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Detecting natural canopy gaps in Amazonian rainforest

The paper presents a study of the structure and ecology of canopy gaps in the tropical rainforest of French Guiana to detect gaps due to natural treefall over a broad scale. The study was combined with the development of a SPOT image remote sensing tool with 20 m spatial resolution.

Opening of the canopy caused by tree fall. The picture is taken from a helicopter.
The gap allows light to reach the lower stratum of the forest stand.
Photo V. Gond.

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RÉSUMÉ

DÉTECTION DE CHABLIS NATURELS EN FORÊT TROPICALE AMAZONIENNE

En établissant des conditions particulières, les chablis contribuent au maintien de la richesse spécifique des forêts. L'étude présentée sur les chablis dans les forêts de Guyane française s'appuie sur des images Spot de 20 m de résolution, qui ont permis de détecter les trouées dans la canopée, sur une large échelle. Les structures et l'écologie de onze trouées sont analysées sur le terrain, au sol et dans la canopée : la repousse à l'intérieur du chablis, les indices foliaires, les espèces d'arbres concernées par la chute ainsi que la topographie du site. À partir de ces données, chaque chablis est cartographié et localisé finement grâce au Gps (Global positioning system). Un filtre d'image binaire, comprenant trois bandes spectrales (visible, proche infra rouge, infrarouge à courtes longueurs d'onde), différencie les chablis de leurs environnements forestiers. Les résultats montrent que la trouée doit potentiellement occuper 25 à 50 % du pixel pour être détectée. La vigueur de la repousse (hauteur et densité) empêche la détection des chablis trop anciens, en cours de fermeture. Les variations topographiques, les ombres et la position relative du chablis dans le pixel influencent également la qualité de la détection. Cette étude nécessite d'autres développements pour améliorer la résolution de l'image satellitaire ainsi que le filtre de détection, afin de pouvoir étudier, à l'échelle du paysage, ce processus caractéristique de la dynamique des forêts tropicales.

Mots-clés : dynamique des forêts, télédétection, Spot 4, forêt tropicale amazonienne, Guyane française.

ABSTRACT

DETECTING NATURAL CANOPY GAPS IN THE AMAZONIAN RAINFOREST

The formation of gaps in the forest canopy creates a variety of ecological conditions and therefore helps to maintain species richness. This paper presents a study of gap structure and ecology in the tropical rainforest of French Guiana to detect natural treefall gaps over a broad scale. The study was combined with the development of a SPOT image remote sensing tool with 20 m spatial resolution. A total of 11 gaps were studied in the field to produce assessments of gap surface areas at canopy and ground levels, gap undergrowth density and height, gap leaf area index profiles and gap-creating tree species, and descriptions of the topographic and geologic gap environment. Mapping and image processing techniques were combined to reconstruct canopy gap structure and location. A binary image filter, based on three spectral bands (visible, near infra-red, short-wave infra-red), was developed to distinguish canopy gaps from the surrounding forest. The results show that the gap area at canopy level potentially had to cover 25 to 50% of the pixel area to be detected. The number of gap pixels retained by the image filter was primarily a function of the density and height of undergrowth in the gap, and therefore of gap age. Topographical variation and gap shape and position relative to image pixel positions further influenced detection. This research could provide an impetus for optimising both satellite image resolution and the gap filter, both being necessary to study the natural processes involved in tropical forest dynamics on the scale of a landscape.

Keywords: gap dynamics, remote sensing, SPOT 4, Amazon rainforest, French Guiana.

RESUMEN

DETECCIÓN DE DESCUAJES NATURALES EN LA SELVA TROPICAL AMAZÓNICA

Al establecer condiciones particulares, los árboles desarraigados o quebrados por el viento contribuyen al mantenimiento de la riqueza específica de los bosques. El presente estudio sobre el descuaje en los bosques de la Guayana francesa se basa en imágenes Spot, con una resolución de 20 m, que permitieron detectar los claros en el dosel, en una amplia escala. Se analizaron sobre el terreno —en el suelo y en el dosel— las estructuras y la ecología de once claros: el rebrote en las zonas de descuaje, los índices foliares, las especies de árboles afectadas por el descuaje y la topografía del lugar. A partir de estos datos, se cartografiaron las zonas de descuaje y se localizaron con precisión gracias al GPS (Global Positionning System). Un filtro de imagen binaria, con tres bandas espectrales (visible, infrarrojo cercano e infrarrojo de onda corta), diferencia los árboles derribados de su entorno forestal. Los resultados ponen de manifiesto que el claro debe ocupar potencialmente del 25 al 50% del píxel para poder ser detectado. El vigor del retoñado (altura y densidad) impide la detección de los casos de descuaje demasiado viejos y en fase de cierre. Las variaciones topográficas, las sombras y la posición relativa de las zonas de descuaje en el píxel influyen también en la calidad de la detección. Este estudio necesita algunos avances que mejoren la resolución de la imagen satelital, así como el filtro de detección, para poder estudiar, a escala del paisaje, este proceso característico de la dinámica de los bosques tropicales.

