Automatic Crown Cover Mapping To Improve Forest Inventory

Claude Vidal[1], Jean-Guy Boureau[2], Nicolas Robert[2], Nicolas Py[2], Josiane Zerubia[3], Xavier Descombes[3], Guillaume Perrin[3, 4]

Abstract.—To automatically analyze near infrared aerial photographs, the French National Institute for Research in Computer Science and Control developed together with the French National Forest Inventory (NFI) a method for automatic crown cover mapping. This method uses a Reverse Jump Monte Carlo Markov Chain algorithm to locate the crowns and describe those using ellipses or ellipsoids. The system works well when the crowns can easily be distinguished (e.g., in old, high forests or in poplar plantations). The outputs of such a system can be used as post-stratification criteria to enhance the precision of NFI results. It will also allow computing results at larger scales and provide new data for a better understanding of forest ecosystems.

Introduction

Since its creation in 1958, the French National Forest Inventory (NFI) has used aerial photographs to collect information during the first phase of an inventory. Using color infrared (CIR) pictures since the 1980s, photo interpreters determine land cover and land use as well as forest structure and major species on sample plots. The information is used for the statistical evaluation of the forest and other wooded land areas and to decide whether the plot should be assessed in the field. Until now, since it was a manmade operation, only descriptive information was entered. Because it was too time-consuming, the count and cartography of trees was out of the scope.

In 2003, the French National Institute for Research in Computer Science and Control (INRIA) started a research program to build an automatic system for tree crown extraction using aerial photographs in close cooperation with the French NFI. Such an automatic analysis of images is interesting to enhance forest inventory capacities. The French NFI conducted the first steps to validate the method and give an assessment of the result's accuracy. According to these preliminary results, some uses and enhancements are proposed.

Development of a Method to Map Tree Crowns

New Needs for Data on Forest Ecosystems

The French NFI changed its forest assessment method in 2004. Observations are now made annually of a systematic sample covering the whole country (Vidal *et al.* 2005). This new sampling design is adapted to produce data concerning a larger area and can include the entire country. The former sampling design was applied at the scale of the *department* (1/90th of the whole country), so the new design is no longer able to provide data at the local level without specific measurement. Since it was unable to measure systematically more plots without considerable expense, the French NFI investigated alternative solutions. Automatic analysis of documents required for usual work, such as aerial photographs, is one way to provide the required additional information for wood volume estimation at a marginal cost.

The French NFI was asked for further information to gain a better understanding of the forest ecosystems and their dynamic. The evaluation of the number of crowns, their size, and the height of the trees on large areas are interesting material for such an analysis.

---

[1] Inventaire Forestier National, Château des Barres, 45290 Nogent-sur-Vernisson, France. E-mail: claude.vidal@ifn.fr.

[2] Inventaire Forestier National, Château des Barres, 45290 Nogent-sur-Vernisson, France.

[3] Institut National de Recherche en Informatique et en Automatique. 2004 route des Lucioles BP93 - 06902 Sophia Antipolis Cedex, France.

[4] During his Ph.D. thesis, the work of Guillaume Perrin was supported partly by the Mathematics Applied to Systems Laboratory from École Centrale Paris and partly by the French National Institute for Research in Computer Science and Control. Thanks to the Action de Recherche Concertée, "Mode de Vie" tests were conducted by the French National Forest Inventory to validate the method and give an assessment of the result's accuracy. According to the preliminary results, some uses and enhancements are proposed.

Result of Close Cooperation Between Foresters and Computer Science Specialists

In 1998, INRIA, National Center for Scientific Research (CNRS), and the Nice-Sophia Antipolis University launched the Ariana project to provide image processing tools for Earth observation and cartography using remotely sensed data. Under this project, several probabilistic models combined with stochastic algorithms were developed for an automated analysis of airborne photographs or satellite images. The major objective was to analyze the structure of the pictures and to extract objects. Specific work has been done in cooperation with the French NFI to analyze the crown cover. The French NFI provided pictures and knowledge about the forest photo interpretation. The Ariana project team proposed the method to create an algorithm. A first program was set up to test the quality of the method.

