

# AUTOMATIC INDIVIDUAL TREE CROWN DELINEATION USING A VALLEY-FOLLOWING ALGORITHM AND A RULE-BASED SYSTEM

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## ABSTRACT

In remotely sensed aerial images or digitized aerial photographs of high spatial resolution (10-100 cm/pixel) tree crowns are typically visible as almost distinct items. To produce semi-automatic forest inventories from such data (even stand-based inventories), it is better for the computer to deal directly with this predominant structural element of the images. A first obvious step is thus, the delineation of the individual tree crowns, preferably in a completely automatic fashion. This step is to be followed by an individual tree crown species recognition and then, a regrouping (if needed) into relatively conventional forest stands. Such a comprehensive approach can provide very detailed forest inventories, specially considering that regroupings can be organized to follow criteria other than that of the present inventories. This paper addresses the automatic individual tree crown delineation process.

The individual tree crown delineation is accomplished by first following the valleys of shade that typically exist between the crowns of dense forest stands. The image from a selected spectral band is first smoothed. Areas that are completely in the shade are masked out by thresholding and local minima are found in the remaining areas, except for non-forested areas that were masked out a priori. From the local minima, valleys are followed to other local minima. Visually, this delineates most coniferous tree crowns rather well. However, not all tree crowns are fully delineated and tree clusters still exist, but most importantly, the process does not yet have the concept of tree crowns as distinct elements. This "awareness" is made possible by the subsequent use of a rule-based system which attempts to follow in a clock-wise fashion the internal boundaries of each individual tree crown (ITC) until a distinct closed area is obtained. Additional rules attempt to recognize tree clusters and separate them into ITCs. From there, additional ITC-based processes, such as an ITC-based classifier (Gougeon *et al.*, 1988), are used to produce detailed information about the given forested area.

This paper will first describe briefly the valley-following algorithm and the rule-based system and then, comment on their strengths and weaknesses, and potential remedies to these weaknesses. Examples will be shown throughout. The paper concludes with a list of possible improvements and future developments.

**Keywords:** forest inventory, computer image analysis, individual tree crown, crown delineation, valley following, rule-based approach, ITC.

## RÉSUMÉ

### DÉLIMITATION AUTOMATIQUE DES HOUPPIERS À L'AIDE D'UN ALGORITHME DE DÉFINITION DE ZONES D'OMBRE ET D'UN SYSTÈME À BASE DE RÈGLES

Sur les images aériennes obtenues par télédétection ou sur des photographies aériennes prises à haute résolution spatiale et numérisées (10-100 cm/pixel), les houppiers des arbres se dessinent presque aussi nettement que s'il s'agissait d'éléments distincts. Pour produire des inventaires forestiers de façon semi-automatique à partir de telles données (même les inventaires basés sur les peuplements), il est préférable que l'ordinateur traite directement avec cet élément structurel prédominant des images. Une des premières étapes consiste évidemment à délimiter les houppiers, de préférence en mode complètement automatique. Cette étape doit être suivie d'une identification individuelle des espèces de houppiers et, ensuite, d'un regroupement (au besoin) en peuplements forestiers relativement conventionnels. Une telle approche approfondie peut permettre de constituer des inventaires forestiers très détaillés, surtout si l'on considère que les regroupements peuvent être organisés de manière à respecter des critères autres que ceux qui servent à établir les inventaires actuels. Ce document traite donc du processus de délimitation automatique des houppiers.

On commence la délimitation des houppiers en suivant les zones d'ombre qui se profilent généralement entre les houppiers des peuplements forestiers denses. L'image obtenue d'une bande spectrale choisie est d'abord ajustée. Les zones se trouvant complètement dans l'ombre sont masquées par un seuillage, et on trouve les valeurs minimales locales dans les autres zones, sauf pour les secteurs non boisés qui avaient été masqués au départ. À partir des valeurs minimales locales, on suit les zones d'ombre jusqu'à une autre valeur minimale locale. Sur le plan visuel, cette démarche permet de délimiter avec une bonne précision la plupart des houppiers des conifères. Cependant, certains houppiers échappent à la délimitation intégrale et il reste encore des grappes d'arbres ici et là, mais il faut absolument souligner que le procédé n'est pas encore à l'étape de la délimitation des houppiers comme éléments distincts. Cette étape est toutefois rendue possible par l'utilisation subséquente d'un système à base de règles qui tente de suivre dans un mouvement horaire les limites intérieures de chaque houppier jusqu'à l'obtention d'une zone fermée distincte. En ajoutant d'autres règles, on tente d'identifier des grappes d'arbres et de les séparer en houppiers distincts. De là, on utilise d'autres procédés basés sur la délimitation des houppiers, comme un classificateur du même type (Gougeon et coll., 1988), pour produire de l'information détaillée sur la zone forestière à l'étude.

Dans le présent document, l'auteur décrit d'abord brièvement l'algorithme de définition des zones d'ombre et le système à base de règles, il commente ensuite sur leurs points forts et leurs points faibles et propose des solutions pour remédier à ces faiblesses. Des exemples servent à appuyer ses propos. L'auteur conclut avec une liste d'améliorations possibles et de développements futurs.

## INTRODUCTION

The spatial resolutions of images available from multispectral airborne sensors, digitized aerial photographs and upcoming earth observation satellites imply a change in the digital image analysis paradigm for forestry. With the increased level of details, individual tree crowns are now visible. The forest stand based approaches relying on pixel-based classifications at low spatial resolutions (10-100 m/pixel) and area-based texture segmentations at medium resolutions (1-10 m/pixel) get increasingly inappropriate. At high resolutions (10-100 cm/pixel), it is better to deal directly with the essential structural element of the forest stands: the individual tree crown (ITC).

