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APPLICATION OF LIDAR TO FOREST INVENTORY FOR TREE COUNT IN STANDS OF *Eucalyptus* sp

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ABSTRACT: Light Detection and Ranging, or LIDAR, has become an effective ancillary tool to extract forest inventory data and for use in other forest studies. This work was aimed at establishing an effective methodology for using LIDAR for tree count in a stand of *Eucalyptus* sp. located in southern Bahia state. Information provided includes in-flight gross data processing to final tree count. Intermediate processing steps are of critical importance to the quality of results and include the following stages: organizing point clouds, creating a canopy surface model (CSM) through TIN and IDW interpolation and final automated tree count with a local maximum algorithm with 5 x 5 and 3 x 3 windows. Results were checked against manual tree count using Quickbird images, for verification of accuracy. Tree count using IDW interpolation with a 5x5 window for the count algorithm was found to be accurate to 97.36%. This result demonstrates the effectiveness of the methodology and its use potential for future applications.

Key words: Airborne laser scanning, tree detection, Local Maximum.

APLICAÇÃO DO LIDAR NO INVENTÁRIO DE FLORESTAS PLANTADAS COM *Eucalyptus* sp PARA CONTAGEM DE ÁRVORES

RESUMO: O *Light Detection and Ranging*, ou LIDAR, tem se tornado uma eficiente ferramenta auxiliar para a extração de dados no inventário florestal e também em outros estudos florestais. Este trabalho foi realizado com o objetivo de estabelecer uma metodologia eficiente para a utilização do LIDAR para a contagem do número de árvores em um povoamento de *Eucalyptus* sp., localizado no sul do Estado da Bahia. Apresenta-se desde o processamento dos dados brutos obtidos em voo até o número final da contagem de árvores. Os passos intermediários são de vital importância para a qualidade dos resultados e os mesmos são obtidos por meio das seguintes etapas de processamento: organização da nuvem de pontos; criação do modelo de superfície do dossel (MSD) por meio da geração de uma TIN e interpolação *Inverse Distance Weighted* (IDW) e contagem automatizada final das árvores com um algoritmo de máxima local com janelas de 5 x 5 e 3 x 3. Os resultados obtidos foram comparados à contagem manual das árvores em imagens Quickbird para a verificação da acurácia. O acerto da contagem foi de 97,36% por meio da interpolação IDW com a janela de 5X5 para o algoritmo de contagem. Esse resultado evidencia a eficácia da metodologia produzida e o potencial para futuras aplicações.

Palavras-chave: Laser aerotransportado, detecção de árvores, Local Máxima.

1 INTRODUCTION

With the expansion of the forestry sector and with timber increasingly becoming a scarce commodity, it becomes vital that long-, medium- and short-term planning be more and more accurate to ensure timber availability over time, maximizing timber yield and reducing production costs.

Bearing this in mind, forest planners are more and more in search of tools from which to derive accurate

information on current forest stock, also looking to model future forest yield. Conventional continuous or prefelling inventory procedures have always been used by forest companies to attain that, constituting a strategic planning tool in that they allow estimation of the dendrometric variables required to determine present and future timber stock with desirable accuracy and viable cost (SCOLFORO; MELLO, 2006).

In Brazil, continuous forest inventory is one of the most popular ways of monitoring forest growth. In

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this type of inventory, permanent plots are installed when stands reach age two or three years, being systematically remeasured at intervals of one to two years (KANEAE JUNIOR et al., 2006; OLIVEIRA, 2006). It has been observed, however, that some inconsistencies may be associated with conventional inventories, including bias in diameter and height mensurations, error in data handling, error in plot area measurements and, especially, errors associated with the sampling procedure, which may vary depending on the dendrometric variable being analyzed, being particularly high for the variable 'number of trees per hectare'. Errors of this sort lead to impaired data quality and thus generate imprecise growth and yield models, consequently affecting forest planning at large. Sampling errors can only be resolved if a census is conducted in the relevant area.

Remote sensing has been proving an important tool for the development of forest sciences, potentially allowing significant gains in forest inventory by helping improve estimates and/or reduce sampling intensity (SOUZA et al., 2007).

