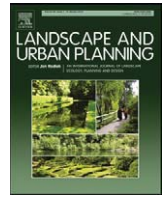




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The visual exposure in forest and rural landscapes: An algorithm and a GIS tool

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ABSTRACT

There have been many different approaches to the delineation and measurement of viewsheds using GIS. However, the quantification of visibility for each element within the viewshed is estimated by imprecise procedures. This paper proposes a GIS tool which analyzes the visual exposure of a terrain from single or multiple observation points, starting from a digital elevation model (DEM). The proposed procedure yields higher precision values than the existing methods, because it directly obtains the solid angle of each visible cell within the DEM. The procedure is based on building a triangle network from a DEM in a regular square grid (RSG), thereby eliminating the need to calculate the slope and aspect, which are necessary steps of other procedures. The visual exposure values for each cell can be added in order to estimate the visual impact of landscape elements represented by a set of cells in the RSG. The development of the tool was oriented towards mitigating the landscape impact caused by forestry activities, in order to comply with certification schemes for Sustainable Forest Management. The tool proved to be useful in assessing alternatives for distributing clear-cutting areas so as to minimize visual impact, and can be applied to any other landscape impact assessment, such as road construction, quarrying, farming or any other land use change.

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1. Introduction

The systematic and objective evaluation of the physical characteristics of a landscape is an important topic in contemporary landscape research (Smardon et al., 1986). Looking at the main set of attributes used in aesthetic evaluation, visibility is always a main factor for decision making in visual impact assessment, as well as in other applications in archaeology, fire towers, radar sites, telephone transmitters, etc. In forest management, aesthetics is a major issue in many areas where forestlands provide recreational use; thus, fragmentation and transformation of the landscape by harvest scheduling must be carefully planned (Borgesa and Hoganson, 2000). A good evaluation of the visibility of harvesting patches and species distribution can be a complementary feature for existing models of multiobjective forest management (e.g., Seely et al., 2004; Shao et al., 2005).

Visibility is computed in 2D GIS environments by definition of viewsheds, on the basis of mutual visibility between two points when there are no obstacles within the line-of-sight. Beyond the geometric calculations, there are multiple factors constraining vis-

ibility that have a strong influence on what the observer actually “sees”; human perception is a combination of optical physics, atmospheric effects, and other more psychological and cultural factors (Ervin and Steinitz, 2003). Gross (1991) notes the following as main factors influencing the visual impact of objects on the landscape: covered surface area on the retina, visual acuity of the human eye, the eye’s resolving capacity, atmospheric extinction, and color difference to the background. He defines specific visibility $S''(r, Ca)$ (unit: sr/m²) as a measure for the optical impression made by an object at a given observer point which must be calculated as an integral above the solid angle area of the retina Ω taken up by the object, evaluated with the visual acuity V ; the color difference to the background and the atmospheric extinction ΔE , related to the observer’s area $dA = 1 \text{ m}^2$.

$$S''(r, \phi) = \frac{1}{dA} \int_{\Omega} V(a) \cdot \Delta E(r, \phi) \cdot d\Omega \quad (1)$$

where, r, ϕ are the polar coordinates (distance and angle) relating the object and the observer; a is the angle of visual incidence on the retina.

Focusing on the geometric question, in reference to the surface area covered on the retina, Llobera (2003) defines “visual exposure” as ‘a measure of the visible portion of whatever is the focus of the investigation’. If we talk of raster cells it would be the measure of how much each cell occupies the field of view of an individual at any location.

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Looking at previous works, one of the pioneer GIS developments, VIEWIT (Travis et al., 1975), implemented commands for visibility analysis that included visual exposure estimation using relative aspect and distance as weighting options. Within the viewshed, the program obtained the visual angle for each cell relative to the observer, taking into account the aspect and slope of the seen cell, elevation of that cell, and elevation of the observer. Each cell was assigned a maximum of 10 points, and this was scaled according to the relative aspect. The distance weighting option allowed the visibility of a cell to be weighted by its distance from the observer. For that purpose the user must define a distance–weight function, which expresses the desired relationship between distance and visibility. Weights are numbers between 0 and 1.0 inclusive.

Llobera (2003) estimated visual exposure for triangulated irregular network (TIN) models by (a) sampling the model at a fixed rate (20 m), (b) selection of a viewpoint location, (c) obtaining the orthonormal vector of the plane at each sampling point, (d) calculation of the line-of-sight (LoS) normal vector, (e) obtaining the visual exposure by projecting the surface orthonormal vector onto the LoS and multiplying by an additional factor derived from the distance between the viewpoint and the target point.

