Forest Remote Sensing in Canada and the Individual Tree Crown (ITC) Approach to Forest Inventories

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Abstract After a brief description of Canada's forest situation and the role of the federal government in forestry, some Natural Resources Canada' country-wide project will be introduced. These include the National Forest Inventories (past and present), the National Forest Information System, the EOSD programs to map land cover, monitor change and evaluate biomass, mostly from Canada-wide coverages with Landsat images. The accounting of carbon and the monitoring of deforestation at a map scale level will also be introduced. The second and most significant part of this paper will describe our Individual Tree Crown (ITC) approach to forest inventories used with high spatial resolution images (better than 1m/pixel). Techniques for individual crown delineation, species classification and regrouping into forest stands that are leading to a semi-automatic production of forest inventories will be described. A locally adaptive technique for tree counts, mostly reserved for young regenerating areas, will also be presented. The synergy of multispectral and LIDAR data (at many levels) will be examined and, the normalization of spectral values within and among aerial images will be considered.

Key word : remote sensing, forest inventory, computer image analysis

Introduction

Canada is a vast country with 402 million hectares of forested areas (about 41% of its total area). This represents 10% of the world's forests or 40% of the world's boreal forests. Of this, 295 Mha are considered of potential commercial value. Canada is the world's largest exporter of forest products, with 16% of global trade. Consequently, the forest sector is a big part of the Canadian economy (3% of GDP), as are other natural resources.

Forestry information is needed at many scales : national, provincial, regional and local, for management or operational purposes. In this paper, we will address the information needs at two opposite scales : national and local. However, with the increasing availability of high spatial resolution satellite data (better than 1m/pixel) and with advanced in computer automation, these could come together within our lifetimes.

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Canada-wide Forestry Information Projects

In Canada, 94% of the forest is publicly owned and mostly managed by provincial and territorial governments. The federal government is involved in forestry on three levels : policy and international affairs ; international trade in forest products ; and mostly, forest science research and development. Of importance for these three endeavors is the acquisition or collection of good information about Canada's forests and forestry sector. The federal government also has a moral responsibility to Canadians and to the international community (e.g., United Nations) to make such Canada-wide information available.

The first efforts in this direction dated from the 1980's, when mid-size computers became powerful enough (and affordable enough) to store vast quantities of geographical data in relational databases and geographic information systems. This led to the creation of the first National Forest Inventory (CanFI), as an amalgamation of provincial level summaries by 10 km^2 cells, and of the national Forest Insect and Disease Survey (FIDS) database, an important federal responsibility of that era.

The newest National Forest Inventory (NFI) is based on sampling using B&W aerial photo interpretation backed by field work. Sample units are areas of 2×2 km^2 randomly chosen on a 20 km grid with the needed density to produce valid forest information for all of the main forest regions of Canada. Although NFI is more rigorous than CanFI in producing Canada-wide summaries, it lacks the spatial cartographic component of its predecessor. This lack is addressed by the Earth Observation for Sustainable Development (EOSD) Land Cover Mapping project, where full Landsat coverages of Canada are used to convey the spatial distributions of generic forest-types. To make sure that these forest-types are as consistent as possible throughout Canada for a given coverage (i.e., time period), atmospheric correction and image normalization schemes are used. The resulting Land Cover Mapping from the Landsat images is also the basis for the EOSD Biomass project and is used by NFI for the more northern regions not covered by aerial photos.

Another aspect of EOSD is its change detection component. Since Landsat coverages were acquired for various time periods (i.e., corresponding to the needs of the Kyoto protocol), one can compare the forest covers between these periods and monitor changes through time. This comparison can be done between the resulting classified Landsat data of each time period or by analyzing rawer Landsat data, or both. In any case, once a change is detected, a specific cause must be attributed to that change. This is the job of the more specific Deforestation project, where deforestation, afforestation and reforestation situations are ascertained, using existing aerial photographs, oblique photos from aerial sorties, auxiliary data and information from local sources.