Use of *Light Detection and Ranging*, or LIDAR, for accurate determination of land elevation began in the second half of the 1970s (LILLESAND; KIEFER, 2000) and, since the 1980s, its use for forest applications has progressed considerably. As high resolution spatial imagery becomes increasingly available, it also becomes possible to obtain forest information on individual trees rather than on plots or stands as a whole (DISPERATI et al., 2007). When a laser beam propagates in space, it has a divergence that results in the diameter of the point cast on the surface (footprint). This area coverage corresponds to the spatial resolution of LIDAR imagery (JENSEN, 2009; LEE; LUCAS, 2007).

Several studies have been conducted for use of LIDAR in inventories of planted forests, whether to estimate plot or individual tree parameters. They include the works of Castro and Centeno (2005), Crow et al. (2007), Heurich and Thoma (2008), Ioki et al. (2010), Jupp et al. (2007), Lauri et al. (2008), Macedo (2009), Maltamo et al. (2004), Naesset and Bjercknes (2001), Popescu (2002), Sasaki et al. (2008), Tiede et al. (2005), Yu et al. (2004), Zandoná et al. (2008), Zonete (2009) and Zonete et al. (2010).

Considering the above, this work was generally aimed at developing methodologies to improve use of distance measurement data by using light waves, or LIDAR, in forest inventory.

Specific objectives included:

- generate a tree count methodology for stands of *Eucalyptus* sp. with spacing of 4 x 3 m, at age 3 years;
- test two local maximum filters, 5 x 5 and 3 x 3, in stands of *Eucalyptus* sp. with spacing of 4 x 3 m, at age 3 years;
- test two interpolators, *inverse distance weighted interpolation* (IDW) and *triangulated irregular network* (TIN), in order to characterize the situation of the tree canopy for *Eucalyptus* sp.;
- test the two interpolators, at different heights, in the two stands of *Eucalyptus* sp. at age 3 years.

2 MATERIAL AND METHODS

2.1 Study site

The study site lies in the southernmost portion of Bahia state, between coordinates 16°7'21"S; 39°21'48"W and 16°7'36"S; 39°21'22"W (Figure 1). Being a coastal region, the local rates of rainfall are high and well distributed throughout the year, and the local topography is flat.

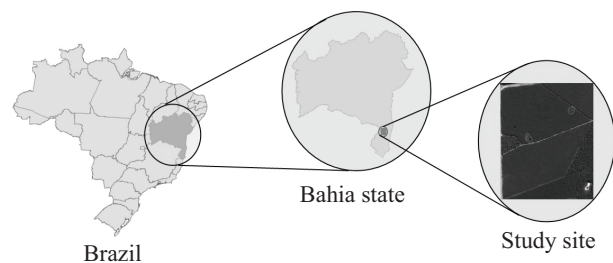


Figure 1 – Geographic location of the LIDAR-scanned stands.

Figura 1 – Localização geográfica dos talhões escaneados com o LIDAR.

Two eucalyptus stands at age three years were used in this study, cultivated with different clones. At three years, stands are young and tree crowns do not intertwine, and it is also at this age that continuous inventory usually begins, hence it being selected. Stand 1 (clone 'a') has an area of 21.71 ha with spacing of 3 x 4 m and has 17,495 tree stems (information obtained by visual tree count using a Quickbird image from /09/April/2007). Stand 2 (clone 'b') has an area of 21.76 ha with spacing of 3 x 4 m and has 17,390 tree stems (information also obtained by visual count). These stands were inventoried using circular plots of 531 m², with the center being georeferenced with DGPS and with 4 plots being randomly distributed per stand.

Table 1 provides the area obtained for the stands against the area reported in existing records, and summarizes information on tree stems in the stands through inventory estimation and visual tree count. In this study, inventory estimation data are only illustrative, since the approach to the technique is intended to determine the exact number of trees in the stand, in addition to the fact that the inventory had a higher sampling intensity than the traditional company's inventory.

Table 1 – Determination of all existing trees in two stands and difference in area.

Tabela 1 – Determinação de todas as árvores existentes nos povoamentos nos dois talhões e diferença de áreas.