The cited methods provide relative values of visual exposure that may be adequate for comparing visibility of different objects in the scene. However none of these methods provides values of solid angle that can be integrated in Eq. (1).

In this paper we propose an algorithm for quantification of the visual exposure of any terrain within the viewshed, evaluated as solid angle or covered surface area on the retina of the observer. The algorithm is implemented in a software tool on ArcGIS.

The solid angle values obtained by the algorithm can be used in Eq. (1) or any other equation for visibility analysis, crisp or fuzzy, that include other influencing factors. Furthermore, the solid angle measure allows the addition of the visual exposure of a set of raster cells containing a given landscape feature; this makes it possible to evaluate the relative importance of the feature in the view.

As a GIS development, the algorithm is vulnerable to several of the sources of error which can occur in viewshed calculation: (a) simplification and aggregation in raster elevation data (Ervin and Steinitz, 2003); (b) factors that may modify the viewshed, such as vegetation screens near the observer, height of the observer, presence of unmapped human artifacts, etc., which cannot be modeled in advance by a traditional DEM model (Anile et al., 2003); (c) a data structure that produces a 2.5D model [only one possible z value for any particular (x,y) location] and is hence unable to deal with structures such as trees or building with any precision (Bishop et al., 2000).

This latter constraint can be overcome through the use of 3D visualization technologies, which have become useful and popular tools for design purposes, evaluating public preferences, and for making decisions regarding forest management (e.g., Wang et al., 2006) or the visual impact from man-made objects (e.g., Gross, 1991). 3D models can provide an agent at a specific location with the visual magnitude of the visible part of any object. However, GIS analysis will provide maps of all locations from which an object can be seen (Bishop, 2003), as well as cumulative viewsheds of times-seen or total visual exposure of each cell from a large set of locations.

2. Materials and methods

2.1. Preliminaries: viewsheds and DEM for visual exposure analysis

Visibility is computed in GIS environments by definition of viewsheds: given a viewpoint V on a terrain, the viewshed of V is the

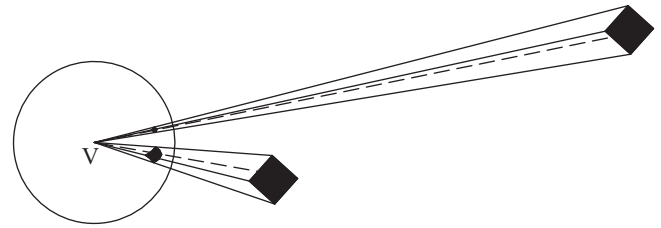


Fig. 1. Different visual exposures (solid angles) of two equal size cells projected on the unit sphere as function of distance. In most cases, the observer will see the cell somewhat obliquely rather than head-on. Consequently the apparent area of the seen cell will also be reduced.

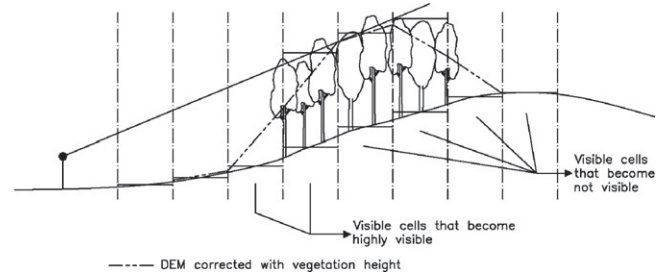


Fig. 2. Changes in visibility owed to vegetation screening and changes in the viewshed defined by the GIS. The line-of-sight showed belongs to the maximum vertical angle as it is read by the GIS from the corrected digital elevation model (DEM_c).

set of points on the surface that are visible from V . The data from those points are provided by a model of the terrain built up from a finite set of data in Euclidean space (x,y,z) , which is called a digital elevation model (DEM); the points can be either distributed in a regular (x,y) grid or scattered. A DEM built on the elevations z of those points represents a surface that approximates to the real topographic surface.

GISs consider two main classes of DEMs: triangulated irregular networks (TINs) and regular square grids (RSGs); the review by De Floriani and Magillo (2003) describes both models as well as the different algorithms that obtain viewsheds from them. In this study we chose RSG as comparison between cells, in terms of visual exposure, is made easier where cells are of the same size (Fig. 1) as opposed to irregular triangles with variable surface areas.