Two other projects within NRCan/CFS complete these Canada-wide endeavors: the Carbon Accounting project and the National Forest Information System (NFIS). As its name implies, the first project attempt to account for the carbon stored (sources and sinks) in our forested areas, initially by modeling carbon at the national level, but increasingly by applying carbon models at a more regional level (i.e., the forest management inventory level, at scales around 1 : 15K). The NFIS project is meant to make all of the results from previously mentioned country-wide projects, forest economics and other related information available on-line to the Canadian public and throughout the world via a World Wide Web interface.

An Individual Tree Crown (ITC) Approach to Semi-Automatic Forest Inventories

Canadian forest management inventories are typically done at a province wide level on a 10-15 year cycle. They typically consist in stand mapping and content assessment derived from medium scale aerial photo interpretation (1 : 10K to 1 : 20K), plus volume estimates derived from field sampling and stratification. The only significant change to that approach has been the recent transition to soft-copy interpretation systems, and in some cases, digital sensors. It is a very demanding process, with a high probability of biases introduced by the interpreters.

High spatial resolution (better than 1m/pixel) digital images from satellites or aerial sensors in concert with semi-automatic computer analysis have the potential to supply the information required for these traditional forest management inventories, and much more. For multi-resource management, just in time selective logging, and more generally for precision forestry, modern forest management inventories will require much more details, with increased precision, accuracy and timeliness.

As individual tree crowns (ITCs) are the essential structural element of such high-resolution images (i.e., most dominant and co-dominant tree crowns are clearly visible), it is better to deal directly with these objects in any computer-based image analysis. If the ITC information "per se" is not required, this process can be viewed as a necessary intermediate step that the computer requires to produce precise and accurate information at the forest stand level. However, we can confidently predict that ITC-level information will quickly gather importance (e.g., selective cuts) once it is known to be available.

Methodology

The individual tree crown approach consists of a suite of techniques for individual crown delineation, species classification and regrouping into forest stands can lead to the semiautomatic production of forest inventories (Gougeon and Leckie, 2003). One of the original assumptions, one often encountered in natural forests, is that the tree crowns are surrounded by shade. Later, we will see how this assumption can be bypassed under certain condi-tions by a proper pre-processing of the images. However, it is important to always keep this main assumption in mind.

The delineation of tree crowns is based on following the valleys of shade that exist between the much brighter crowns. Since crowns often touch each other and branches from individual trees often intertwine, this process does not succeed in separating all tree crowns. It is followed by a rule-based program that attempts to finish the job by taking additional decisions leading to more crown separation. At the end, depending on the spatial resolution of the image and various viewing geometry considerations, there will always be some remaining tree clusters that are output as distinct objects of their own. We often refer to these objects as "isols", when we want to differentiate them from pure ITCs.

Under good circumstances, up to 81% of the resulting objects can correspond one for one with those delineated by an interpreter. In addition, errors of omission and commission (i.e., over-split crowns) often balance each other to a certain extent, such that the delineated tree crown counts (i.e., isols counts) can be as close as 8% from ground counts (in an ideal forest plantation situation imaged at 31 cm/pixel) (Gougeon, 1995). Obviously, the results will not be as good in complicated multi-storied forests and/or with images of cruder spatial resolution and/or of poorer quality. However, when the ITC information (e.g.: counts, species, crown areas, heights, ...) is regrouped at the forest stand level, it still leads to very precise information by today's standard.

With multispectral images (and to some extent with panchromatic images), the ITCs can be classified into species based on their color content differences (Fig. 1). In this process, a human interpreter delineates on the image areas that are known to contain single species, or single species in particular situations (e.g., young or mature individuals, sunny/shaded side of hills, brightly lit emergent crowns). Later, the computer gathers the multispectral information within the ITCs that are within such training areas to create representative species (or class) signatures. When this is done for all the situations (species, classes) of interest, a maximum likely-hood classifier is invoked to classify all of the ITCs in the image into the closest spectral class (species). Typically, test areas for each class are also delineated at the same time as the training areas in order to be able to test and improve the classification accuracies