The ITC approach consists of separating the crowns from one another and from the background vegetation, recognizing one by one their species and, if needed, regrouping them into forest stands. It could enable the production of semi-automatic forest inventories from digital remote sensing data. The species composition of these automatically generated stands (or even existing stands) would be known with an increased level of precision. However, such an approach gathers additional importance when taking into consideration the fact that modern forest management inventories, meant to manage the forest resource in

accordance with much stricter rules taking biodiversity, wildlife, environmental and recreational concerns into account, require even more details than what is currently available. Additional forestry parameters such as tree crown areas, canopy closure, stand density, non-forested gap distribution, etc., are also easily obtained for each stand. The ITC approach also offers the capability to retain the specific individual tree-based information. This could be particularly useful for silviculture treatments, selective cuts, biodiversity assessments, and other applications.

The first obvious step in this ITC-based approach is the delineation of the individual tree crowns, preferably in a completely automatic fashion. This is accomplished by first following the valleys of shade that typically exist between the crowns of moderate to dense forest stands. Then, a rule-based system is used to further delineate the tree crowns. This paper will first describe briefly these two processes and then comment on their strengths and weaknesses. The paper concludes with plans for further testing and improvements in the coming years.

## INDIVIDUAL TREE CROWN ISOLATION

Although perceived as uninteresting background information, one of the important image features that allows humans to detect individual trees in average to dense coniferous stands on aerial photographs or high resolution multispectral aerial images is the presence of thin bands of shade separating the crowns. The automatic "valley following" isolation process uses the same feature. The idea behind the process, following the valleys of shade in a grey-level image, can be easily conveyed by a geographical/topographical analogy (Figure 1). From an illumination point of view, the bright individual tree crowns in an image appear like mountains (i.e., high pixel values). The darker areas surrounding them, the shaded lower branches and understory, appear like valleys (i.e., low pixel values). Furthermore, the mountains may have well lit sides and shaded sides, like mountains at low sun elevation (e.g., sunset), but fortunately, the valleys are typically slightly darker. By following the continuum of locally darkest areas of a grey-level image, the process ends up isolating most of the individual tree crowns from each other and from the background shaded vegetation.

Before using the "valley following" isolation process, some preprocessing is typically required. Firstly, if using a digitized colour aerial photo or a multispectral image, a selection must be made of the appropriate grey-level image (i.e., spectral band) to use. This image is then referred to as the "illumination" image. For general forest inventory purposes, a near infrared band is typically used because of its sensitivity to illumination variations and its good response to vegetative material. However, if defoliated trees are of interest, one of the visible band is typically more appropriate since tree branches and bark produce low responses in the near infrared part of the spectrum. It is also possible to combine the potentially different information available from the various spectral bands by using processes such as "principal component" (Richards, 1986) or "Intensity-Hue-Saturation" transformations (Lillesand & Kiefer, 1994). Secondly, unless the illumination image selected comes from a transformation, the selected image is typically smoothed by a filtering process. This removes some of the natural variability of the data and alleviates some potential difficulties in isolating tree crowns. It also minimizes problems that may be due to sensor (or digitization) noise, noise that is specially prominent in the shaded parts of images. It may also help with the occurrences of branches sticking out of one crown and reaching another one. In addition, depending on the spatial resolution of the image, a stronger smoothing filter may be used and still produce beneficial effects. It could alleviate difficulties related to having too much detail within the crowns, for example, large branches that may have their own shadow within the crown or any self-shaded areas within the lit side of crowns. Thirdly, non-forested areas and forested areas that do not respect the premise of having bands of shade separating their tree crowns should be removed or masked out. This can be accomplished by manually delineating these areas to create a mask or, more often than not, by running a generic pixel-based unsupervised classification and selecting appropriate classes that will be merged into a single mask.

The first step in the "valley following" process involves a threshold that is used to eliminate a priori large shaded areas. These areas, that can be visualized as plateaus within the valleys of shade, are not well suited for an algorithm meant to follow V-shaped valleys. The threshold is presently decided upon by the user examining the typical grey-level values found at the perceived junction of trees crowns and their neighbouring shaded understory material. All pixels with grey-level values below this threshold are then set in the "shaded material" bitmap. The second step involves finding local minima in the remaining areas. Ideally, with the previous

threshold operation and the a priori masking of irrelevant areas, only moderate to densely forested areas would remain to be considered by this operation. In the geographical analogy, these points of local minima correspond to points where lakes collecting water from the whole watershed would exist. These points are then set in the "shaded material" bitmap (Figure 2b). The third step corresponds to the valley following per se. It consists in: (a) scanning the image, looking for the next pixel of "shaded material", which at this point should be a local minima or the boundary of a large shaded area delineated by the threshold; (b) looking around that pixel from a connected pixel flanked on both side by pixels with higher grey-levels (i.e., a V-shaped valley); (c) setting that pixel as "shaded material"; and (d) repeating step "b" and "c" until the valley thus followed connects with a pixel of "shaded material", then step "a" is invoked again. With the addition of allowances for flat bottom valleys that may have 2 or 3 pixels of similar values before a grey-level rise on each side, this algorithm essentially follows all of the shaded valleys in the image. Again, in our geographical analogy, it is akin to going up a valley (from a lake), finding a pass in the mountains, and going down the next valley to the next lake. Visually, this process appears to isolate most of the individual tree crowns visible in the areas of interest (Figure 2c). However, numerous potential crowns are actually tree clusters that could use further separation. In addition, it only knows about "shaded material" and does not know of the crowns (or clusters) as distinct entities. The rule-based delineation process that follows carries out these two mandates.