Palabras clave: dinámica de los bosques, teledetección, Spot 4, selva tropical amazónica, Guayana francesa.

Introduction

Dynamic forest cycles are maintained by regular disturbance of relatively large areas as gaps form in the tree canopy (PHILLIPS, GENTRY 1994; MOLINO, SABATIER, 2001). These change the understorey microclimate, resulting in greater availability of substrate, space, light and nutrients, lower relative humidity and higher evapotranspiration (CANHAM *et al.,* 1990), all of which influence plant regeneration. Gaps in the canopy are critical in the forest cycle because the plants that develop there will determine the floristic composition and forest structure of the future stand. On the scale of a landscape, gap formation processes result in a mosaic of forested surfaces that are all in different phases of development. RIÉRA (1983) and DURRIEU DE MADRON (1993) found canopy gaps in French Guiana to affect, on average, 1.1 and 1.3% of the tropical forest surface area per year, respectively.

Satellite remote sensing is a powerful tool for analysing local, regional and global ecological processes. The SPOT programme (*Satellite Pour l'Observation de la Terre*) is operated by the French space agency CNES. It consists of a series of optical remote sensing satellites that are used to obtain earth imagery for applications concerning land use, geology, water resources and GIS.

The objectives of this study were:
- to develop a transparent and appropriate method to locate, describe and analyse canopy gap structures;
- to detect, examine and quantify natural canopy gaps in a tropical rainforest using a remote sensing tool.

Materials and methods

Study site

The research was conducted in the evergreen lowland tropical rainforest of Counami, situated in the northern part of the Amazon basin (5°21'N, 53°15'W), on the north-eastern slope of the Guiana plateau in French Guiana. Annual rainfall is approximately 2 750 mm, with dry seasons (‹ 100 mm month^{-1}) in September and October, and sometimes in March. The mean annual temperature is 26 °C, with diurnal variations not exceeding 12 °C. Relative humidity is about 80% during the dry season and 90% during the rainy season. The soil texture resulting from ferralitisation is a kaolinitic clay, ranging from 2 to 10 m in depth. There are numerous hills up to 130 m above sea level. From the top to the bottom of these hills, the impervious clay horizon comes closer to the soil surface, blocking water percolation and root development (PAGET, 1999; CLARK, CLARK, 2000). Differences in soil water retention characteristics largely determine vegetation patterns in tropical rainforest (TER STEEGE, 1993; SABATIER *et al.,* 1997). Local forest structure thus depends on its topographical situation (BARET *et al.,* 2001; GOND *et al.,* 2002). This forest is dominated by species of *Lecythidaceae*, *Leguminosae*, *Sapotaceae*, *Chrysobalanaceae* and *Burseraceae* (COUTERON *et al.,* 2003). Around 150 different tree species ha^{-1} are found (NELSON *et al.,* 1990). The understorey is generally very dense, especially in the humid thalweg where palm trees are abundant. The main canopy is around 30 m high with emergent trees reaching up to 55 m.

Field data were collected during three successive weeks, in July and August 2002. Three days were used at the end of September 2002 to evaluate the analyses. A total of 11 gaps were studied in detail.

Opening of the canopy caused by tree fall. The picture is taken from the ground.
The intact edge of the canopy is visible around the gap.
Photo V. Freycon.

Gap definition

Two distinct definitions of a canopy gap were used in the field studies to delimit the surface area of canopy gaps. The first definition refers to the ground level and is based on the direct ecological impact of gap formation. RUNKLE (1981) defines a gap as the ground area under a canopy opening which extends to the base of the surrounding canopy trees, these usually being considered to be taller than 10 m, with a trunk diameter at breast height (DBH) ≥ 20 cm. For this study, we used a revised definition of gap area at ground level. Here, the gap includes trees that have been physically hit by falling trees, even if they do not comply with RUNKLE's size restrictions, and excludes unharmed trees. A second gap definition also used in this study is based on the canopy level, and is closest to BROKAW's (1982) proposal. This author states that a gap is a "hole" in the forest extending through all levels down to an average height of 2 m above the ground. We used a modified definition here, as was done by VAN DER MEER AND BONGERS (1996), in which the limits of the gap are where vegetation over 20 m tall is encountered. Any tree foliage below 20 m is not regarded as part of the canopy.