	Visual count	Inventory estimate	Area reported in company records	Area obtained by LIDAR
Stand 1	17,495	17,486.33	21.71ha	22.05 ha
Stand 2	17,390	18,135.72	21.76 ha	21.75ha

2.2 LIDAR data acquisition and preprocessing

LIDAR data were collected between 5 and 9 September 2008, using an ALTM 3100 system coupled to a twin-engine Piper Seneca II aircraft. The flight was operated at 150 km/h, at an altitude of 1,000 m, with a beam diameter of 20 cm, a beam divergence of 0.3 mrad, a scanning angle of 15°, a scanning frequency of 58.7 Hz and 1.5 point intensity per square meter. The planimetric error was 0.5 m (1.0 sigma), the altimetric error was 0.15 m (1.0 sigma) and the laser area coverage was 0.32 m.

When a laser signal reaches objects without a well-defined surface, it may produce various reflection records (returns or pulses). Although some LSA systems, such as Aeroscan (Leica), are capable of registering the return of up to 5 pulses, in forestry studies the most important pulses are the first and the last: the first provides information on the uppermost portion of objects and is used for canopy surface modeling; the last pulse is reflected on the lowest level reached by the laser and is used for terrain modeling. This allows separating low ground vegetation for generation of a digital heights model (CASTRO; CENTENO, 2005; COELHO; VARGAS, 2007; JENSEN, 2009; MIQUELES et al., 2003).

Data from LIDAR signals related to the area of the two stands were structured based on information

about coordinates latitude, longitude, altitude (x, y, z), returns (1st, 2nd and 3rd pulse) and signal intensity. The result of this systemization is a spreadsheet where each laser pulse is depicted in rows and its respective information is provided in columns. This information determines the point density of the resulting cloud. Density can range between 0.5 and 5 points per square meter, where the accuracy of the laser scanner is in the order of about 15 cm (CROW et al., 2007). Each row in the spreadsheet can also be depicted using x, y and z coordinates, forming a point cloud in three-dimensional space which is stored in vector file format in the Geographic Information System.

Once information was structured, the flight route of the aircraft was analyzed so as to avoid overlay of successive passages. Overlay information was ignored in this study because of the greater concentration of noise observed in such areas. This was probably due to canopy shift influenced by wind at different aircraft passages.

2.3 LIDAR data processing

In order to better understand the methodology, Figure 2 provides a step sequence diagram for its implementation.

At this stage, point cloud information was separated into terrain models (DTM) and surface models (DSM). For that, binary logic rules were used assessing information on pulse, altitude, vertical and horizontal angulation between adjacent points with the standard deviation of the altitudes of each pulse. The point cloud can be assessed three-dimensionally, as rendered in Figure 3.

With the difference of DTM and DSM, height information was generated for all points relative to the soil. Concurrently, the point cloud was categorized as follows:

- Soil (points with one return only and last returns of the remaining points, which interact with a flat angulation of 8° and a vertical angulation of 88° through a triangulation with neighboring points, up to 8 standard deviations);
- Undergrowth (points 0.35m to 2.5m in height relative to the soil);
- Branches (points 2.5m to 13m in height relative to the soil);
- Canopy above 13 m (canopy with branches above 13m in height);
- Canopy above 14 m (canopy with branches above 14m in height).