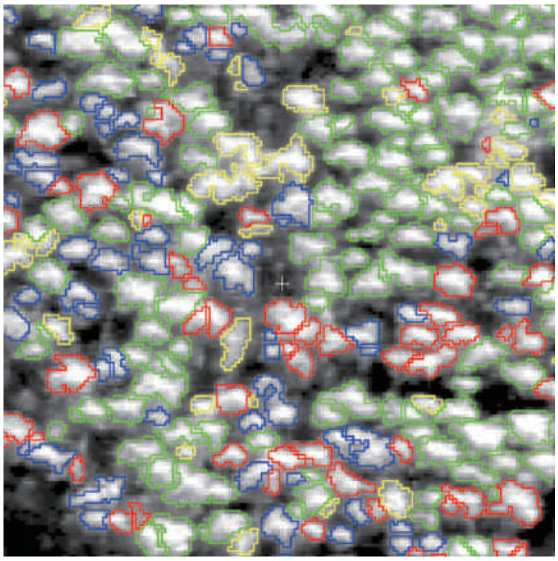

Fig. 1 Examples of delineated and classified Individual Tree Crowns (ITCs) from aerial sensor data acquired at a spatial resolution of 36 cm/pixel. There are still some tree clusters, but 81% of the crowns are the same as that of an interpreter.

by subsequently modifying some classes or, introducing or removing others.

One of the advantages of the valley following crown delineation process over most other crown segmentation processes is that it delineates fuller crowns. That is, it delineates the well-lit part of the crowns as well as the shaded part of the crowns, as the later are still brighter than the deep shade between individual crowns. On one hand, this fuller crown delineation is a better reflection of reality and is more amenable to produce better crown area and crown diameter statistics. On the other hand, it can be detrimental to the ITC signature generation and classification processes, as signatures become more related to the percentages of lit to shaded pixels in ITCs than their intrinsic species-related color. Consequently, the ITC spectral signatures are typically generated using only the pixels from the lit-side of the crowns (Gougeon, 1995b).

Species classification accuracies of the order of 60% to 75% separating 4-6 coniferous and 4-6 deciduous species have been consistently achieved with a variety of data sets spanning spatial resolutions from 30-100 cm/pixel (e.g., Gougeon, 1995b ; Gougeon and Leckie, 2005 ; Chubey *et al.* 2009). With the higher spatial resolution images (10-30 cm/pixel), ITC texture and structure signatures can be added to the multi-spectral information to help the species classification process (Gougeon, 1995b). This mimics to a certain extent the species recognition process of human interpreters as they mostly use texture and structure to recognize species, especially on panchromatic images.

For tree crowns not meeting the minimum requirement (of 2×2 pixels) for full crown delineation such as, mature trees in lower spatial resolution images (～1 m/pixel) or, in higher resolution images, trees that have a very small crown (e.g.: lodge pole pine, black spruce) or, very young regeneration (i.e., few meter high), the TreeTop (or local maxima) technique is often used (Gougeon, 1997). It consists in finding the most brilliant pixel within a given image area (3×3, 5×5, or 7×7). Of course, the TreeTop technique does not lead to any crown area information, but it does permit stem counts and tree speciation.

The TreeTop technique is generally used under the same conditions as the valley following technique, namely, in fairly closed canopy forests where tree crowns are surrounded by shade. A version of the TreeTop technique was also developed for sparsely populated forest areas, that is, where specific shadows are visible. This technique looks for local maxima with a shadow patch at a specific distance in a direction opposite to that of the sun. A Locally Adaptive TreeTop (LATT) technique switches on-the-fly between both techniques using an a priori generated mask, typically based on image directionality (i.e., the preponderance of a gradient direction) (Gougeon, 1997).