Assessment of gap geometry

Each of the unharmed canopy trees was individually marked with a number P_x. A laser device (LaserAce 300, Measurement Devices Ltd., Aberdeen, Scotland) was used to measure the distance (accuracy: 0.01 m) and azimuth (accuracy: 0.1 °M) between each perimeter point: from $P_x = P_1$ towards P_{x+1}, and from the latter to P_{x+2} and so on, until the initial marked tree P_1 was reached again. Absolute position was calculated using a handheld GPS (Magellan 315, Thales Navigation Inc., Santa Clara, CA, USA). The GPS readings provided longitude and latitude measurements for a point called V_1 inside the gap. Using the laser device to measure distance and azimuth from V_1 towards a point P_x, we calculated the P_x coordinates as follows:

$$x_2 = x_1 + (d * \sin[az - 18]);$$
$$y_2 = y_2 + (d * \cos[az - 18])$$

With $x_1 = EV_1$, $y_1 = NV_1$, $x_2 = EP_x$, $y_2 = NP_x$ where E = East and N = North, d the distance between points (in m), az the azimuth (in °M) as measured from (x_1, y_1) towards (x_2, y_2). The azimuth units had to be converted to geographic degrees, hence (az - 18). Using the same formulae and the

Palms in a humid zone perturb the canopy roof and cause confusion with real tree-fall gaps.
Photo F. Colson.

coordinates obtained for P_1, the coordinates for P_2 were calculated, and so on until all the marked gap perimeter points were located absolutely.

The exact surface areas of each gap were calculated using MapInfo software (MapInfo Corporation, New York, NY, USA). Landmark measurements in the Counami region using GPS were made in November 2001 (Baret *et al.,* 2001). By importing the MapInfo geocoded (WGS 84) canopy gaps as a vector, using ENVI 3.5 image processing software (Environment for Visualizing Images, Eastman Kodak Company - RSI, Boulder, CO, USA), the canopy gaps studied were projected onto the SPOT 4 satellite image.

To delimit the gap area at canopy level in accordance with the definition given above, the laser device was used along with a clinometer (Suunto PM 5, Suunto Corporation, Vantaa, Finland). The clinometer was used to determine the exact location on the ground of the vertical projection of the innermost point reached by the canopy foliage. This was done by determining the point at ground level above which these leaves were situated at an angle of 90°, i.e. right above the viewer's head. The positions of these points G_x were assessed using the laser device, from a known ground perimeter point P_x. Distance and azimuth were measured and used to reconstruct the two-dimensional gap area at canopy level. To quantify the topography, a general slope measurement was made using the clinometer.

Assessment of gap ecology

For each gap, all fallen tree species were identified. The number of gap-makers per gap event was recorded, and their height (length) and DBH measured. In the case of fallen branches, the diameter was measured at the base of the branch. In the case of snapped trees, the height of the remaining stem was also measured. The fall direction was determined using the laser device: the azimuth was measured from a standing position on the fallen stem. From a nearby perimeter point P_x, the relative position of the base of the uprooted or snapped tree, the main branching point(s) and the "highest" point(s) of the crown were determined using the same device.

Regrowth species were identified and classified by height and density: ‹ 1 m, 1 - 3 m, › 3 m; low, medium or high density. Digital pictures of the undergrowth or canopy gap area were taken to produce a better classification of undergrowth density, and to illustrate gap structure and formation. A Fuji FinePix 1300 with a 5.8 mm lens (Fuji Photo Film Company Ltd., Japan) was used.

Measurements of leaf area index (LAI) were made using a LAIL ("LAI-*léger*") device as described by Cournac *et al.* (2002). LAI transects were made in the main fall directions or in the N-S and E-W directions, taking measurements every 2 m.

Satellite observations

The SPOT 4 satellite image of the study area was taken on October 18 2001, at 10:18 a.m. Calibration and navigation processes were conducted by SPOT-Image. The SPOT 4 satellite carries two HRVIR (high resolution visible and infra red) detectors with 20 m spatial resolution. Individual pixel reflectance values were derived from three wavelength bands: visible (VIS [red]: 0.61 - 0.68 μm), near-infra red (NIR: 0.79 - 0.89 μm) and shortwave infra red (SWIR: 1.58 - 1.75 μm), which were appointed to the B (blue), G (green) and R (red) image composing bands, respectively. These reflectance values, called digital numbers or DNs, were processed following Meygret (2004) to obtain an absolute top-of-atmosphere calibration. The atmospheric correction was done using the black target process described by Chavez (1988).

