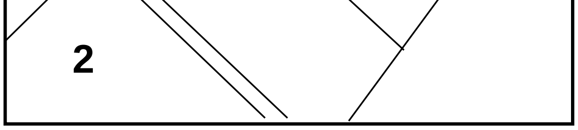


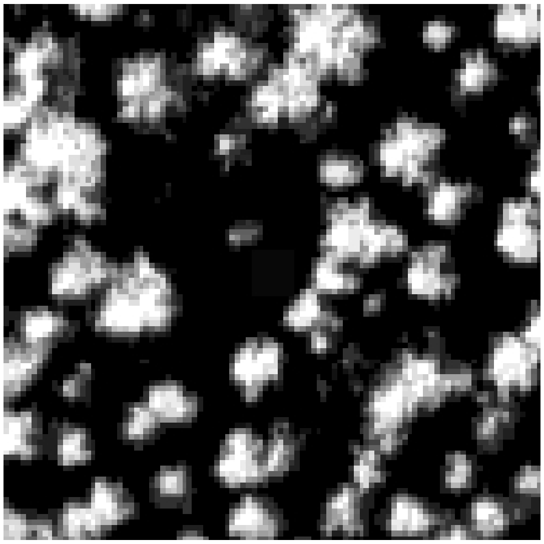
Figure 1 - MEIS-II image (31 cm/pixel) of the Hudson plantation at the Petawawa National Forestry Institute, Chalk River, Ontario, acquired Nov. 22, 1982, from an altitude of 1440 ft.



Compartment Content

1 White spruce
2 Red pine
3 Strongly illuminated red pine
4 Red spruce
5 Norway spruce
6 Red pine and white spruce

Figure 2 - The Hudson plantation compartments used in testing.



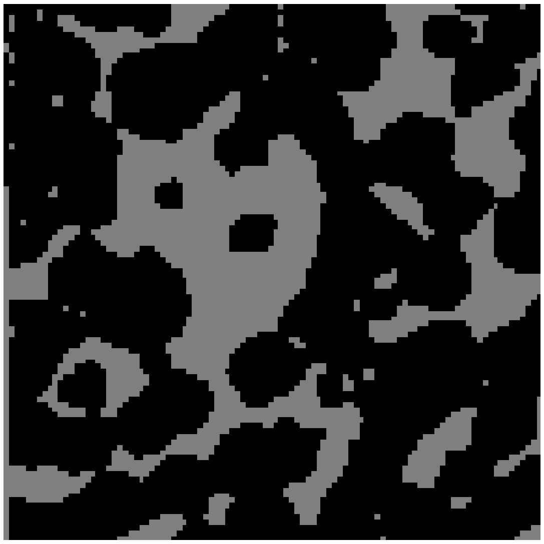
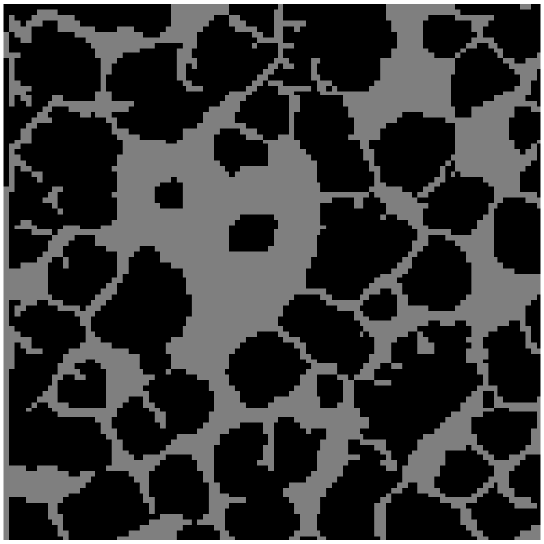


Figure 3a (left) - Upper left corner (100 lines x 100 pixels) of Figure 1.