The surface area covered by an object on the retina is called solid angle; thus an object's solid angle is equal to the area of the segment of unit sphere. The units of solid angle can be called steradian (sr). The sphere has 4π sr and an infinite plane measures 2π sr. In order to evaluate the visual exposure of each RSG cell we need to measure the value of solid angles of each cell from the viewpoint.

Vegetation and other obstacles on the terrain are not considered in the DEM although they have significant effects on visibility (see Figs. 2 and 3). Thus, in order to obtain a visibility analysis as close as possible to reality, the vegetation canopy can be considered

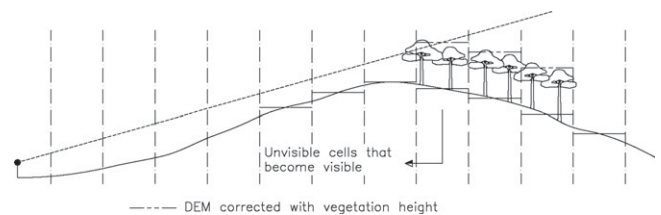


Fig. 3. Changes in visibility owed to vegetation screening and changes in the viewshed defined by the GIS. The line-of-sight showed belongs to the maximum vertical angle as it is read by the GIS from the corrected digital elevation model (DEM_c). In this case the visible area increases owing to the height added to the terrain level by the vegetation canopy.

Table 1

Average estimated height of vegetation as screen for reducing visibility in forest dominant areas in SW Spain. Vegetation density ranges from 0 (nothing) to 1 (full covering).

Land use	Average height (m)	Average density	Screening height (m)
Woody agriculture	3	0.5	1.5
Water	0		0.0
Bare ground	0		0.0
Eucalyptus	8	1	8.0
Eucalyptus and conifers	8	1	8.0
Eucalyptus and shrubs	8	0.63	5.0
Eucalyptus and Quercus	8	0.63	5.0
Conifers	8	1.00	8.0
Conifers and shrubs	8	0.63	5.0
Low density Quercus	7	0.57	4.0
Quercus and conifers	8	0.63	5.0
Industry	0		0.0
Shrubs	1	1.00	0.0
Shrubs and rangeland	1	0.3	0.0
Mining	0		0.0
Farming	0		0.0
Rangeland	0		0.0
Urban	0		0.0

an accident of the terrain model. Taking a land use digital map, a height value can be assigned to each land use, to create a vegetation elevation model that can be added to the DEM. Nevertheless, it is important to take into account certain assumptions (a, b and d given by Hernández et al., 2003):

- (a) The vegetation is dense enough to be impenetrable to sight. There are no filter effects to the visual calculation process.
- (b) Only trees and shrubs can be modeled.
- (c) The height of a vegetation polygon is assigned taking the average height of each tree or shrub species for the whole polygon.
- (d) The maximum volume of the vegetation is the same at the base and at the highest point.
- (e) The average forest density of each land use is taken as a reduction factor of the screening effect of vegetation.

The heights assigned are presented in Table 1 and the corrected terrain model will be addressed as DEMc.

The high precision elevation data made available by Airborne Laser Scanner Data (LiDAR) (Kraus and Pfeifer, 1998) also provide extremely accurate tree heights (e.g., Zimble et al., 2003). Once LiDAR data become publicly available (around 2011 in Spain, it is expected), high precision DEMc will be achievable.

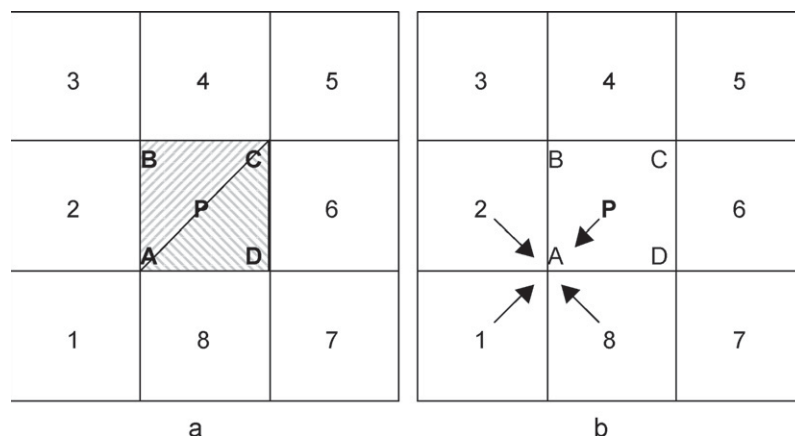


Fig. 4. (a) Division of square grid cell in two triangles and (b) cells that share vertex A and contribute to the calculation of its height.