Results and discussion

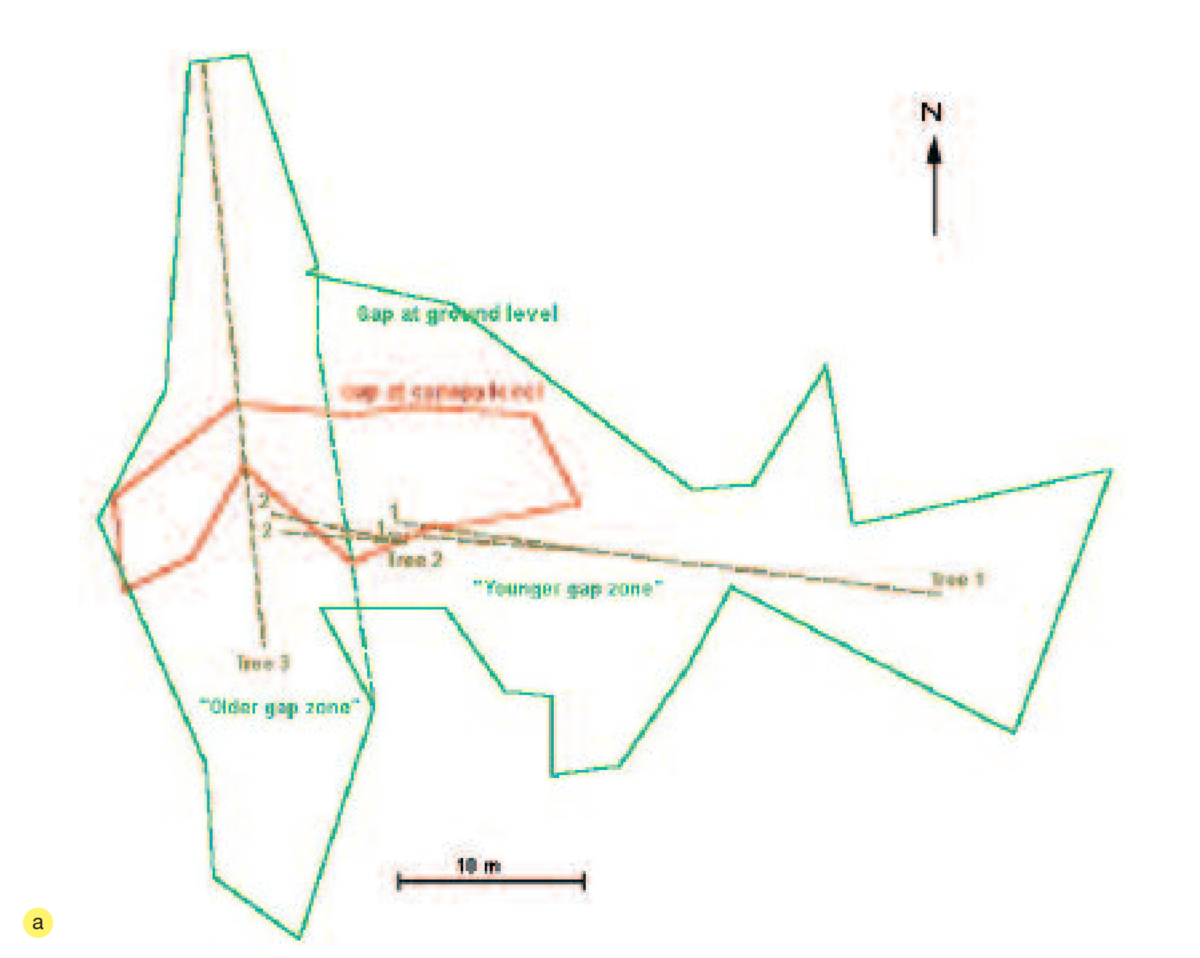
Gap geometry and ecology

If we take the modified Runkle (1981) definition of a canopy gap used in this study to define the limits of the gap on the forest floor, a tree could still be part of the surrounding canopy and not have a DBH of 20 cm. This was especially the case for trees at the edge of the gap, which benefit from more light and therefore invest in shoot growth before trunk thickening. Poorter *et al.* (2003) have confirmed that light-demanding species need a slender stem to be able to attain or maintain a position in the canopy. This allows large-stature tree species to reach their reproductive size rapidly with low expenditure for construction and support. If a tree had been hit (snapped branch, for example), it was considered for this study to be part of the gap interior, even if it had not fallen down and would have been large enough to delimit the gap as defined by Runkle. Abandoning the size limits imposed by Runkle's definition and including the injury parameter allowed for a more accurate description of the actual gap shape as the range of its physical impact at ground level.