When analyzing sizeable areas, such as a typical Canadian forest management unit, the individual tree information (species, crown area, height, etc.) is usually reported by forest stand polygons. These polygons could be forest stands obtained by conventional photo-interpretation means or, freshly generated ITC-based forest stand polygons (see next paragraph). The Polygon Content Description program adds new fields (attributes) to each polygon and uses them to report on the results of the ITC image analysis. For each polygon, the program will report its area and the number of ITCs it enclosed, assess stem density and crown closure, evaluate the average ITC crown area and height (if a Digital Canopy Model (DCM) image is present (see next section)), and report the same for each species, organized in order of prevalence (by crown closure or number of ITCs). Of course, such information is readily transferred (e.g., as a shape file) to Geographic Information Systems, where forest inventory information typically resides.

The ITC-based forest stand polygons are typically generated following a methodology that combines criteria such as species composition, stem density, crown closure, and if available, stand heights from a LiDAR generated DCM (Gougeon, 1997b ; Leckie et al., 2003). These are essentially the same criteria as used by interpreters when delineating forest stands. For a forest management unit, variations in stem density and crown closure can be conveyed in an image form by averaging their numbers over a small area such as half a hectare. Species composition is harder to convey. However, a series of species by species stem density images can be used as surrogates for species composition. These images, combined with a DCM image if available, are fed to an unsupervised pixel-based classifier which creates classes based on these criteria. Some classes may need to be combined, but already a good forest stand separation typically emerges. When satisfied with the breakdown, a filter to remove noise and one to merge small areas into surrounding bigger one (based on legislated minimum area for a forested stand) are applied. Then, it suffices to convert the resulting forest stands from raster areas to outlining polygons and attach the fields summarizing their ITC content.

Synergy with LiDAR Data

LiDAR (Light Detection and Ranging) data, typically acquired from airplane flights over an area of interest, can take many forms. Here, we will address only LiDAR data acquired in the form of first and last returned pulses, spanning the area of interest at a particular sampling rate. We will consider a low sampling rate to be of the order of one pulse per square meter (1 p/m^2) and a high sampling rate to be of the order of 10 p/m^2. The return signals from a pulse convey a position (X, Y) and a height (Z) where enough material was encountered for the pulse to be returned to the detector. First returns are often used to make Digital Surface Models (DSM) and last returns to produce Digital Terrain Model (DTM) images. The DTM can be subtracted from the DSM to create a Digital Canopy Model (DCM), where heights correspond to vegetation heights in forested areas.

Synergy with LiDAR returned pulse data and their derivatives (DTM, DCM, DSM) can occur at many levels. The most obvious one, typically using a DCM made from a low sampling rate acquisition, is to provide a forest stand height for each forest stand polygon. Also, as seen above, such DCM may have already contributed in-part to the semi-automatic forest stand delineation process. With a DCM from a high sampling rate acquisition, one can think in terms of individual tree heights by picking up the maximum return within ITCs. In any case, such tree heights will generally underestimate the real heights (for numerous reasons) and may need to be adjusted with regression-based inferences (Leckie *et al.,* 2003b).

Another important function that LiDAR-generated DCM can provide, even from low density acquisitions, is to help an ITC analysis of aerial (or even satellite) images by supplying a mask (based on a simple height threshold) indicating low lying vegetation and bare ground. This will allow the ITC analysis to fare well even in open canopy forest, thus allowing the ITC delineation process a welcomed divergence from its main assumption that crowns need to be surrounded by shade. This is particularly useful to isolate individual tree crowns in wide open fields or in very sparse forested areas. Similar thresholds can also be used to control the application of different techniques (e.g., ITC vs LATT) to different types of forested areas depending on their heights (e.g., TT on young regeneration). Of course, such thresholds are also an easy way to remove roads and agriculture areas from the ITC analysis.