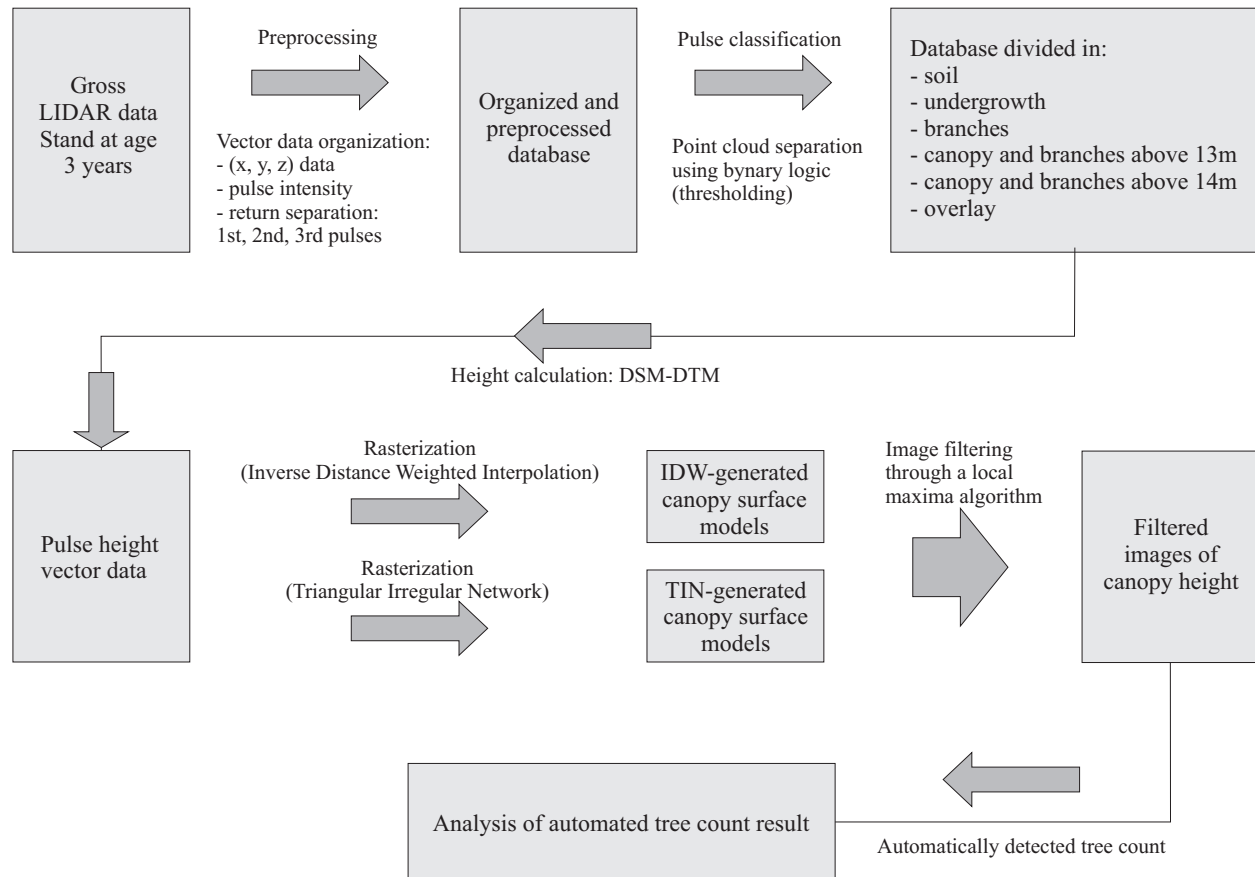


Figure 2 – Tree count step methodology diagram.

Figura 2 – Esquema de passos para a execução da metodologia de contagem de árvores.

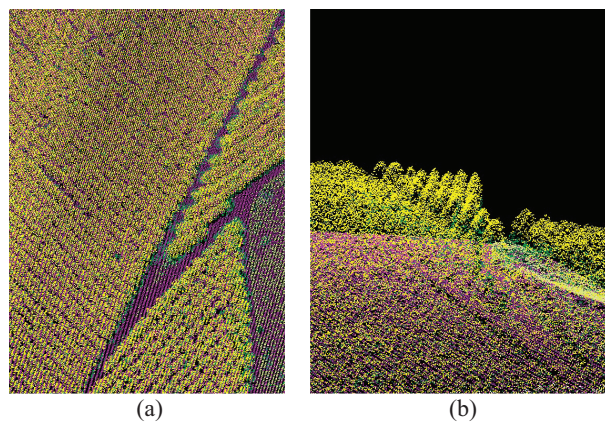


Figure 3 – Rendered LIDAR 3D point cloud, originated in the stand of *Eucalyptus* sp.

Figura 3 – Nuvem de pontos 3D do LIDAR renderizadas, originadas do povoamento de *Eucalyptus* sp.

Canopy above 13 meters and canopy above 14 meters were selected because it was at these average heights that tree crowns started in each stand. This division was necessary because the clones differed by about 1m as to where the crown base started, and by about 2m in the total height (Figure 4).

Height information was used for all classes as a whole and separately for application of IDW (Figures 5a to 5e) and TIN (Figures 5f to 5j) interpolations (BURROGH; MCDONNELL, 1998). In this data set, a variation was observed in the shade gradation of the images. This variation influences height values, crown shape and points of local maxima, causing some trees to be excluded or divided in the detection result. Figure 5 indicates detected trees through red dots and undetected trees through red circles. The resulting effect of TIN triangulation is depicted in Figure 5j (red square).