## INDIVIDUAL TREE CROWN DELINEATION

The more precise delineation of the individual tree crowns and the "awareness" of the crowns as distinct entities for which specific information can be gathered (i.e., position, crown area, ...) is done by a rule-based delineation process. Generally speaking, it attempts to follow in a clockwise fashion a given crown outline by following in a rule-guided way the "shaded material" (extracted by the previous process) that is surrounding that crown. The process starts on the left side of a potential crown and the rules favour right-sided turns, dealing with increasingly complex exceptions from that general rule. When a crown (or tree cluster) has been delineated, the process starts over with another potential crown. Additionally, some of the higher level rules can split a cluster of "vegetation material" into more than one tree. The full process leads to a bitmap of individual tree crowns and, optionally, a database containing information on each tree crown.

More specifically, after having read the bitmap of "shaded material" (SM) and "non-forested" areas produced by the "valley following" isolation process, the delineation process starts by scanning the image (right and down) for a first minimal block (2x2 pixels) of "vegetation material" (VM - defined here as the converse of the bitmap just read in). Starting on the left side of this block, it tries to follow the SM up, or up and right, moving by one pixel. It will continue to move one pixel of SM at a time, favouring a move in its on-going direction or preferably, one pixel to the right of its on-going direction (level 1 rules). Sometimes the only possible move will be to the front-left of its on-going direction, for example, if a tree branch is protruding from the crown. This move will be acceptable under level 2 rules, assuming that level 1 rules have been checked previously. On other occasions the only path available while following the SM is 90 degrees counterclockwise to the on-going direction (e.g., larger branch sticking out). Such a move may be acceptable (level 3 rules), but only after having checked that a more favourable move cannot be executed by bridging a one-pixel-wide gap to some SM on the right or in front. Similarly, level 4 rules make possible turns that are 135 degrees counterclockwise, but only after substantial checking in the front-right direction for better moves that could be done by bridging gaps up to one meter wide. Finally, level 5 rules deal with possible moves implying a complete direction reversal from the on-going direction. Such situations typically represent a serious inlet into a crown (e.g., due to self-shading) or a serious indication that two or more crowns are present and should be separated. Again, a check is performed for SM up to a meter away from the end of the inlet to estimate whether a gap should be bridged. If it succeeds and the gap is bridged, it is possibly separating two distinct tree crowns. If this fails, the situation is considered as an irrelevant inlet within a single crown, and the inlet is actually erased before continuing the crown delineation. Higher level rules using less local perspectives and capable of decisions relative to tree cluster separation into crowns or re-merging of crown parts have not been implemented yet. A more detailed explanation of the existing rules can be found in Gougeon (1995). Typical results of the rule-based crown delineation programme are shown in Figure 2d.

Some of the factors used in the rules (e.g., one meter away) are not fixed and are actually dependent on a combination of the spatial resolution of the image and the sizes and types of trees being analysed. The spatial

resolution of the image is simply picked up from information stored in the image file header. The user can also orient the delineation process by using parameters such as: TREETYPE = regeneration, young, or mature. In fact, both the isolation and delineation processes are implemented within a suite of user-friendly C programs known as the ITC-suite (Gougeon *et al.*, 1998) requiring a minimum user interaction, keeping in-line with the goal of producing modern multi-resources forest inventories as automatically as possible. Finding the trees of a one metre resolution image covering an area of 5 km x 5 km on the ground (i.e., the kind of images expected from the next generation of satellite) can take as little as ten minutes (with a 200 MHz processor). It is expected that the full analysis of such an image, leading to individual tree species recognition and regrouping into forest stands or environmental strata, will not take an inordinate processing time (i.e., calculated in minutes). The amount of time for human interventions will be much more considerable, specially to train the classifier and verify the accuracy, and could take one or two days' worth of work at the computer.

## STRENGTHS AND WEAKNESSES

Although delineation accuracy has not been completely tested yet (e.g., crown area accuracy), early results (Gougeon, 1995) indicated automatic tree counts from the delineation process to be within 7.7% of counts on the ground. When omission and commission errors (which tended to cancel each other) were taken into account, the tree counts were found to be 81% accurate. These tests have been done on a 31 cm/pixel MEIS image of mature coniferous plantation stands and compare favourably with human interpretations of aerial photos (1:2000) and of the MEIS image itself. However, the delineation approach is not always as efficient at properly separating individual tree crowns at coarser spatial resolutions. It tends to delineate more tree clusters (>20% reported above).

Preliminary tests of stem densities on 49 year old Douglas-fir plantations that had undergone thinning and fertilization experiments seen in a 60 cm/pixel *casi* image are not as encouraging. Tests using 27 plots ranging in densities from 650 to 1750 stems/ha (dominant and codominant trees) led to crown delineation densities of 525 to 775 stems/ha (average absolute error = 36.7%). Its theoretical limit, giving small trees that perfectly occupy the minimum 2x2 areas of "vegetation material" with valleys of shade of a minimum one pixel wide (even after smoothing), is of the order of 3000 stems/ha. However, this does not necessarily point to a tendency for the delineation process at 60 cm/pixel to saturate at a given upper limit of density (i.e., at 775 stems/ha). Indeed, when the stem densities found are shown as a relative stem density image (Figure 3), the situation corresponds well with the stem densities known to be present (Brix, 1993, Figure 1). Efforts to bring in other techniques, for example those based on finding local maxima (Gougeon & Moore, 1989; Pinz, 1991; Eldridge & Edwards, 1993; Dralle & Rudemo, 1996), to improve stem density estimations have not been very fruitful. It should be noted, however, that human assessment of that image is also problematic. There is a lack of visible separation of individual tree crowns which could be due to specific acquisition conditions. This is still the subject of investigations. Nevertheless, the test site was successfully used to derive volume estimations from "vegetation index" and "uniformity" parameters derived from the *casi* image (Magnussen & Boudewyn, 1998).