Overview of the Method

The principle to map tree crowns using aerial infrared photographs is to fit a set of objects (circles, ellipses, etc.) on the original picture. The proposal is created using a random process (van Lieshout 2000). The fitting is obtained using a reversible iterative algorithm: Reverse Jump Monte Carlo Markov Chain (RJMCMC) (Green 1995).

To evaluate the quality of the proposal, two different criteria based on photo interpretation are measured (Perrin *et al*. 2005):

1. An external criterion resulting from the comparison between the original picture and the obtained set of objects after rasterization;
2. An internal criterion corresponding to prior information on the size, shape, and spatial organization of the crowns modeled by local interactions between objects.

To create the predicted proposal and evaluate both aspects, a description of crowns (color, shape, etc.) is required. To describe the crowns in a simple mathematical representation, shapes are used.

Model Varieties

The analysis of the photo-interpretation process led to the use of different shapes, depending on the general characteristics of the crown in the analyzed image. Two- and three-dimensional (3D) shapes are used. In the two-dimensional (2D) case, ellipses are used (Perrin *et al*. 2005, Perrin *et al.* 2006a). Each shape is described by the following random variables named marks (van Lieshout 2000), defining the geometry of the object (fig. 1):

1. Position of its center (*u, v*).
2. Length of the two orthogonal axes (*a, b*).
3. Orientation (*a*).

The 2D models are efficient for dense cover, when the shadows of the trees are not entirely visible and crowns are very close. These models roughly describe the size and shape of the crown's visible part.

Four subfamilies of 2D models are used (fig. 2), depending on the quality of the picture (saturated colors or visible differences

Figure 1.—*Parameters of the ellipses used to model crowns.*

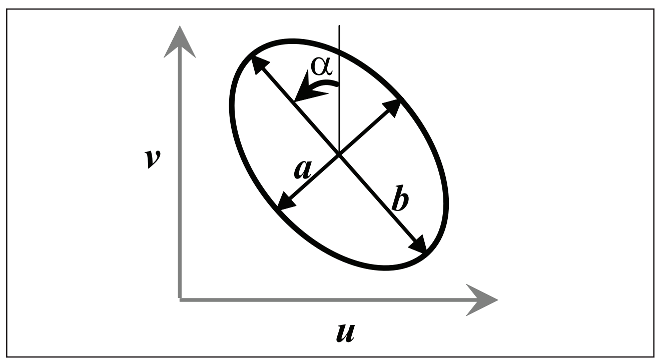
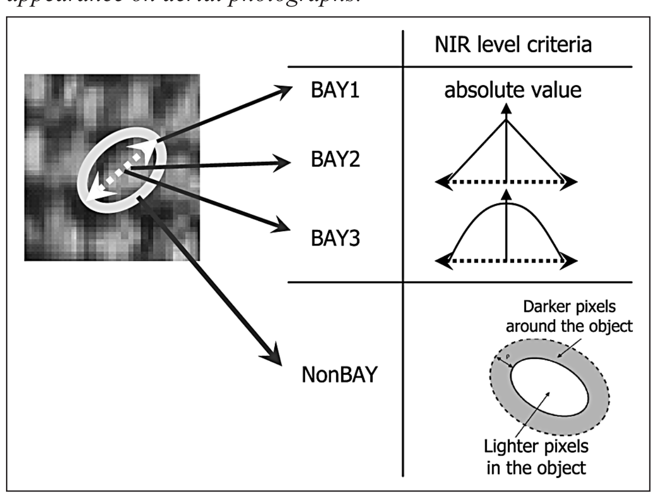


Figure 2.—*Four two-dimensional models to describe the crown appearance on aerial photographs.*