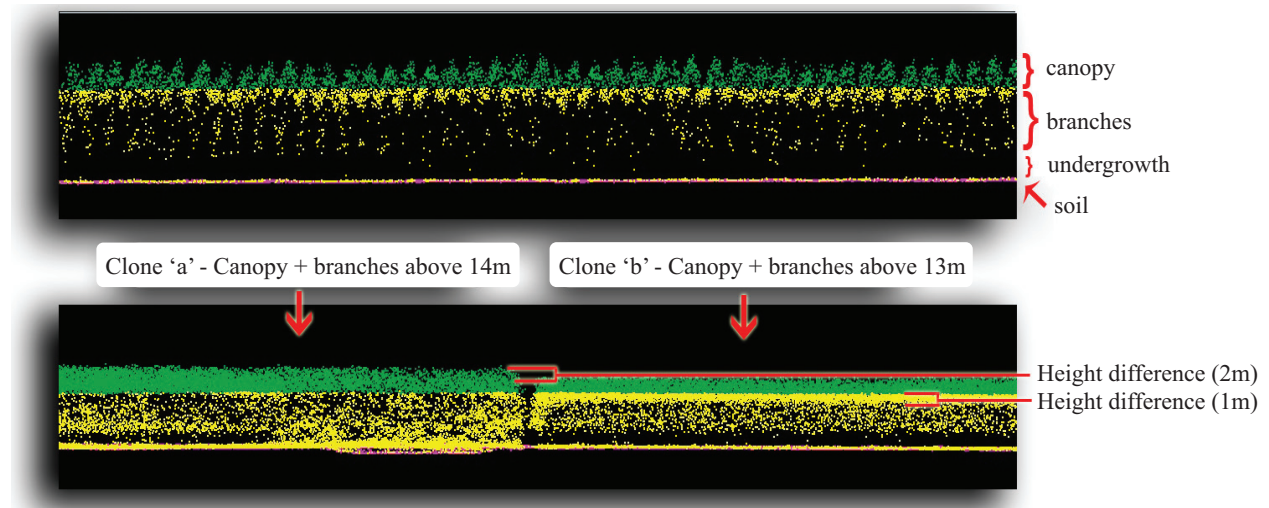


Figure 4 – Profile of the *Eucalyptus* sp. stand as depicted by LIDAR point cloud.

Figura 4 – Perfil do povoamento de *Eucalyptus* sp. na nuvem de pontos obtidas pelo LIDAR.

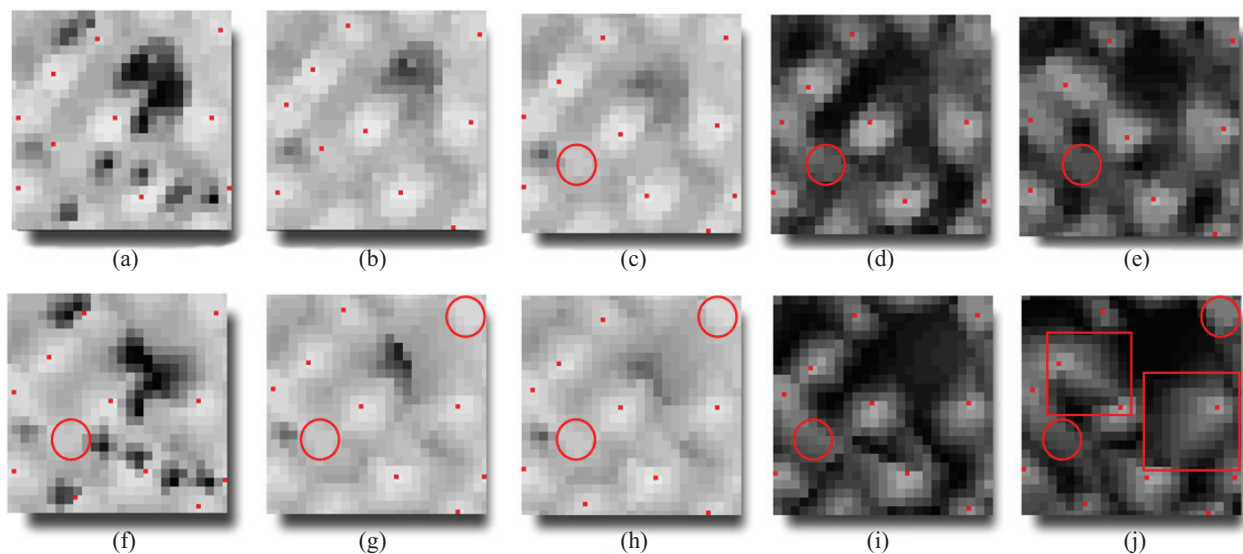


Figure 5 – Results of IDW interpolation: (a) including all first returns from soil to canopy, (b) returns from undergrowth to canopy (c) branches to canopy (d) canopy and branches above 13 m (e) canopy and branches above 14 m; TIN interpolation is exemplified in figures (f) through (j) with the same return sequence situations.