Figure 3b (right) - Classified shaded area and local minima



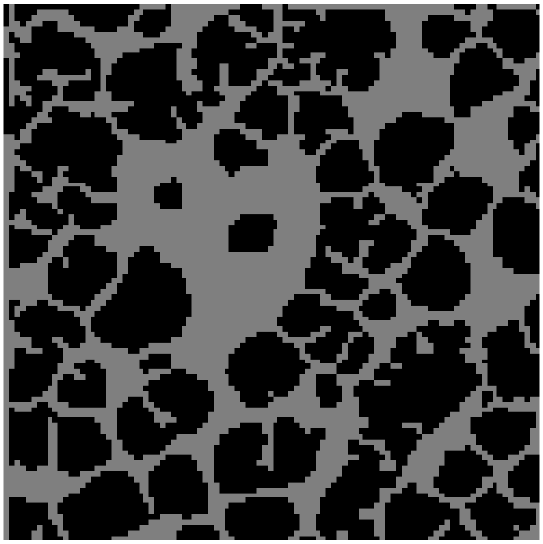
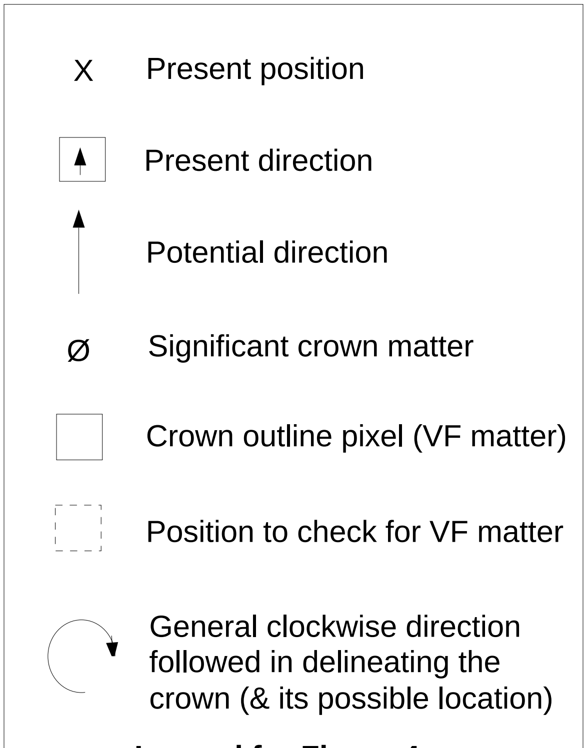


Figure 3c (left) - Results after one pass (favouring valleys going to the right and down) of the valley-following program

Figure 3d (right) - Results after completion of the valley-following program



Legend for Figure 4

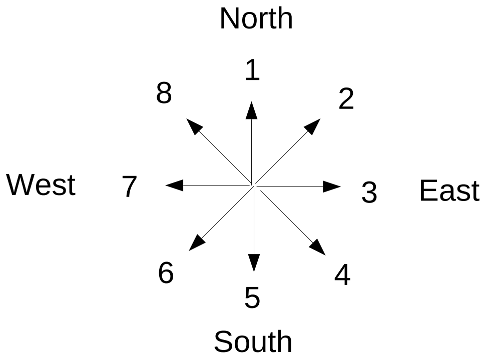


Fig. 4a - The eight directions used

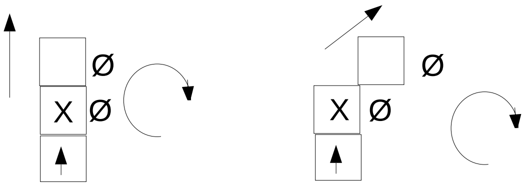


Fig. 4b - Some Level 1 allowable moves
(only clockwise directions 1 and 2 (0°, 45°)
from present direction IDIR=1)

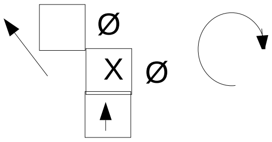


Fig. 4c - One Level 2 allowable move.
Deals with minor breaches (- 45°) to
generally clockwise strategy.

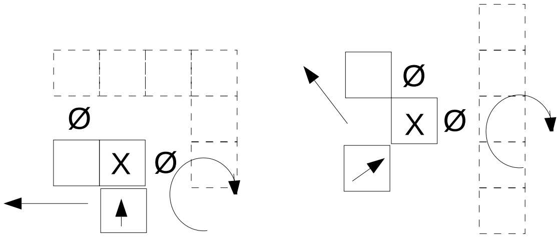


Fig. 4d - Some Level 3 allowable moves.
Deals with possible 90° counter-clockwise turns
while following tree crown outline.