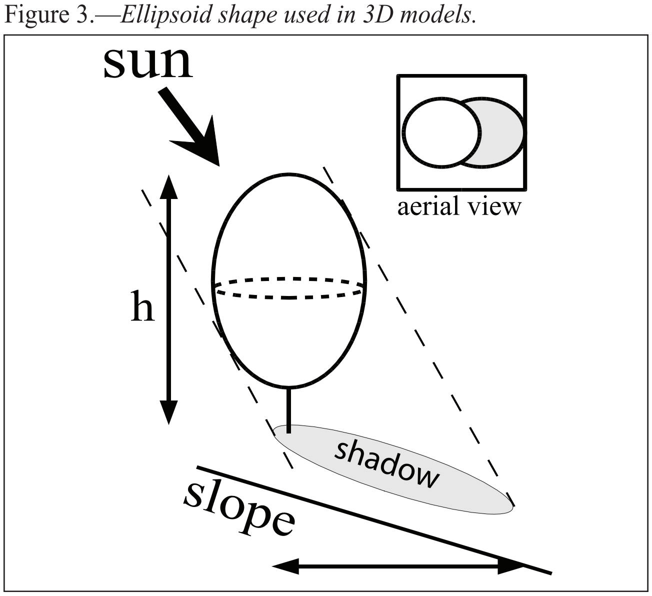
between the border and the center of the crown), the usual shape of the trees (conic top such as sessile oak, or triangle top such as spruce), and the surrounding shadow.

The first model, called BAY1 (for Bayesian model 1), takes into account the absolute reflectance value in the near infrared (NIR). It is assumed that crown's shapes are close to ellipses and are strongly contrasted in the NIR. The second and third models consider a variation of the radiometry inside the ellipse, with higher reflectance in the center of the crown. This variation can be either linear (BAY2) or conic (BAY3). The last shape is combined with a non-Bayesian model (NonBAY), and analyzes the contrast between the outer and the inner parts of the predicted crown and tries to identify a shadow area around this predicted crown.

The 3D shape is an ellipsoid (fig. 3) described by the same parameters as the 2D model, plus height (*h*). This shape is efficient for sparse trees, when the shadows are fully visible, or to determine the height of stands in the edge, when sunshine conditions are sufficient. Such a model considers the high reflectance of the vegetation in NIR, the orientation of the sun, and the relief and shadows around trees.

The type of objects is manually selected, depending on the differentiation level between crowns and shadows. This choice has a strong influence on the results.

Figure 3.—*Ellipsoid shape used in 3D models.*



RJMCMC Algorithm

To fit a random proposal of tree location and characteristics to the original image, an RJMCMC algorithm is used (Green 1995). An image corresponding to the random proposal is predicted. An energy is attached to the system "predicted picture—original picture" to measure the quality of the prediction. The better the proposal, the lower the system's energy. The goal of the iterative process is to find the most accurate prediction (equivalent to the lowest energy).

A random initialization using a rough number of trees creates the initial proposal. The energy of this system is calculated. At each step of the interactive process, a new proposal is built, starting from the previous one, and changes are proposed. These changes consist of the creation or the suppression of the tree crowns, moves of the crown centers, or modification in the size of crowns. Then, the energy of this new system is evaluated and compared to the previous one. If the energy is lower, then the new proposal is taken to the next step. If the energy increases, the new proposal is either rejected, and the next step starts with the former proposal, or accepted with a given probability depending on the model and a temperature parameter. A proper acceptation ratio (Green 1995) ensures the convergence of the process to a configuration that minimizes the energy.