Figura 5 – Resultados dos interpoladores IDW: (a) incluindo todos os primeiros retornos desde o solo até o dossel, (b) retornos desde a vegetação rasteira até o dossel (c) galhos até o dossel (d) dossel e galhos acima de 13 m, (e) dossel com galhos acima de 14 m; o interpolador TIN é utilizado nas figuras de (f) a (j) com a mesma sequência de situações para os retornos.

After converting information into raster format, a local maximum filter was applied (CARVALHO, 2001, 2008), with 3 x 3 and 5 x 5 moving windows, in order to compute all existing trees in the stand. This result

was compared to plot inventory estimates (Table 1) and these two methods were checked against information obtained by visual count using a Quickbird image from 09/April/2007 (Figure 6).



Figure 6 – Manual tree count using Quickbird images.

Figura 6 – Contagem manual das árvores, utilizando imagens Quickbird.

3 RESULTS AND DISCUSSION

Data obtained with the local maximum algorithm using 3 x 3 filtering (Tables 2 and 3) were not as effective if compared with results obtained using 5 x 5 filtering (Tables 4 and 5), since all results found with 3 x 3 filtering tended to overestimate the number of individuals in the stand, generating a higher error of commission. This result contrasted with the result obtained with 5 x 5 filtering, which tended to underestimate the population in both

stands and detected values closer to reality, with a minor error of omission. This result relates to the spacing being used in the plantation (4 x 3), suggesting that if spacing is reduced in the study site, the 3 x 3 filter may have better performance while the 5 x 5 filter, worse.

These results can be rated excellent, considering that Zadoná et al. (2008) found an average accuracy of 82.8%, against the 98.85% reached with the proposed methodology in stand 1, equivalent to an error of 202 trees in a population of 17,293 trees (Table 4), and 96.58% in stand 2 which is equivalent to 599 trees in a population of 16,791 trees (Table 5). Results are also very satisfactory in relation to Norway Spruce and Scots Pine forests in the work of Maltamo et al. (2004), who obtained an accuracy of 91.8% for the average number of trees per plot using a similar methodology to generate a canopy surface model. The result found by McCombs et al. (2003) for two stands with spacing of 2.4 m and 3.0 m was 64.7% and 87.3%, yet by merging statistics with multispectral (550, 675, 700 and 800 nm) and high resolution data (0.61 m) they improved the result to 83.5% and 94.8%, outlining a potential methodology for improvement of tree count results. Morsdorf et al. (2004) found that only 60.48% of the existing trees were

Table 2 – Tree detection by the local maximum algorithm using 3 x 3 filtering, for stand 1.

Tabela 2 – Detecção de árvores pelo algoritmo de máxima local, filtro 3 x 3, para o talhão 1.

Classes generated with 1st pulse	(TIN) trees	Error (no. trees)	Error (%)	(IDW) trees	Error (n° trees)	Error (%)
All classes with soil	26208	-8713	-49.80	29628	-12133	-69.35
Undergrowth, branches and canopy	24082	-6587	-37.65	26516	-9021	-51.56
Branches and canopy	22962	-5467	-31.25	25242	-7747	-44.28
Canopy and branches above 13m	21394	-3899	-22.29	22490	-4995	-28.55
Canopy and branches above 14m	21418	-3923	-22.42	22399	-4904	-28.03

Table 3 – Tree detection by the local maximum algorithm using 3 x 3 filtering, for stand 2.

Tabela 3 – Detecção de árvores pelo algoritmo de máxima local, filtro 3 x 3, para o talhão 2.