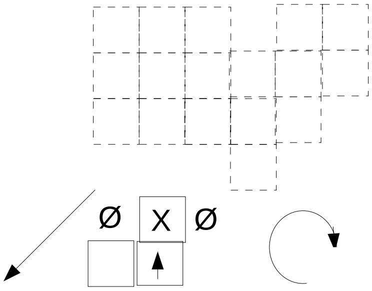


Fig. 4e - One Level 4 allowable move.
Deals with possible crown countour
turn of 135° counter-clockwise

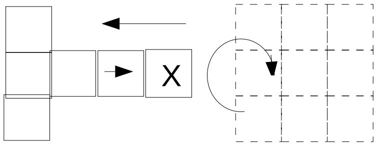


Fig. 4f - One Level 5 allowable move.
Deals with potential direction reversals,
like inlets into a crown.

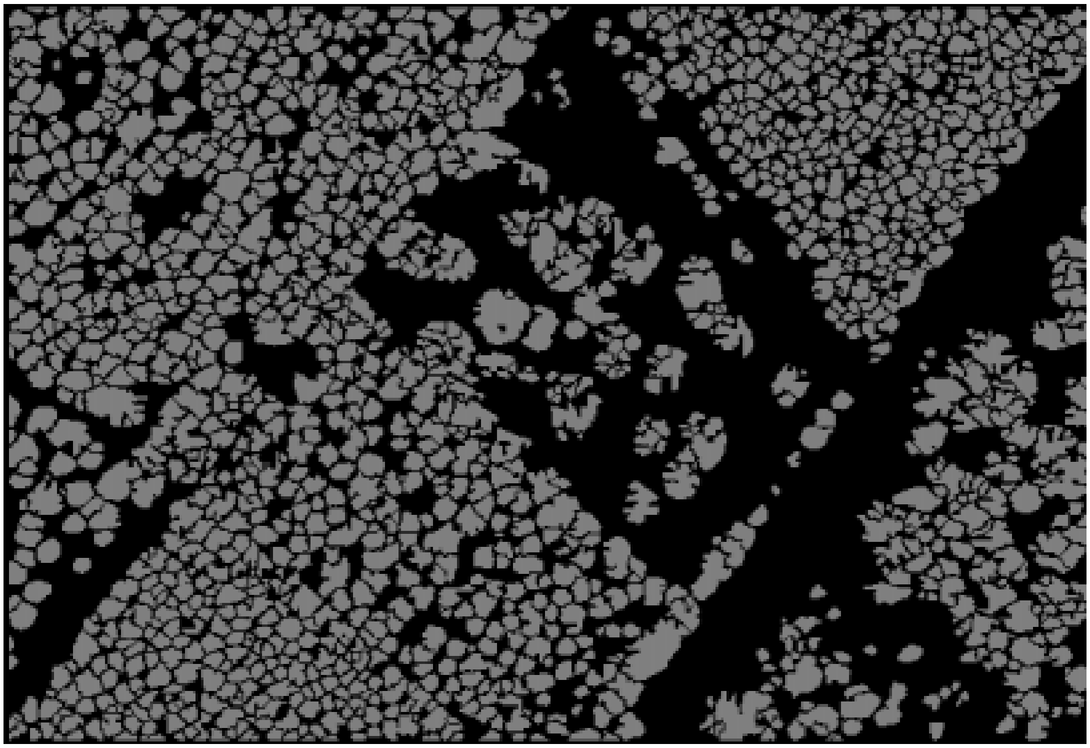


Figure 5a - Final results produced by the rule-based crown delineation program

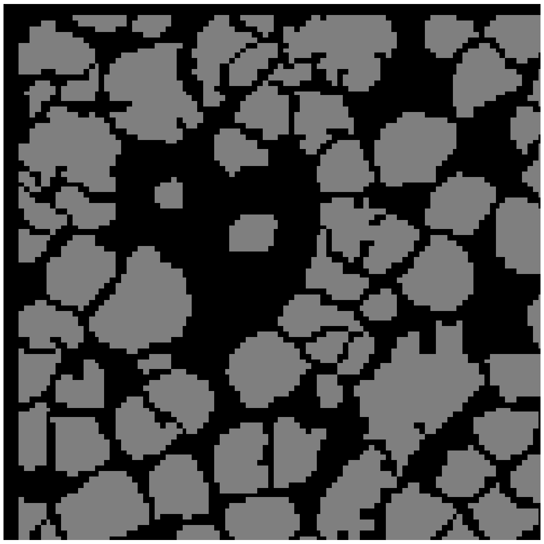


Figure 5b - Upper left corner (100 lines x 100 pixels) of Figure 5a