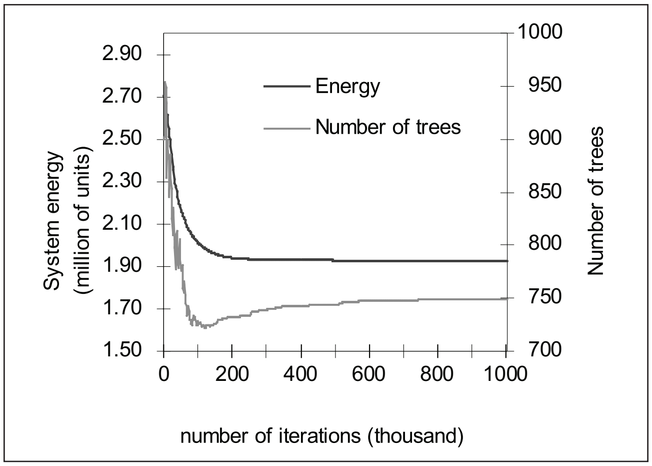
Changes between iterations are randomly proposed, and both the number and the extent of changes are regulated through a term called temperature: the lower the temperature, the fewer the amount of changes. The algorithm starts with high temperatures so as to consider the higher number of possibilities. The temperature is progressively turned low so that few changes are proposed, converging to an optimal solution. The algorithm ensures the convergence of the process to a configuration that minimizes the energy (see example in figure 4).

Assessment of the Quality of the Prediction

Test Sites

Three sites, representing an important part of French forest, have been selected. These sites are examples of hardwood or coniferous mature high forest.

Figure 4.—*Variation of the energy of the system and the number of detected trees.*



1. Site 1: "Indre-et-Loire." This oak, regular high forest in the Loches State Forest is located in a flat zone in the center of France. According to the zones, this managed forest presents various intensities of thinning, from full cover to very clear stands. Corresponding CIR photography was recorded in June 1995 (scale of 1/20000, *f* = 152 mm).
2. Site 2: "Moselle." Located in the Vosges massif in the northeast of France, this mature, regular high forest of fir is also a managed forest with variable densities of cover from one stand to another and the presence of some clear cuts. As in the test site above, it is easily possible to separate tree crowns. CIR photography was recorded in August 1989 (scale of 1/17 000, *f* = 213 mm).
3. Site 3: "Loir-et-Cher." Composed of maritime and Scots pines, this forest is located in the "Grande Sologne" in the center of France. This picture is composed of two parts. In the first part, the structure of afforestation is still quite visible. The shape and space distribution of trees are regular, dense, and homogeneous. In the second part, which is less dense, the tree crowns have more heterogeneous shapes. CIR photography was recorded in August 1993 (scale 1/20 000, *f* = 214 mm).

Collection of Reference Data

The evaluation of the quality of the model requires precise identification of the trees on the image. These data were obtained by simple photo interpretation. The identification of trees was realized with high density (800 dpi) but not an orthorectified digital image. A stereoscopic analysis was carried out in parallel. Each tree crown was identified by a point placed as near as possible to its top (fig. 5).

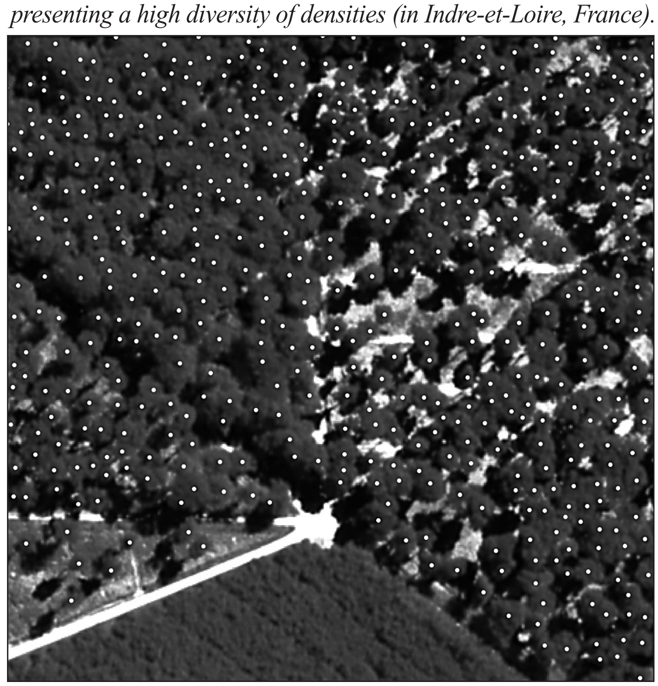
This method offers numerous advantages: orthorectification is not necessary, the information is easily and quickly obtained, and its cost is very low; however, only the mature trees are easily identifiable. When the canopy cover is too dense, group of trees tend to form only one summit but with a specific form and dimension different from insulated trees. Lastly, the partly dominated trees are hardly identifiable.