The main weakness of the delineation approach is directly related to its prime assumption: that the tree crowns in an image are usually separated by bands of shade. This means that, at present, this approach could be limited in its application to moderate to dense forest stands. It is also much more appropriate to the conical shape of softwood trees which typically leads to the creation of shade between the tree crowns. Fortunately, these are conditions that are often encountered in Canada's forests. In addition, when dealing with multispectral imagery, it is often possible to eliminate bright understory and open areas by various pre-processing techniques (see Gougeon & Leckie, 1988).

Another potential weakness, which could affect tree crown area estimation, is the use of a simple threshold to eliminate a priori the large shaded areas before the valley following *per se* actually starts. Figure 4 is an example of different results obtained with various thresholds. In addition, the illumination within these shaded areas is also affected throughout the image by the sun and view angles (and topography). This non-uniformity implies that for a given fixed threshold, crowns close to large shaded areas in certain parts of the image will tend to be larger, everything else being constant, than in other parts. The use of a BRDF-adaptable threshold (Yuan & Leckie, 1992; Leckie *et al.*, 1995) or a more sophisticated shade segmentation process (Gwinner & Schaale, 1997) may eliminate this problem.

Another problem arises when dealing with trees of substantially different sizes within the same image. With large tree crowns and/or high spatial resolution, and with certain tree crowns exhibiting pronounced radial branching patterns and self-shading properties (e.g., big Norway spruce), the delineation process has a tendency to penetrate the crowns and break them into numerous smaller crowns (Figure 5). It is possible to alleviate this tendency by using additional smoothing on the image. However, this is detrimental to the isolation and delineation of smaller trees on the same image. A self-adjusting smoothing filter, that locally applies more or less smoothing depending on the size of crowns it encountered (based on local variance or variograms), may be an appropriate solution.

The present rule-based system uses the assumption that crowns are relatively round objects. However, tree crowns that are seen significantly off nadir are anything but round. For coniferous trees, significantly off-nadir crowns can appear as triangles if front lit, or an inverted V, if backlit. Nevertheless, the present rules seem not to be encountering too many problems and the assumption of round objects seems not to be too detrimental to delineating objects of other shapes. In addition, with *casi* and MEIS images the off-nadir situations are not as dramatic as expressed above. These situations are more likely on large scale aerial photographs. In such cases, it is often possible, because of the high percentages of overlap between flight paths, to concentrate on image centres. More importantly, this problem is not going to be an issue with images from the next generation of satellite because of relatively narrow field of view.

A related possible weakness of the present delineation system is that of crown area accuracy. It may be assumed that even under ideal circumstances (at nadir, with trees immediately adjacent to each other), crown areas will be systematically underestimated by factors related to the spatial resolution of the image and the tree sizes themselves. For example, it is known that theoretically (assuming that the shaded side of crowns can be properly delineated from the shaded understory), tree crown areas will be deprived of at least half a pixel's width worth of area all around their circumference because the valleys of shade used to separate the crowns are at least one pixel wide. However, at this point in time, such a "systematic" underestimation is only a hypothesis and would, of course, only be valid close to nadir. With increasing off-nadir angles, the situation becomes a lot less predictable (see below). In on-going work (Leckie & Gougeon, 1988), where automatically delineated tree crowns are compared with their manually delineated (on screen) counter parts for species classification accuracy and crown delineation capability, encouraging preliminary results have been obtained with 36 cm MEIS data (Figure 6). On average, for a total of 357 manually delineated trees of 19 species in 24 field plots, crown areas, stem counts and canopy closure are in error by only 1.2%, 8.7% and 7.4%, respectively. However, on a one-on-one basis, only 58% of the automatic crowns intersect with the manual crowns by more than 50%. This difference between human and machine crown delineation needs to be investigated further, but currently, stand (or plot)-based estimations appear useful.

Even if good crown area estimations could be achieved (with a systematic error) at nadir, it would certainly break down with increasing view angles and the front-lit/back-lit situations mentioned previously. The tree crown localisation approaches based on a geometric modelling of the crowns (Pollock, 1994; Larsen, 1997) should have an advantage in this regard, as the model can be used to predict the real tree crown area from the apparent (viewed) tree crown. However, for satellite images, off-nadir viewing effects (significantly non-circular crown) are not a problem because of the satellite sensor's limited field of views. Similarly, complete aerial coverage of an area is typically done with substantial overlap between the image strips (or photos), allowing for the computer analysis to be concentrated on the centre sections of each strip (or photo). Nevertheless, geometric modelling of crowns could help in further separation of tree clusters. Thus, if partially integrated in the present system, it could serve these two purposes.