The gap surface areas at ground level varied from 522 to 1 987 m² and at canopy level from 56 to 991 m² (Table I). Of the 57 fallen trees recorded, whether felled domino-wise or initiating a fall, 60% were uprooted and 40% snapped off. These were not evenly distributed among the gaps studied: in one gap (8), as many as 15 snapped-off trees were recorded. Another gap (2) was created by major branches falling from two neighbouring trees: a *Humiria balsamifera* measuring 41.8 m, with a DBH of 1.29 m, and a *Dicorynia guianensis* measuring 29.4 m, with a DBH of 0.94 m, which lost branches of 71 and 60 cm in diameter, respectively. This created

Table I.
Overview of parameters influencing SPOT 4 satellite gap detection, for all gaps studied. Gap surface areas are given at canopy and at ground level, as calculated with MapInfo software. Gap undergrowth is classified in terms of height (‹ 1 m = small; 1-3 m = medium; › 3 m = high) and density (visual estimation based on multiple comparisons between gaps: low, medium, high). Numerous leaf area index (LAI) measurements were made along different transects (East/West – North/South, or following a main gap-making tree) and the lowest value for each transect is presented in the table. No LAI measurements could be made in gap 8 due to bad weather conditions. The number of main gap-makers per event was recorded and their diameter at breast height (DBH) was measured. Gap area slopes › 10% were also indicated (yes/no). The final detection using the developed spectral filter is indicated (yes/no) and discussed in the text.

Gap	Gap surface area at canopy level (m^2)	Gap surface area at ground level (m^2)	Regrowth height category	Regrowth density category	Minimal LAI value (m^2/m^2)	DBH of gap makers (cm)	Slopes › 10%	Filter detection
1	56	522	high	medium	4.12 (old zone) 2.43 (young zone)	50, 70	no	no
2	78	657	medium (*Humiria*) small (*Dicorynia*)	medium (*Humiria*) low (*Dicorynia*)	2.77 (*Humiria*) 2.15 (*Dicorynia*)	94, 129	no	no
3	240	571	medium	low	2.87 3.92	10, 15, 21, 47, 54, 89	no	no
4	143	937	high	high	4.48 (old zone) 1.63 (young zone)	45, 50, 50	yes	no
5	206	855	medium high	medium	2.00	20, 20, 25, 45, 55	yes	yes
6	346	661	high	high	2.77 2.43	20, 25, 25, 30, 35, 60	yes	yes
7	326	1055	medium	medium	2.03 2.86	15, 30, 30, 37, 46, 54	yes	yes
8	337	1040	high	low	-	11, 15, 19, 43, 86	yes	yes
9	636	1987	medium high	low	2.67 2.55	12, 17, 25, 26, 32, 40, 41, 50, 65, 69, 102	no	yes
10	884	1950	medium	high	2.96 2.69	40, 60, 130, 150, 157	yes	no
11	991	1576	small	high	2.40 2.50	30, 40, 45, 45, 60, 90	no	yes



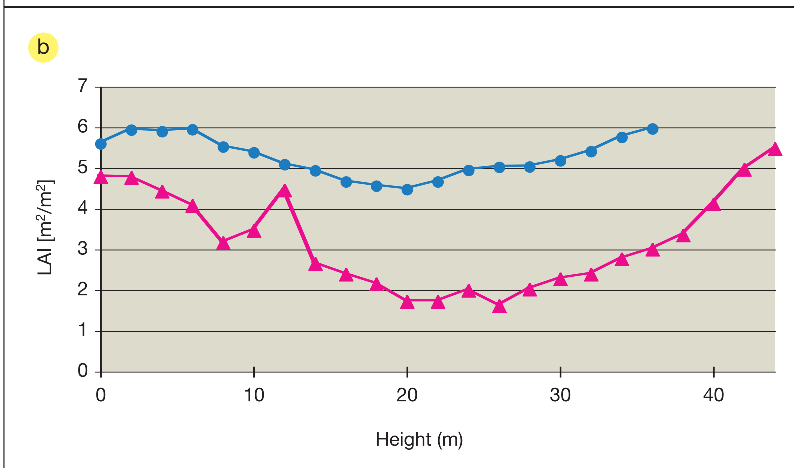


Figure 1.
(a) Reconstruction of the geometry of gap 4, using the perimeter points Px surrounding the gap geo-located by GPS and plotted with MapInfo software. The gap area at canopy level is delineated in red (143 m^2), and the gap area at ground level in green (937 m^2). The latter area is further divided into a younger and an older zone, based on gap maker freshness, canopy closure and undergrowth height and density. The three main gap-makers are marked with "tree x" at the base of their stems.
(b) Two leaf area index (LAI) transects were made along tree 3 (older gap zone, higher LAI-values, minimum of 4.5, ●) and tree 1 (younger gap zone, lower LAI-values, minimum of 1.6, ▲).

one common gap of 78 m^2 at canopy level. Measurements of LAI ranged between 5 and 7 for the undisturbed forest, and were around 2 for gap areas. Table I shows the lowest LAI value for each transect.