These limitations, compared to those in field observation, do not constitute a problem insofar as the processing is carried out on the same image. The aim of the model is to identify trees on an image and not to represent the real situation.

Test Protocol

Model Selection. The model selected is the classic BAY 1 (cf. *Model Varieties*), because of the contrast and the image structure. Pixels on the image are split: vegetation or no vegeta-

Figure 5.—*Example of photo-interpretation results on an image presenting a high diversity of densities (in Indre-et-Loire, France).*



Note: A total of 515 crowns were recognized on this part of the image. The lower part was not photo-interpreted because of the too high density of the trees.

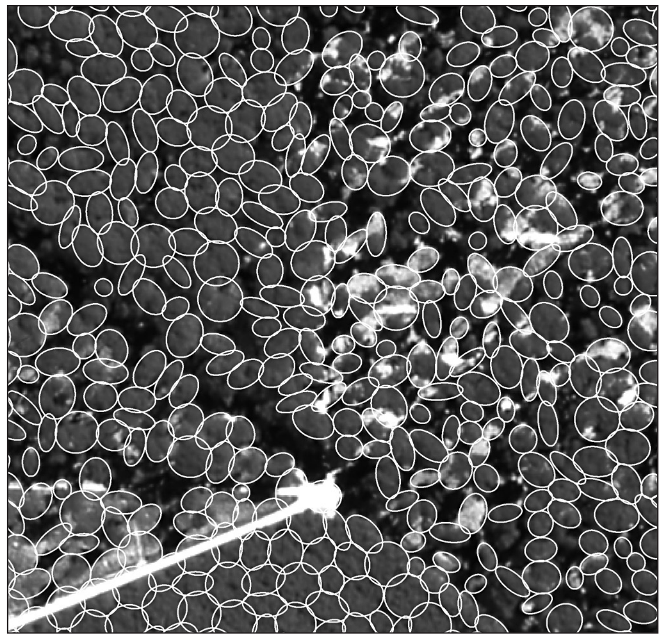
tion. The vegetation class corresponds to highest reflectance in NIR. Only the absolute value of this reflectance is considered. These classes are described by their average and standard deviation, which are used by the model to distinguish crowns from shadows and nonstocked areas.

Parameter Definition. The approximate minimum and maximum sizes of the tree crowns must be specified. These values (number of pixels) have been determined by measuring some trees on the digital images. The values obtained for each site are as follows:

1. Indre-et-Loire, oak forest: from 6 to 16 pixels = 3.6 to 9.6 m.
2. Moselle, fir forest: from 6 to 20 pixels = 3 to 10 m.
3. Loir-et-Cher, pine forest: from 4 to 10 pixels = 2.4 to 6 m.

In the realized test series, the number of iterations was set between 1 and 30 million so as to evaluate the number of required iterations. After 1 million of iterations, the system is approximately stabilized. A very good stabilization is reached between 3 and 5 million. Finally, around 10 million iterations, the temperature reached by the system is very low and no change is noticeable. On the site of Indre-et-Loire, for example (fig. 6), in an oak high forest, the number of trees detected after 10 million or after 30 million iterations is practically identical (749 and 753, respectively).

Figure 6.—*Example of results obtained using the BAY 1 model (piece of the Indre-et-Loire image).Note: In the lower part of the image, the prediction of many large crowns covering the whole sector is due to the BAY 1 model that does not use shadows and cannot work in the very high-density regular cover of the young regular high forest. In this part of the image, it is also almost impossible to manually map the crowns.*



Validation of the Results

Processing Time. The noted processing times vary with the number of iterations, the image size, and the number of objects. It takes generally 1 to 4 hours to process 5 to 10 ha (12.4 to 24.7 acres) and with an iteration number varying from 10 to 30 million.