One advantage of a rather precise delineation process (specially at resolutions such as 30 cm/pixel) over the geometric modelling approach is that it makes possible an analysis of crown contour. Such information could be of use to infer (correlate with) actual tree crown structure. Other advantages, specially relative to methods that merely locate tree crowns (e.g., local maxima), are the possibilities of analysing the crown's textural and structural characteristics, as well as, some finer spectral characteristics. These may lead to better species recognition capabilities.

In some cases, specially at the lower spatial resolutions (60-100 cm/pixel), detailed ITC contour delineation may not be a concern. Similarly, apart from assessments of stem densities, sub-perfect crown separation may not be critical. It may be adequate to deal with a mixture of ITCs and tree clusters. Using the present delineation process with a 60 cm/pixel case image, species identification and regrouping into forest stands for species composition assessments provide very encouraging results (Gougeon, 1997; Gougeon *et al.*, 1998). In addition, compared to the model-based approaches mentioned above, this delineation approach is less computer intensive.

## POSSIBLE FUTURE DEVELOPMENTS

Numerous possible improvements to the individual tree crown delineation process have been mentioned above. Some are already the subject of on-going research. The following list highlights some of the possible future developments:

- the automatic determination of a "large shaded area" threshold
- the development of a BRDF-adjustable threshold
- the elimination bright understory and open areas by various pre-processing techniques
- crown area accuracy testings (systematic underestimation / off-nadir effects)
- a shade segmentation process (by region growing) to replace the "large shaded area" threshold
- crown-size-adaptable smoothing (as preprocessing)
- access to the multispectral data to help the initial crown separation using multiple valley followings
- access to the multispectral data to help final crown separation by the rule-based system
- use of local maxima and/or moments to help decide on additional crown separations
- higher level rules using "less local" parameters to detect and further separate tree clusters
- higher level rules using "less local" parameters to detect and regroup crown segments into single crowns
- geometric modelling of crowns to help with tree cluster separation and off-nadir crown area estimations
- improvements of rules specifically geared to hardwood crown delineation
- non-erasure, in the valley following phase, of serious inlets into crowns because they could be used:
  - (a) for higher level separation decision later
  - (b) to produce valuable information on crown boundary structure for species recognition
- potential use of crown closure and stem density for biomass or merchantable volume estimations
- implications/importance of adding height information from LIDAR data
- addition of a digital terrain model to evaluate its importance

These are a few of the current short and long term research ideas being considered. Of course, new ones will surface as the work progresses; in particular, numerous issues will be raised as we try to operationalize this type of work.

## CONCLUSION

A system based on following valleys of shade and contouring rules to automatically delineate individual tree crowns in remotely sensed aerial images or digitized aerial photographs of high spatial resolution (10-100 cm/pixel) was presented. Its present strengths and weaknesses were outlined. It works remarkably well at delineating individual tree crowns (ITC) at spatial resolutions around 30 cm/pixel (81% are 1:1 crowns), but its delineation capabilities have not been quantified yet at lower resolutions such as 50-100 cm/pixel. At these resolutions, tree clusters seem to be a bit more prevalent. Of course, numerous improvements are possible and some are already in the works.

The main benefit of this automatic ITC delineation system is that it makes possible a more complete system of ITC-based species recognition, followed by regroupings into automatically generated or existing forest stands, or environmental strata. Such an approach provides rather precise information about the content of stands and/or environmental strata, including species composition, stem density, canopy closure, gap assessments, to name but a few. This kind of information has not been previously available from digital remote sensing. Moreover, it should be possible in the near future to get it from satellite images. The kind of new

information this can potentially provide, such as gaps distribution for wildlife corridors or forest details for selective logging plans, is very compatible with a multi-resources management of our forest.