There were wide variations in undergrowth height and density between gaps: from small size and low density for gap 2, to high and dense for gaps 4 and 6. A similar range of variation also occurred within gaps, e.g. gap 4, which consisted of two gap zones that differed in age (Figure 1), and gap 2, where the differences in rates of decomposition between the two (branch fall) gap-makers created a favourable and less favourable zone for plant growth (around the *Humiria balsamifera* and the *Dicorynia guianensis*, respectively) (Table I).

Satellite observations

In order to discriminate between the natural canopy gaps that were studied in the field and the surrounding (dense) forest, several spectral band masks were constructed using ENVI software:

1. (NIR – SWIR) $\in$ [0.0504015, 0.063383]

2. (VIS) $\in$ [0.024799, 0.034874]

Mask 1 eliminated dense forest, which exceeded this (NIR – SWIR) range, and the access road and gaps formed by logging activities, which had smaller (NIR – SWIR) values. Mask 2 eliminated clouds, which had greater reflectance in the visible (red) region of the spectrum. Cloud shadows were eliminated by this mask's minimum reflectance: they reflected less visible light. This mask also filtered out the sea and coastal marshes. To filter out more subtle shadows cast over the numerous shallow valleys, three more masks were combined:

3. (NIR – SWIR) / (NIR + SWIR) $\leq$ 0.34017306

4. NIR $\geq$ 0.109571

5. SWIR $\geq$ 0.059457

A combination of these five masks finally resulted in a filtered image, leaving canopy gaps and some artefacts. This procedure is illustrated for gap 9 in Figure 2.

Gap detection: gap-related features

Gap surface area

Only three of the gaps studied had a surface area at canopy level exceeding the pixel size of 400 m^2: gaps 9, 10 and 11, with 636, 884 and 991 m^2, respectively (Table I). Gap 9 (636 m^2; 1 987 m^2) was marked by seven pixels on the filtered image, which represents a total affected area of 2 800 m^2 (Figure 2). Gap 11 (991 m^2; 1 576 m^2) was marked by one pixel only. Thus, there was no direct relationship between the gap area measured in the field and the number of gap-pixels retained by the image filter. This was confirmed by the detection of smaller gaps. Also, gap 10, which was the second largest gap in this study, did not appear as a gap area in the filtered image (Table I).

Gap undergrowth

The undergrowth density factor could explain the difference between the numbers of gap pixels retained for gap 9 and for gap 11. The latter (one pixel) had a very dense understorey while gap 9 (seven pixels) had a sparse one (Table I). Gap 10 was not clearly detected on the satellite image, nor by the image filter. The main difference between being detected or not for the two larger gaps 10 and 11, both densely covered by plant regrowth, was the height of their regrowth: gap 11 was covered by small shoots (< 1 m), while the average regrowth height in gap 10 was between 1 and 3 m (Table I). LAI measurements in gap 10 decreased to minimum values around 3 for only a few meters, and so confirmed the influence of regrowth on the gap's spectral reflectance. In general, it was clear that even inside a gap the LAI never dropped to values close to zero, due to the presence of undergrowth and because the LAIL sensor received the incoming light through a lens with a 180° view angle. The gap edge plants or nearby trunks, branches or leaves could influence the reading. For instance, leaves from small stemless *Arecaceae* like *Astrocaryum paramaca* could be up to 7 m long, and caused a marked drop in the amount of light reaching the forest floor.

This interaction between height and density is further illustrated by gap 8. Regrowth here was high (> 3 m) but sparse, and the gap was detected. In contrast, regrowth in gap 11 was small but dense, and this gap was also detected. Gap 10, however, was undetected by the satellite image filter although regrowth here was similar to the detected and medium-sized gap 6 (346 m^2; 661 m^2). This made it clear that gap size and regrowth (density and height) were not the only factors influencing spectral gap characteristics.

Gap detection: external features

Topography

Gap detection by satellite was influenced by topographical features. Shadows cast by steep slopes were difficult to eliminate without losing too much valuable information. Spectral band masks 3, 4 and 5 had to be applied with care to avoid confusion between shadows and actual gaps. This image noise might have confused detection of several gaps, e.g. 5, 10, but its real influence was difficult to assess.

Shape and relative pixel position

Gap 3 was in a very difficult position relative to the image-composing pixels: although it was narrow (only 240 m^2 at canopy level), 5 pixels were hit. Therefore, at a sub-pixel level, too small a percentage of the ground cover had gap characteristics.