Model Stability. To test the model stability, the application was launched five times with the same parameters on the whole fir plantation in the Moselle site. Data have been recorded and, therefore, it is possible to compare the results in terms of number of trees, ellipse coordinates (*x, y*), parameters and areas of ellipses (axis lengths and orientation angle), and computing time.

To compare the results, five stability indicators have been calculated:

1. Indicator 1: Average and standard deviation of the number of detected trees.
2. Indicator 2: Detected crown cover rate. Stability of the image percentage detected as tree crown.
3. Indicator 3: Stability of the ellipse parameter distribution. Comparison of averages, variances, and standard deviation for the small axis, the large axis, the orientation, and the area.
4. Indicator 4: Stability of the barycenter for ellipse centers and Euclidean distance of the points to the ellipse centers.
5. Indicator 5: Visualization of images and predicted ellipses for the five simulations. Observation of consistencies and inconsistencies.

The results provided by the model for indicator 1 show a rather good stability: average of 822 trees, standard deviation of 9. For indicator 2, stability is obvious (61% ± 0.1%). The results obtained for indicators 3, 4, and 5 show the same overall stability with variation coefficients generally quite lower than 2 percent.

Comparison Between Photo Interpretation and Automatically Obtained Results. The results obtained are gathered in table 1. If the number of detected trees on the Moselle site is very close to the one seen by photo interpretation, the results will seem

Table 1.—*Comparison between the number of detected trees and the number of trees counted by photo interpretation.*

Site	Area (ha)	Number of detected trees	Number of photo-interpreted trees
Indre-et-Loire	9.0	672	940
Moselle	4.3	667	698
Loir-et-Cher	6.5	1,264	1,962

worse on the two other sites. An unsuited parameter setting, in particular maximal and minimal sizes of the tree crowns, could at least partly explain this wrong detection.

These general results mask rather significant disparities on each site according to the local context. We note either an over- or underdetection according to the species (hardwood or coniferous), the density of the trees, and the nature—chlorophyllian or not—of the ground.

1. Underdetection is often observed in continuous cover but without sufficient shadow to separate the crowns even if each tree could be distinguished in visual analysis. Underdetection is frequent also with small crowns (see fig. 7).
2. On the other hand, an overdetection can occur, for example, with NIR reflective ground spots surrounded by shadow. The model considers them as trees.

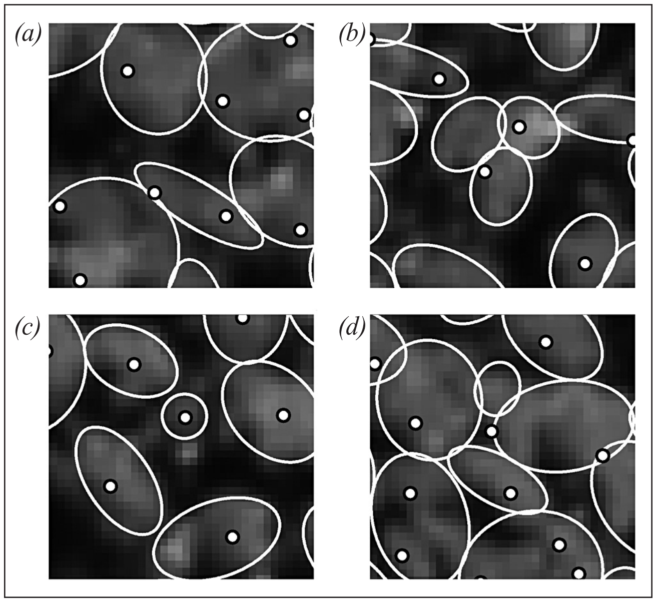
The use of Normalized Difference Vegetation Index (NDVI) instead of the infrared (IR) channel only and the improvement of the thresholding of images would improve these first results.