2.2. Description of the algorithm of visual exposure

The calculation of the solid angle covered by each grid cell from a single observation point follows several steps: (a) the division of each cell into two triangles, (b) the placement of each triangle in 3D-space at the closest position to real terrain, (c) the filtering of the cells out of the viewshed, and (d) the calculation by vector algebra of the solid angle of each triangle and the total solid angle of each cell.

2.2.1. Cell division

As various authors have maintained (e.g., De Florian and Magillo, 2003) representing a terrain surface by means of triangles provides a good approximation to real terrain. In Fig. 4a, each cell, centered at P, having vertices A, B, D, C is divided by diagonal AC to obtain triangles ABC and ADC.

2.2.2. Placement of the triangles in 3D-space

In order to fit the triangles to the terrain, the height (z_A, z_B, z_C, z_D) of each vertex is obtained as the average height of the four cell centers that share each vertex (Fig. 4b).

For the grid borders, the vertex height is obtained as the average of the two cell centers that share the vertex, and for the grid corners corresponding to the single cell takes the same height as the cell center.

The cell triangles appear in 3D-space as shown in Fig. 5c.

The complete set of coordinates of each cell centered at P will be:

$$x_A = x_P - \frac{l}{2}; \quad y_A = y_P - \frac{l}{2}; \quad z_A = \frac{z_P + z_1 + z_2 + z_8}{4}$$

$$x_B = x_P - \frac{l}{2}; \quad y_B = y_P - \frac{l}{2}; \quad z_B = \frac{z_P + z_2 + z_3 + z_4}{4}$$

$$x_C = x_P - \frac{l}{2}; \quad y_C = y_P - \frac{l}{2}; \quad z_C = \frac{z_P + z_4 + z_5 + z_6}{4}$$

$$x_D = x_P - \frac{l}{2}; \quad y_D = y_P - \frac{l}{2}; \quad z_D = \frac{z_P + z_6 + z_7 + z_8}{4}$$

where l is the cell size; $P(x_P, y_P, z_P)$ are the coordinates of the cell center; A, B, C, D are the cell vertices; and z_i ($i = 1-8$) are the heights of the surrounding cells (see Fig. 5a).

This vertices calculation is performed only once for each raster DEM; the steps outlined below must be performed as many times as the number of selected viewpoints.

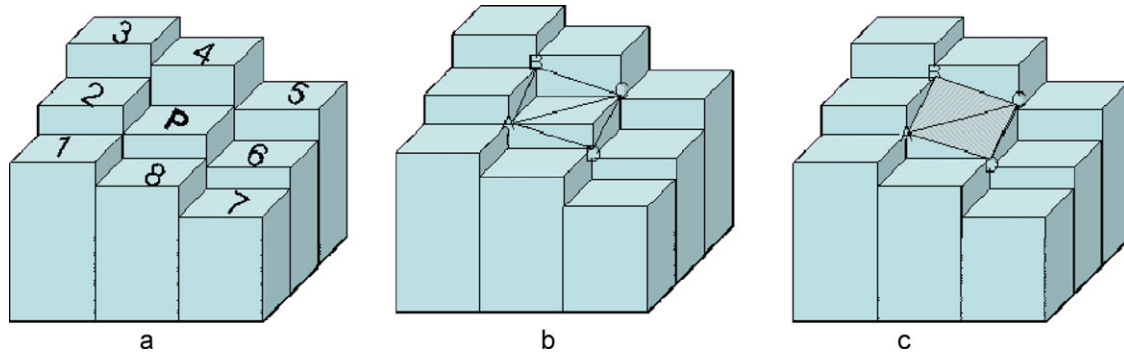


Fig. 5. (a) 3D view of raster cells; (b) position of vertices A, B, C, and D for cell P, obtained as the average height of the cells that share each vertex; (c) 3D view of triangles ABC and ADC for cell P.

2.2.3. Obtaining viewsheds

For each viewpoint V, the viewshed of the DEM is obtained using the standard algorithm provided by ArcGIS v. 9.2®.