Human disturbances

The relatively narrow tracks used by skidders to reach and extract timber logs were sometimes confused with natural canopy gaps. As in natural gaps, no plants on these roads were actually removed from the forest: rather, they were pushed aside or crushed, sometimes creating a gap in the forest canopy, and left to decompose. In general, the actual logging gaps were very poor in plant growth, as log extraction left the soil highly compacted with little biomass to decompose. Such logging gaps

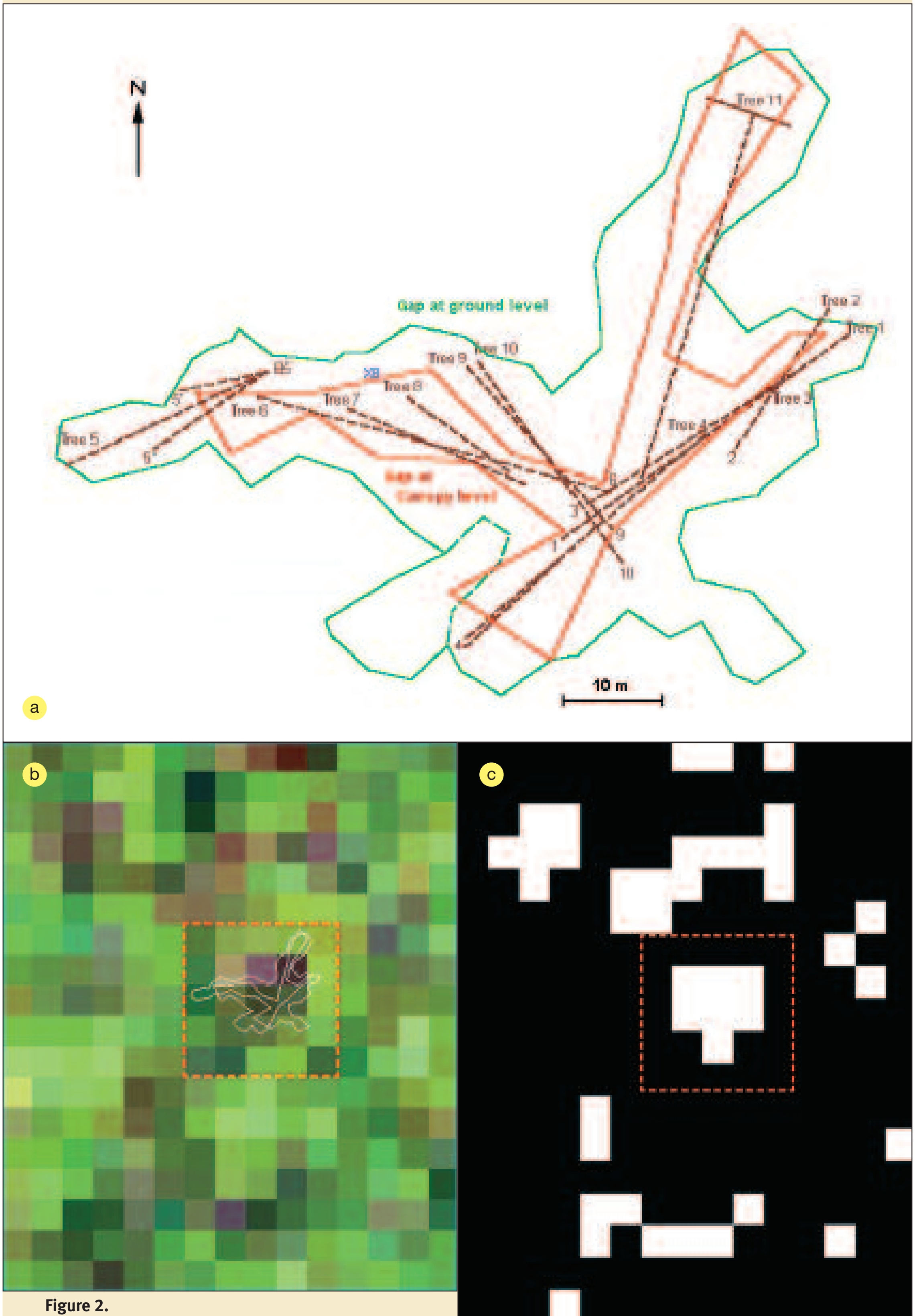


Figure 2.
The data analysis process illustrated for gap 9.
(a) Reconstruction of gap geometry (using MapInfo software), as measured in the field. The gap surface area at canopy level is delineated in red (636 m^2), and the area at ground level in green (1987 m^2). The gap-makers are projected onto the figure.
(b) The surface areas of the gap at both canopy and ground level, projected onto the multi-spectral SPOT 4 image (R: SWIR; G: NIR; B: VIS; HRVIR sensors; spatial resolution of 20 m) using ENVI 3.5 software.
(c) After applying the binary filter (consisting of a discriminating combination of five spectral masks), this particular gap left seven “gap-pixels” on the satellite image.

were rightly eliminated by the image filter, which was explicitly constructed for the detection of natural gaps only. Confusion was noticeable in logging gaps where large parts of cut trees had not been removed from the forest.