Classes generated with 1st pulse	(TIN) trees	Error (no. trees)	Error (%)	(IDW)	Error (no. trees)	Error (%)
All classes with soil	20235	-2845	-16.26	23369	-5979	-34.17
Undergrowth, branches and canopy	19687	-2297	-13.13	22362	-4972	-28.42
Branches and canopy	19603	-2213	-12.65	22183	-4793	-27.40
Canopy and branches above 13 m	19093	-1703	-9.73	20447	-3057	-17.47
Canopy and branches above 14 m	19276	-1886	-10.78	20301	-2911	-16.64

Table 4 – Tree detection by the local maximum algorithm using 5 x 5 filtering, for stand 1.**Tabela 4** – Detecção de árvores pelo algoritmo de máxima local, filtro 5 x 5 para o talhão 1.

Classes generated with 1st pulse	(TIN) trees	Error (no. trees)	Error (%)	(IDW)	Error (no. trees)	Error (%)
All classes with soil	17033	462	2.64	17683	-188	-1.07
Undergrowth, branches and canopy	16732	763	4.36	17293	202	1.15
Branches and canopy	16736	759	4.34	17216	279	1.59
Canopy and branches above 13 m	16569	926	5.29	16957	538	3.07
Canopy and branches above 14 m	16560	935	5.34	16945	550	3.14

Table 5 – Tree detection by the local maximum algorithm using 5 x 5 filtering, for stand 2.**Tabela 5** – Detecção de árvores pelo algoritmo de máxima local, filtro 5 x 5, para o talhão 2.

Classes generated with 1st pulse	(TIN) trees	Error (no. trees)	Error (%)	(IDW)	Error (no. trees)	Error (%)
All classes with soil	16771	619	3.54	16776	614	3.51
Undergrowth, branches and canopy	16718	672	3.84	16780	610	3.49
Branches and canopy	16706	684	3.91	16791	599	3.42
Canopy and branches above 13 m	16574	816	4.66	16435	955	5.46
Canopy and branches above 14 m	16390	1000	5.71	16316	1074	6.14

detected using a K-means segmentation algorithm. This is partly due to canopy outspreading (spacing between tree crowns is often less than 1 m). Other results can be found in Koch et al. (2006), who used the computer vision framework HALCON with Watersheding techniques for segmenting and discriminating between different crowns and decision rules. Results reveal an accuracy of 87.3%, in which the author differentiates results as correct or at least satisfactory.

Despite proving more effective with 3 x 3 filtering than IDW (Tables 2 and 3), TIN was not thought of as ideal, since all Errors were higher than with 5 x 5 filtering, demonstrating that the latter is more suitable for the tree spacing being studied. Therefore, when comparing again TIN and IDW interpolations (Tables 4 and 5), IDW was found to have better performance, with less error than TIN for both stands, except for canopy in stand 2.

It was noted that TIN interpolation tends to misrepresent the shape of tree crowns, as they tend to be rendered triangular (Figures 5j, 7i and 7j inside the red square). IDW interpolation, in turn, tends to preserve the shape of tree crowns, as illustrated in Figure 6, as a result of the high resolution optical image.

Another point to note is that when only canopy information is evaluated, a greater error is generated than when information is evaluated of combined canopy with branches and undergrowth for the entire population (Figures 7a to 7j). This difference was found to be due to trees having impaired height growth as a result of a soil or fertilization condition, causing them to be suppressed in relation to the rest of the population. This assertion is illustrated by Figures 5a to 5e, which show that trees below canopy height level were not detected in the dominant tree layer.

By removing the error obtained from analysis of the population in relation to 1st pulse information excluding soil, it was found that it is possible to generate a percentage of suppressed trees in the stand, as illustrated in Table 6 and in situations found in Figures 5 and 7. Another important observation was that besides the number of trees present in the stand, height information which is more difficult to obtain and often less precise in forest inventories is also generated for each tree detected.

The above information can be very useful for assessing stand quality and site quality and for improving volume modeling, since suppressed trees will have less volume than the rest of the population.