2.2.4. Calculation of solid angle for each visible cell

The calculation of solid angles of each triangle seen from viewpoint V is performed by means of the algorithm of Van Oosterom and Strackee (1983).

$$\tan\left(\frac{\Omega_1}{2}\right) = \frac{|\mathbf{abc}|}{(abc + (\mathbf{a} \cdot \mathbf{b}) * c + (\mathbf{a} \cdot \mathbf{c}) * b + (\mathbf{b} \cdot \mathbf{c}) * a)}$$

$$\tan\left(\frac{\Omega_2}{2}\right) = \frac{|\mathbf{adc}|}{(adc + (\mathbf{a} \cdot \mathbf{d}) * c + (\mathbf{a} \cdot \mathbf{c}) * d + (\mathbf{d} \cdot \mathbf{c}) * a)}$$

where Ω_1 and Ω_2 denote the solid angles of triangles ABC and ADC (see Fig. 6); **a**, **b**, **c**, and **d** are the vector positions of A, B, C, and D taking V as coordinate origin (thus, vectors **VA**, **VB**, **VC**, and **VD**); **|abc|** denotes the determinant of matrix that results when writing the vectors together in a row; a, b, c, and d are the magnitudes of each vector (origin-point distance); and **(a·b)** denotes the scalar product (of vectors **a** and **b**).

Depending on the position of the triangles ABC and ADC, the values of Ω_1 and Ω_2 can be positive or negative so, in order to

calculate the total solid angle, absolute values must be taken:

$$\Omega = |\Omega_1| + |\Omega_2|$$

where Ω is the solid angle of the cell in steradians (sr). Taking into account that the absolute value of $\frac{1}{2} \Omega_1$ or $\frac{1}{2} \Omega_2$ could eventually be greater than $\pi/2$, the inverse function for the tangent function must be “atan2”.

A new raster grid (the same size as the DEM) is created with the Ω values; this is the visual exposure map from point V.

2.3. Treatment of visual exposure data

In consequence of above, for each viewpoint we obtain a raster file that quantifies the visibility of each cell in terms of solid angle. In case we need to work with multiple viewpoints (e.g., roads, tracks, urban areas), the set of raster maps can be summed by means of a map algebra tool to obtain a cumulative map (Wheatley, 1995; Llobera, 2003) of visual exposure for the settled viewpoints.

A change in the scale of the visual exposure values may be very useful for visualization of results due to the uneven distribution and very low values of most solid angles. We propose the following inverse-logarithm change:

If $\Omega \geq 0.2\pi$ then $VE_n = 1$ and if $\Omega < 0.2\pi$ then VE_n

$$= \frac{1}{-\log(\Omega/2\pi)}$$

where VE_n is the rescaled value of Ω .

This way the values of VE_n will range from 0.1 to 1; values of Ω over 0.2π may occur at the viewpoint and adjacent cells where the visual exposure is obviously high.

All these processes, either for single or multiple viewpoints, have been implemented in a tool running on ArcGIS 9.2®, called “Visual Exposure”.

3. Results and discussion

We tested the developed GIS tool in a forested area of SW Spain where foresters planned clearcutting of a Eucalyptus stand of 18.28 hectares in three stages with intervals of four years between each stage. The main objective of this logging parcellation was the reduction of visual impact, but it may provide other benefits such as erosion control and biodiversity conservation.

The terrain at the stand offered two parcellation alternatives (Fig. 7): (A) three roughly square sections labeled from west to east; (B) three strips labeled from north to south. A greater number of sections was not considered as it would lead to higher logging costs.

Fig. 8 shows the distribution of visibility and visual exposure in each clearcutting section, for each alternative. Table 2 shows the absolute and relative values of visual exposure for each land