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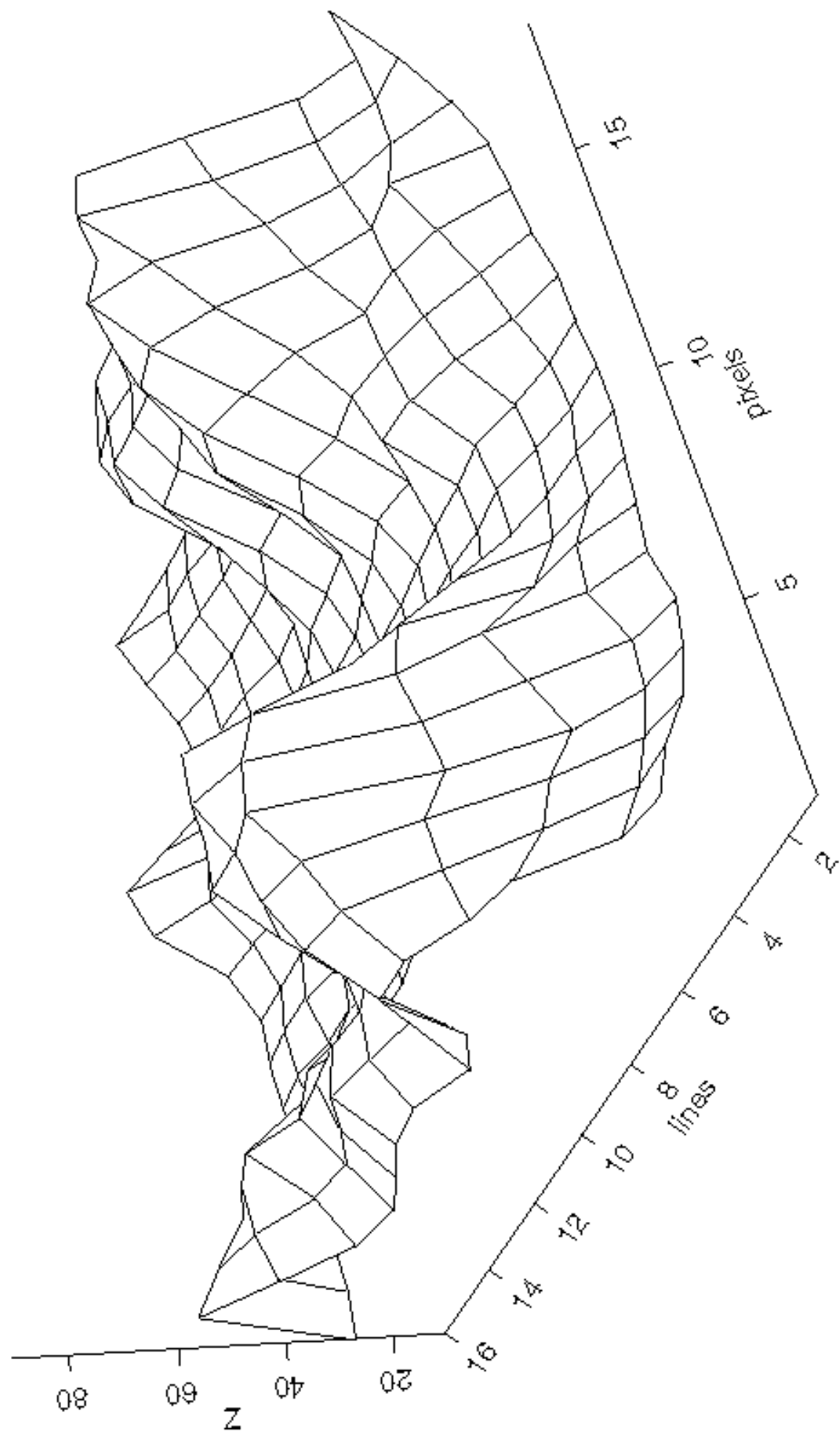
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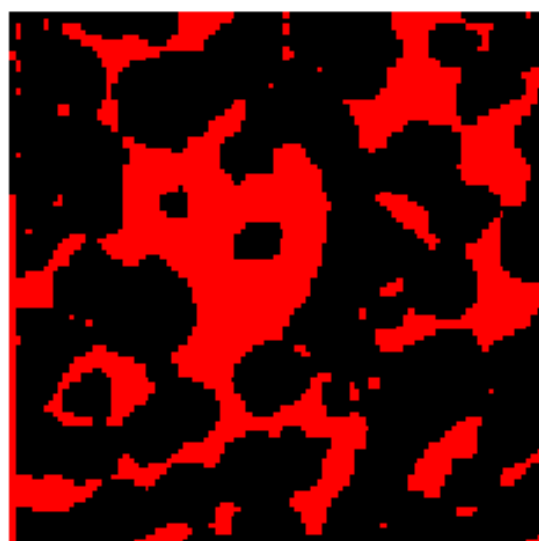
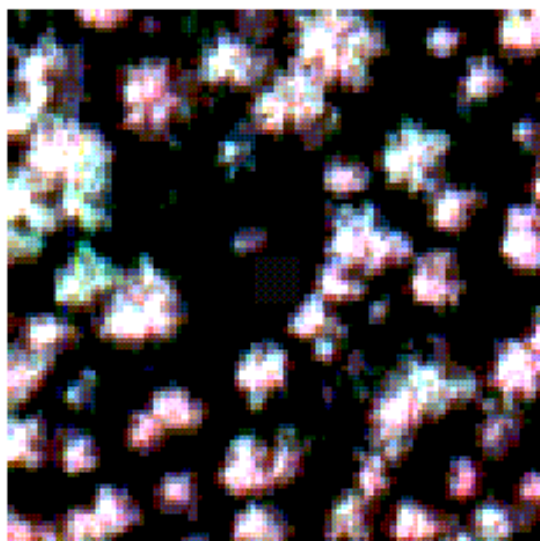
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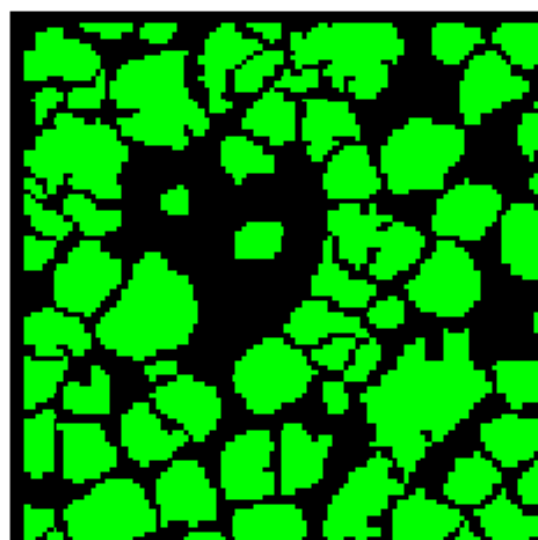
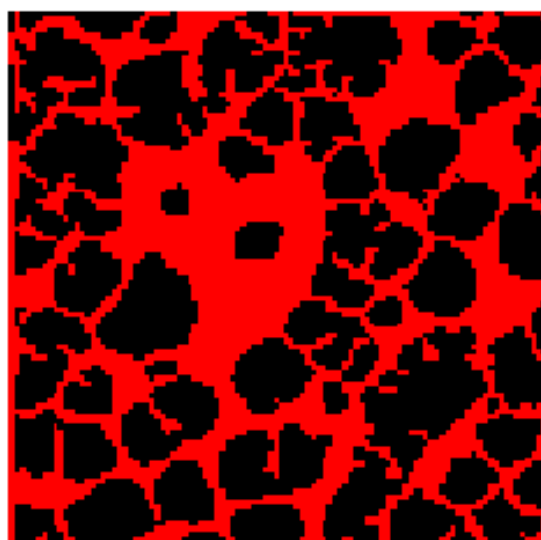


**Figure 1.** A three-dimensional view of a small section (16X20 pixels) of a MEIS-II image showing the tree crowns brightness as mountains with valleys of shade separating them.