Possible Use in NFI

Context

Today, the results of very high resolution (decimeter) digital image processing provide information not only at the stand scale but also at the tree scale. Information includes number of stems, local density, dimension and form of the crowns, type of space distribution, and georeferencing of the trees if the image was first orthorectified. Beyond this elementary information, data such as the origin of the forest, its age class, and the present group of species can thus be estimated. This information is impossible to obtain by traditional photo interpretation because

Figure 7.—*Example of results and comparison between photo-interpreted (PI) center of the crowns (points) and predicted ellipses (lines).*
(a) several PI centers in ellipses.
(b) no PI center in ellipses.
(c) good results—one PI center in each ellipse and no empty ellipse nor PI center outside ellipses.
(d) PI centers outside ellipses resulting from problems with size of detected objects.



of costs or the characteristics of visual interpretation. This method is able to synthesize much information but remains not very powerful for a quantitative analysis of the image, especially at the tree scale. A real complementarity now exists between the results of the visual analysis and those of the automatic processing, at least for mature forests.

The requirements in spatialized information, at the tree scale, are increasing for (1) a better knowledge of the ecosystem functioning, (2) the survey of landscape evolution at a very large scale, and (3) a low-cost improvement of the precision of the inventory results. The French NFI is interested in such an automated system, because it allows a more indepth analysis of existing CIR photographs to enhance the quality of the results and the diversity of collected data at a marginal cost.

Improvement of the French NFI's Main Missions

Forest resource assessment is one of the main objectives of the French NFI. The automatic crown mapping program is expected to improve resource assessment accuracy through the automated analysis of numerous aerial photographs taken all over France. The application could be used to analyze the forestry cover around the photo-interpreted inventory plots (55,000 plots a year, including more than 15,000 forestry plots). It will provide additional information concerning the plots such as number of crowns, density, and repartition. These data can be used as criteria in a post-stratified computation and especially when computing number of stems or tree volume. This will enhance the estimators, even if the confidence level of the application results is low. Using this tool should increase the precision of the results at the national and regional levels. In addition, the increase in precision could possibly provide data at lower scales (e.g., at the *department* level).

Such a tool can also be used for small study areas to produce rough estimators of the crown cover, number of stems, and other variables. Combined with field observations, it might be possible to produce information at the scale of the forest stand.

Within the forests, poplar stands are very specific. Because these stands are usually regularly planted with well-separated crowns, they can be analyzed easily using the automated system (Perrin *et al*. 2005). In these cases, the system will provide good results for the cover rates, the number of trees, and the tree location. It will give a better knowledge of (1) the space heterogeneity of these plantations, (2) their distribution in age groups according to the dimension of the crowns, and (3) their spacing.

Finally the French NFI also carries out an inventory of (1) hedges, (2) tree rows and other trees, and (3) sparse trees in the agricultural landscape. The number of trees and the length of linear elements are statistically estimated. Currently, no systematic map of these trees out of forest has been established. The automatic detection of the crowns enables the analysis at the tree scale within these formations to improve the estimate of tree volumes.

Other Missions

Automatically obtained tree scale information can enrich traditional approaches (visual image analysis and ground measurements) for a better knowledge of the diversity of wooded ecosystems and their evolution. The definition and calculation of many biodiversity indicators, for example, could benefit from these results in digital processing of very high resolution images. Currently, the stand structure, a very important component of forest biodiversity, is rarely available in cartographic form. The detection of individual trees within a stand would enable the characterization of the composition, the spatial organization of mixed forest, and the density of the stems, and other heterogeneities of the forest cover at different scales. We will thus be able to establish main characteristics of vertical and horizontal structures of forest stands and be able to obtain a spatial representation of the forest mosaic. For example, by having access to tree-level information and stand-spatial structure, these first results would allow a qualitative and quantitative step toward understanding links between stand characteristics and plant richness.

The analysis of the evolution of the tree presence in a mosaic landscape answers a similar need. The stands' dynamic (i.e., their natural or anthropic evolution) can thus be approached and mapped by applying the same processing to images registered at different dates. New descriptors calculated on a great number of elementary sampling surfaces would allow the followup of these evolutions at the tree scale.