It is also important to note that the valley-following approach to crown delineation can be used directly on a smoothed DCM from a high sampling rate acquisition (Leckie *et al.,* 2003), generally leading to better positioned fuller crowns compare to those from aerial images. Theoretically, the ultimate crown delineation process would combine delineation efforts in the multispectral space with delineation efforts on a high resolution DCM image, as they provide two different perspectives on the same trees (Leckie et al., 2003b). However, apart from the trees that are close to nadir in both domains, it may be extremely difficult to precisely align these domains for that synergy to occur everywhere, especially in regards to aerial images. Similarly, even with separate ITC analyses, it may be difficult (but not impossible) to just bring about one feature (such as height or species) to the other domain. This may be easier done with satellite images, as their limited field of view (~2°) does not overly displace objects such as trees from their real positions. However, the presence of important relief and/or a satellite image acquired at an angle may displace objects significantly. In any case, the cost of high sampling rate LiDAR acquisitions covering large areas is still prohibitive for most operational forestry applications at this point in time.

BRDF Correction and Normalization of Aerial Data

Images from aerial sensors bring many additional challenges to an ITC analysis. Their large view angles (±32°) show increasingly leaning trees as one gets away from the image centre (nadir), making crown delineation difficult and increasing the probability of trees being completely hidden. For scanned photos and digital frame cameras, this phenomenon occurs in a circular pattern. For "push-broom" sensors, that acquire their images line by line, this occurs in only one direction. For the sake of simplicity, we will address the later case first.

This off-nadir view angle situation, that changes the visible shape of tree crowns, is compounded by affects due to the sun illumination angle, affecting their multispectral returns (i.e., colors) and making their species spectral recognition difficult. Since the sun illumination direction will rarely be along the flight line direction, the trees on one side of the image will be essentially front lit while those on the other side, essentially backlit, changing their apparent shape as well as their color returns. BRDF (Bidirectional Reflectance Distribution Function) corrections of images are meant to alleviate these color changes within an image. In addition, they can also be used to normalize color between images. For multispectral (or even RGB) images, different BRDF corrections are collected and applied to each channel (i.e., color band).

The first step in BRDF corrections consist in establishing a curve describing these effects across the image. For crude resolution images, this can be done by accumulating a histogram of pixel averages in each column of an image. For this to work properly, one as to assume that the image is very long and/or that the ground features are random enough so that their spatial distribution does not overly affect the curve. Alternatively, the BRDF curve can be created from a single feature prevalent throughout the image, preferably the type of feature one is analysing (e.g., forest areas).

The second step consists in normalizing that BRDF curve relative to the grey-level value at nadir. Then, the curve represents typical additive or subtractive values found at off-nadir positions, relative to the average grey-level at nadir. The inversion of that curve becomes the correction curve. It describes the grey level correction values to apply to each pixel based on its position off-nadir.

With high resolution data, experience has shown that it may be better to acquire a separate curve for each specific feature, such as coniferous or deciduous tree crowns (Fig. 2), as they respond differently to sun-view angle geometry because of their different shapes (i.e., conical trees *vs* rounded trees). This implies some pre-processing to secure masks showing these feature distributions in the image. A simple texture analysis is often sufficient. The BRDF corrections can then be applied based on these masks or following a weighting scheme between all of the correction curves (Yuan and Leckie, 1992).

BRDF correction curves can also be used to normalize colors between images or flight lines of a given aerial coverage. Because BRDF correction curves are all relative to their average grey-level at nadir, it suffice to decide on a single fixed grey-level value (per channel) to be assigned to the nadir of all images to normalize the colors between them. A recent test of BRDF corrections and normalization was carried out between two adjacent flight lines acquired with a Leica ADS-40/52 "push-broom" sensor. It showed that for two sample areas (one of softwoods, one of hard-

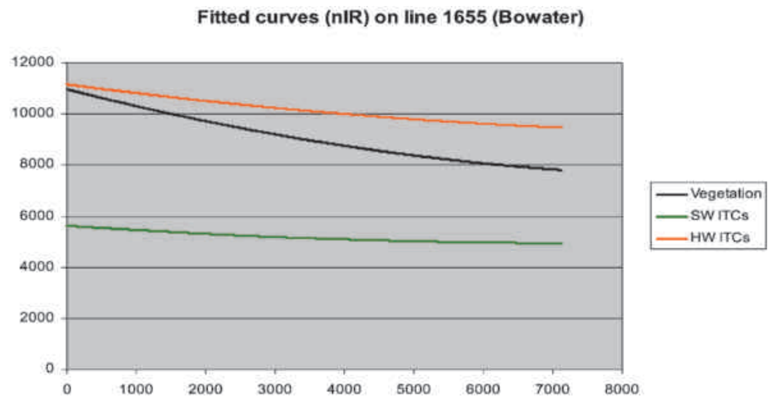

Fig. 2 In high resolution images, BRDF curves can be quite different depending on the image features under consideration (vegetation, softwoods, or hardwoods).