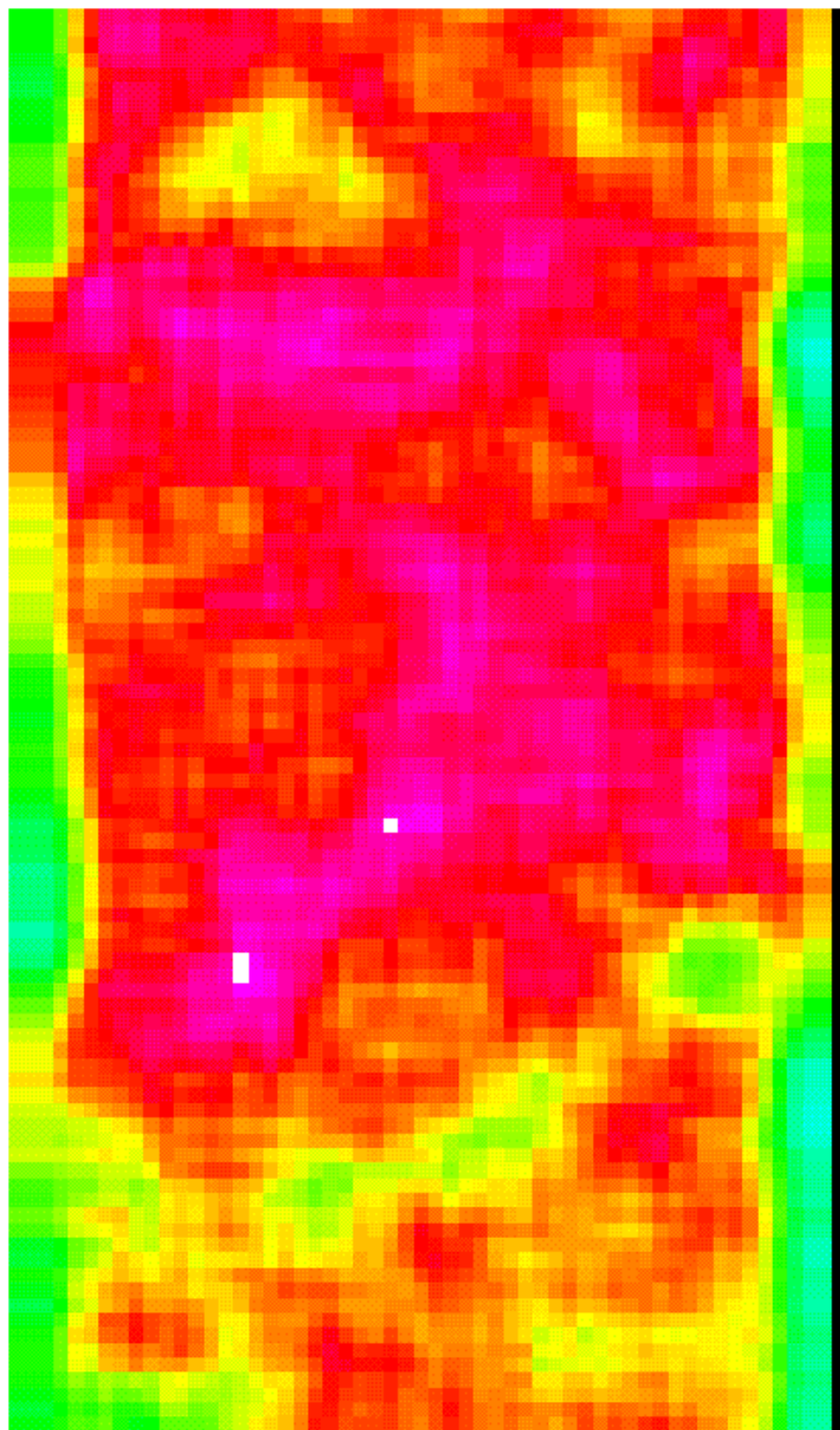
**Figure 2a (left).** Section (100x100) of the near infrared channel of a 31cm/pixel MEIS image (from Gougeon, 1995).