Future Improvements

This method was developed using a selection of high-quality pictures. Now it must be tested in real conditions to determine the limits of the model. Future developments such as a mapping of the crown shape and a combination with radiometry to recognize main tree species categories are also expected.

Reference data can be obtained, as presented above, by simple photo interpretation. The system can also use orthorectified images so that results are comparable to the Global Positioning System measurement of the tree positions. This method requires a perfect adequacy between the accurate correction of the image and the georeferencing of the trees on the ground. Tests are conducted to specify the interest of this approach depending on the forest types, both for a validation of the model and for its later use.

The first validation tests presented here do not permit an analysis of the model behavior under varied conditions of use. The effects of topography, angle of solar incidence, distance to nadir, spatial resolution, and local contrast of image, in addition to those of spectral bands or type of sensor, also have to be analyzed. It seems, however, that the slope is a secondary problem if the angles of illumination and sighting allow a good observation of the trees.

Similarly, the model has been validated in mature and monospecific forest stands managed in regular high forest, but it has only been tested in mixed forest with a strong vertical heterogeneity (Perrin *et al*. 2006a).

The species identification is based simultaneously on radiometric and crown shape criteria. For the model presented here, post-processing is possible after obtaining the ellipses. This would permit getting information on the real shape (or shape class) of the crowns. This result combined with reflectance values would lead to a better identification of the species (or groups of species).

Conclusions

The major advantages of this method are (1) a limited cost of the inputs (photographs are already available), (2) a short computing time for limited size images, and (3) reproducible results. The results can be used to improve the statistical quality of the French NFI's results, especially number of stems, growing stock in high forests (representing 45 percent of the forest area in France), or standards (80 percent of the growing stock). Better knowledge of the heterogeneity of the top of the crown cover and the height differences can be interesting for landscape and biodiversity purposes.

The French NFI uses segmentation tools development by the French National Geographic Institute to map forests and tree rows. Thanks to a combination of those tools and the crown mapping application, it will be possible to better estimate the standing volume in hedges, using the predicted number of trees, tree height, and crown size. This would help (e.g., in enhancing the wood fuel resource evaluation).

Literature Cited

Green, P. 1995. Reversible Jump Markov Chain Monte Carlo computation and Bayesian model determination. Biometrika. 57: 97-109.

Perrin, G.; Descombes, X.; Zerubia, J. 2005. Point processes in forestry: an application to tree crown detection. Res. Rep. 5544. Sophia Antipolis, France: French National Institute for Research in Computer Science and Control. http://hal.inria.fr/inria-00070463.

Perrin, G.; Descombes, X.; Zerubia, J. 2006a. A non-Bayesian model for tree crown extraction using marked point processes. Res. Rep. 5846. Sophia Antipolis, France: French National Institute for Research in Computer Science and Control. http://hal.inria.fr/inria-00070180.

Perrin, G.; Descombes, X.; Zerubia, J. 2006b. Forest resources assessment using stochastic geometry. Res. Rep. Sophia Antipolis, France: French National Institute for Research in Computer Science and Control. ftp://ftp-sop.inria.fr/ariana/Articles/perrin_emmcvpr.pdf. (11 January 2009).

van Lieshout, M.N.M. 2000. Markov Point Processes and their applications. London, United Kingdom: Imperial College Press.

Vidal, C.; Bélouard, T.; Hervé, J.C.; Robert, N.; Wolsack, J. 2005. A new flexible forest inventory in France. In: McRoberts, R.E.; Reams, G.A.; Van Deusen, P.C.; McWilliams, W.H., eds. Proceedings, seventh annual forest inventory and analysis symposium. Gen. Tech. Rep. WO-77. Washington, DC: U.S. Department of Agriculture, Forest Service: 67-74.

Additional Reading

Project Ariana: http://www.inria.fr/ariana/.

French NFI: http://www.ifn.fr/.