Arecaceae

Pure communities of *Arecaceae* were often encountered in the near-flooded valley bottoms, and along small creeks following the drainage network. Populations of *Euterpe oleracea* especially (vernacular name: "Pinot"), but also some *Oenocarpus bataua* (vernacular name: "Patawa"), were abundant in these swamp-like environments. The crowns of such palms are unable to form a canopy as tightly closed as other (non-palm) canopy trees, stratification was almost absent and the dense undergrowth was small in size (photo p. 74). In at least two cases, such areas were mistaken by the image filter for natural canopy gaps.

Time-lag

Due to the time-lag between the satellite image and the field work, some newly formed natural gaps were found in the forest but not on the filter image. Most original canopy openings present on the 2001 image have gradually been closing due to the lateral extension of adjacent vegetation, but they may also have been further enlarged by the fall of exposed trees on the edge of gaps. This possible source of error due to changes occurring during the one-year hiatus is common in studies using a remote sensing research approach, especially in the humid tropics. Furthermore, seasonality can influence and alter a number of important detection parameters, also in tropical forests (DE WASEIGE, DEFOURNY, 1997), but this is probably less relevant in this study, since both the satellite image acquisition and the fieldwork occurred during the dry season.

Table I indicates the threshold values limiting satellite detection of canopy gaps at a spatial resolution of 20 m. Gaps smaller than 100 m^2 –or ¼ image pixel size– at canopy level will probably never be detected: e.g. 1, 2. In these gaps, LAI was sufficiently low, the undergrowth varied and there were no shadows cast by steep slopes. The most important factor determining their detection was therefore size. In the best of circumstances (optimal shape and position relative to pixel position), gaps 1 and 2 could have occupied 14 and 19.5% of the pixel surface area, respectively, which is not enough for detection. The fact that gap 3 was not detected by the image filter was most probably due to its narrow shape and its unfavourable position relative to the image pixel position. Gap 4 (143 m^2 at canopy level) was not detected either, but had very high and dense undergrowth and highly varied topography. Thus, the smallest gap detected (gap 5) had a surface area at canopy level of 206 m^2. As all larger gaps were detected by the image filter (except for gap 10), the size-detection threshold was between 100 and 200 m^2, or 25 to 50% of the pixel surface area potentially covered by the gap area. Note that natural gaps are highly unlikely to be confined within a single pixel, even when their size does not exceed the image resolution. We therefore emphasize that size threshold values refer to *potential* area coverage. Gaps larger than this could have dense and high regrowth (e.g. gap 6; 346 m^2) or marked topographical heterogeneity (e.g. gap 8; 337 m^2): these were detected. Gap 10 was very large (884 m^2), but was a special case in several respects: it extended over part of one slope onto the opposite slope, thus including the uneven valley bottom, it had very dense undergrowth of variable height and, in addition, it included an ellipsoid "island" of untouched canopy trees inside the actual gap. It was not detected.

This concurs with the findings of ASNER *et al.* (2002), who studied selective logging in Amazonia using Landsat ETM+ satellite imagery (30 m spatial resolution). These authors concluded that forest damage (including decking, roads, skidding and tree falls) could not be resolved with Landsat reflectance or texture data when the canopy gap fraction was less than 50%.

Conclusions

Above a given size limit of 100 to 200 m^2, successful detection of canopy gaps using 20 m resolution SPOT 4 satellite images mainly depends on the height and density of regrowth vegetation. The number of gap pixels retained is almost independent of gap size. This could become an advantage when the technique developed is used to analyse time series of images, since fresh gaps will very likely be detected thanks to their low regrowth height and density, even if their size is below pixel level. Only the rate and extent of their regrowth will determine how quickly these gaps will "disappear" again into the surrounding closed forest. Since this is a spectral filter technique, it is suited to images of higher spatial resolution containing the same sensor bands or spectral information. Clearly, the technique should not be used for remote assessments of canopy gap size.

Future research should systematically assess and refine the gap filter developed. Acquiring a satellite image of the study region on a regular basis, e.g. yearly, could reveal a lot of information on the broad-scale dynamics and turnover of an ever-changing tropical forest. The detection of treefall gap densities over a large area could help forest managers to eliminate low logging potential zones quickly during inventories, and ecologists to locate these biodiversity hot spots.

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