**Figure 2b (right).** Shaded areas and local minima of Fig. 2a (from Gougeon, 1995).

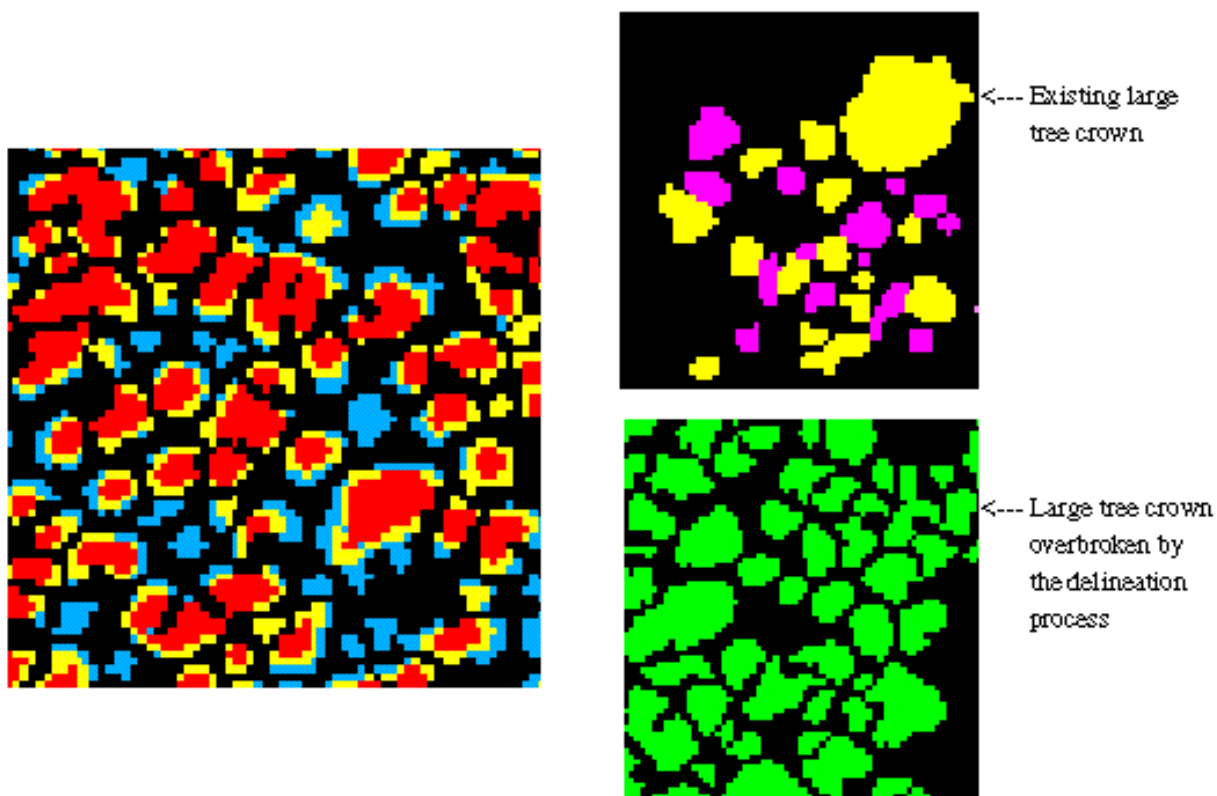


**Figure 2c (left)** Results after completion of the valley-following program (from Gougeon, 1995).

**Figure 2d (right).** Final results produced by the rule-based crown delineation program (from Gougeon, 1995).

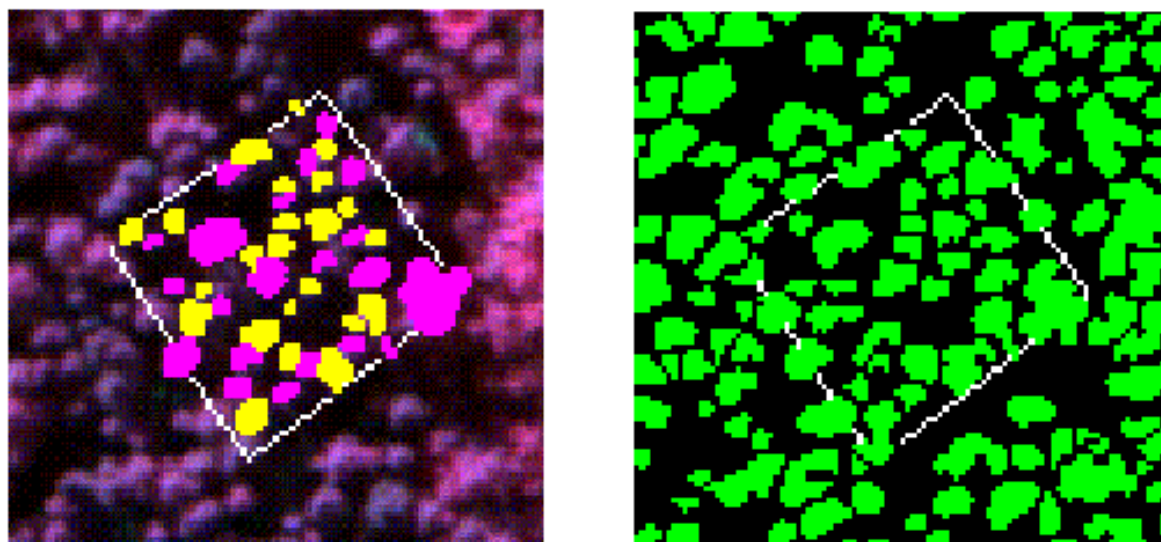


**Figure 3.** Stem density image derived from the automatically delineated individual tree crowns in a 60 cm/pixel aerial image of the Shawnigan test area, Vancouver Island, British Columbia. The "hotter" colours represent the denser areas.



**Figure 4 (left).** Section of a 36cm/pixel MEIS image showing the differences in delineation results when different thresholds are used (blue = 23, yellow = 33, and red = 43).

**Figure 5 (right).** Example of a large tree crown being overbroken by the delineation process.



**Figure 6a (left).** Section (200x200) of a 36cm/pixel MEIS image showing a test plot and the manually delineated tree crowns within.

**Figure 6b (right).** The crowns automatically delineated by the ITC system for the same area as Fig. 3a