woods) found on both images, the intensity differences between images could be brought down from 28% and 20%, respectively, to 3.2% and 3.4%, respectively (Chubey *et al.,* 2009). Although these results illustrate well the strength of this BRDF approach, such residual differences may still be too big to ensure consistent spectral-based species classification throughout an area covered by multiple flight lines. However, one should take into consideration that these two sample areas were at 20^0 and 25^0 off-nadir, respectively. If we stay to closer to nadir, these differences may become more manageable.

For this reason, and others having to do with the quality of crown delineation, we have recommended an overlap between flight lines such that the areas being analysed on each image is within $\pm 15^0$ of nadir. This should allow the ITC analysis to concentrate on only the central portions of each image or flight line, while producing decent results throughout the full area of interest. Of course, for sensors with a wide field of view ($\pm 32^0$), this represents a 50% overlap, which is more overlap than typical with visual interpretation (~30%) and thus, may imply additional aerial acquisition costs.

Concluding Remarks

The ITC approach has been very successful at delineating tree crowns, assigning them species and regrouping them into forest stands with data from numerous satellite and airborne sensors at a variety of spatial resolution around 50 cm/pixel. The ITC approach is also efficient on Digital Canopy Model images produced from high sampling rate LiDAR data (around 10 p/m^2), although species separation is not generally available with this media alone. Important synergies, such as the analysis of sparsely forested areas, are achieved when analyzing multispectral images in collaboration with even low sampling rate LiDAR data (around 1 p/m^2). Such LiDAR data is predicted to be more readily available in the near future, as it contributes to the creation of precise Digital Terrain Models used by forest road engineers and, pays for itself with that application alone.

Although, the ITC approach is getting close to operational, there are still numerous research issues. We need to better parameterize the various accuracies (tree counts, crown delineation, species recognition, forest stand level information such as height and volume) one can expect from the various satellite sensors and, the airborne sensors at various spatial resolutions. Of course, this is a long term endeavor, as new satellite and airborne sensors are made available every year and, as there are numerous different forest situations for which to parameterize these accuracies.

At the crown delineation level, we still suffer from some crown under-splitting (remaining tree clusters) and over-splitting (broken crowns). Although, this is often not critical when information is only desired at the stand level, it could be very important for individual tree volume and biomass estimations. In order to get multiple forest situations automatically analysed at the same time (e.g., mature *vs* regeneration, small *vs* big crowns, dense *vs* open *vs* sparse canopy), more pre-processing tools are needed to guide the necessary context switching or adaptive processing. Illumination and view angles effects, as well as topographical effects, need to be better defined and compensated. Is normalization between images from same/different flight lines sufficient not to have to retrain the species classifier, over which distance? This could be a crucial operational factor when analysing substantial areas. How much does health or tree dominance affect species recognition? Can crown texture and structure, or can contextual information be integrated in the species recognition process? These are some of the questions that are only partially answered at this point in time.

With our current emphasis on technology transfer, the ITC analysis concept is starting to spread within provincial jurisdictions and the Canadian forest industry. Now that precise species composition, computerized forest stand delineation and, individual-tree-based forest stand level information are possible via semi-automatic computer analyses, foresters are starting to get more interested in the individual tree information "per se". Consequently, after years of working towards the development of a full system, some of our research is now directed back at improving our crown delineation algorithms in order to get even less tree clusters. At the other end of the spectrum, as the use of high resolution multispectral satellite data becomes more ubiquitous, thoughts should be given to using this approach for some of the federal government Canada-wide level projects described earlier.

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