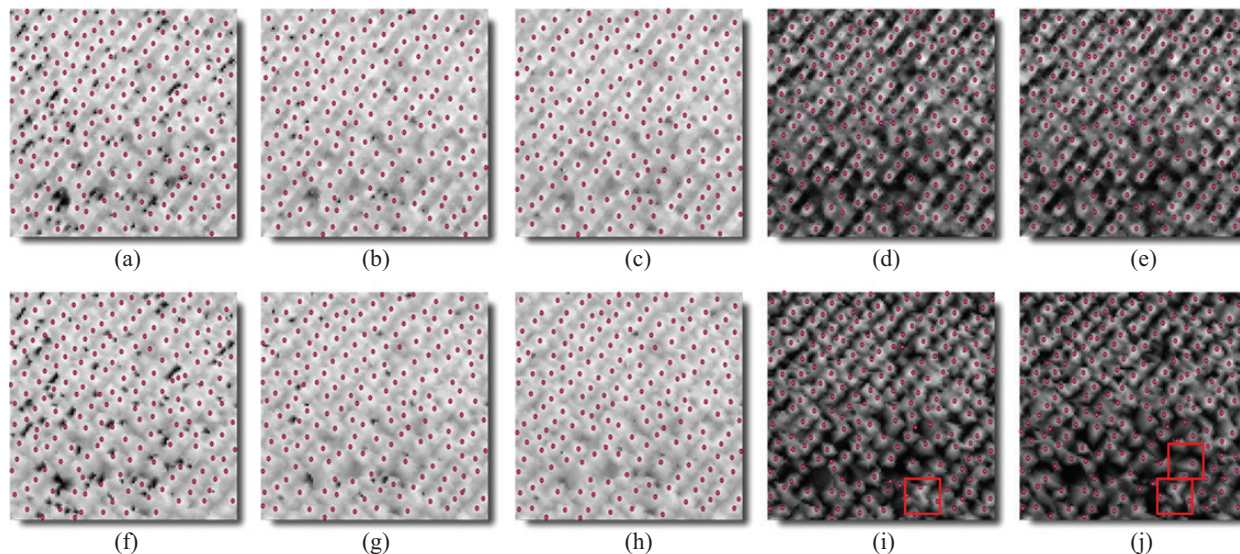


Figure 7 – Tree count results for data interpolated by IDW: (a) including all first returns from soil to canopy, (b) returns from undergrowth to canopy (c) branches to canopy (d) canopy and branches above 13 m, (e) canopy and branches above 14 m; data interpolated by TIN is exemplified in (f) through (j), with the same sequence situations.

Figura 7 – Resultados da contagem para os dados interpolados por IDW: (a) incluindo todos os primeiros retornos desde o solo até o dossel, (b) retornos desde a vegetação rasteira até o dossel (c) galhos até o dossel (d) dossel e galhos acima de 13 m, (e) dossel com galhos acima de 14 m, e a mesma sequência para contagem usando os dados interpolados por TIN de (f) a (j).

Table 6 – Number of suppressed trees found in stands 1 and 2.

Tabela 6 – Número de árvores suprimidas encontradas nos talhões 1 e 2.

Classes generated with 1st pulse	No. trees (Stand 2)	Error (no. trees)	Error (%)	No. trees (Stand 1)	Error (no. trees)	Error (%)
All classes with soil	16776	-	-	17683	-	-
Undergrowth, branches and canopy	16780	0	0	17293	0	0
Branches and canopy	16791	-	-	17216	77	0.44
Canopy and branches above 13 m	16435	345	1.97	16957	336	1.92
Canopy and branches above 14 m	16316	464	2.65	16945	348	1.99

4 CONCLUSIONS

It was possible to generate a specific methodology to obtain forest inventory data, more specifically to do tree count in stands of *Eucalyptus* sp. with spacing of 4 x 3 m. For that, it was essential to use only information on branches and crown canopy, as obtained by using 1st pulse LIDAR data.

The 5 x 5 local maximum filter succeeded in detecting treetops, allowing tree count in stands aged 3 years, providing an error of 202 trees (1.15%) in a population of 17,495 trees (clone 'a'), and 599 trees (3.42%) in a population of 17,390 trees (clone 'b').

Inverse distance weighted interpolation (IDW) proved more effective than the *triangulated irregular network* (TIN) procedure in characterizing tree canopy status for *Eucalyptus* sp.

With the proposed methodology, it was possible to indicate the number of suppressed trees in cloned stands of *Eucalyptus* sp. at age 3 years.

There are many challenges yet to be faced in order to use the full potential of information provided by LIDAR. Other studies should be conducted in order to evaluate this methodology for different stand ages, tree spacing and topographic conditions.

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