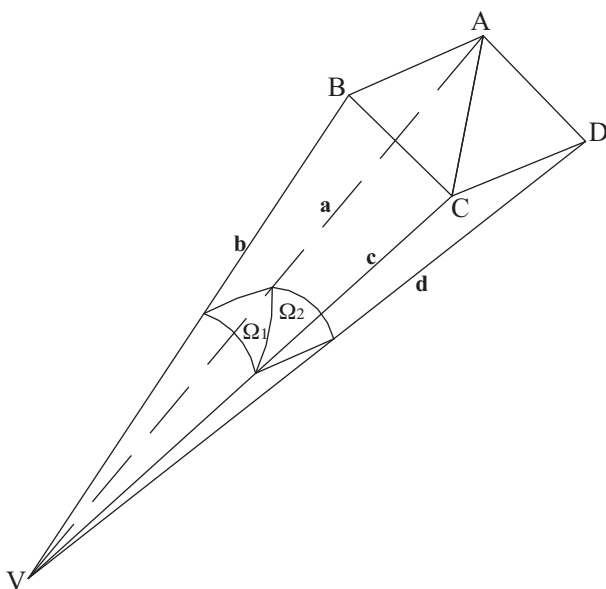


Fig. 6. Solid angles Ω_1 and Ω_2 at V subtended by the triangular surfaces BAC and BDC of the raster cell.

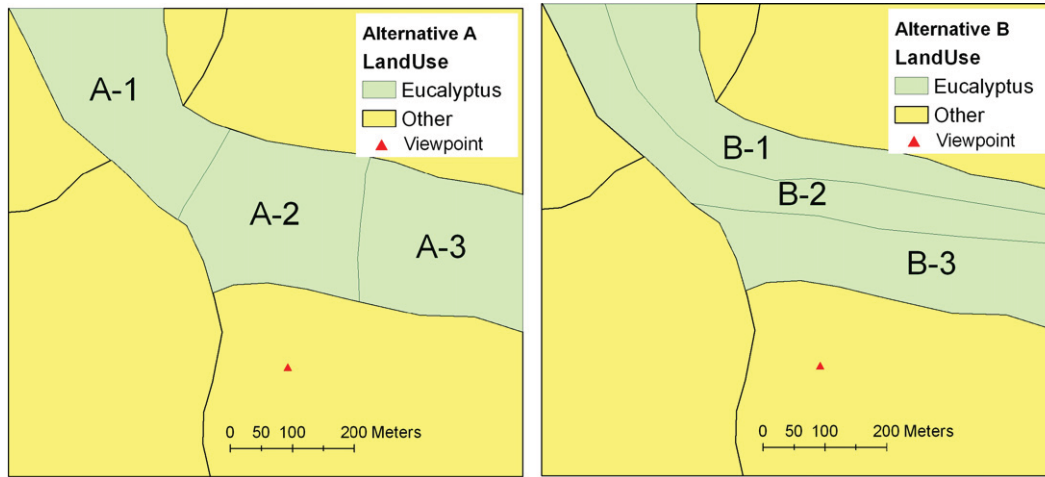


Fig. 7. Parcellation alternatives for clearcutting: (a) Alternative A and (b) Alternative B.

Table 2

General data of the area studied depending on land use. It can be seen that even though the Eucalyptus stand takes 63.53% of the viewshed area, to the eye of the observer it only represents 2.23% of the view.

Land use	Area (ha)	Viewshed area (ha)	SUM VE ^a (sr)	% Visible ^b	% VE ^c
Other	44.80	3.10	4.9316	36.47	97.77
Eucalyptus	18.28	5.40	0.1126	63.53	2.23
Total	63.08	8.50	5.0442	100.00	100.00

^a Total values of viewed solid angles (visual exposure in steradian).
^b Ratio of visible cells of each land use to total cells in the viewshed.
^c Ratio of visual exposure of each land use to the total view.

use, along with the distribution of viewshed cells; it can easily be seen that while the Eucalyptus stand contains nearly two thirds of the viewshed area this only represents 2.23% of the observer's view. This is in itself an interesting result because it shows the low significance of the stand, in terms of visibility, from the selected point of view.

Fig. 9 shows 3D views of the study area and the parcellation alternatives.

As can be seen in Table 3, the visible surface ratio of each clearcutting section is quite different from the ratio of visual exposure. Section A1 contains 35.74% of the visible cells in the stand but they only represent 11.41% in terms of visual exposure, whereas

Table 3

Distribution of the viewshed and visual exposure for parcellation of Alternative A.

Logging section	Area (ha)	Viewshed area (ha)	SUM VE ^a (sr)	% Visible ^b	% VE ^c
A-1	6.17	1.93	0.0128	35.74	11.41
A-2	6.20	2.78	0.0936	51.48	83.18
A-3	5.91	0.69	0.0061	12.78	5.41
Total	18.28	5.40	0.1126	100.00	100.00

^a Total values of viewed solid angles within the Eucalyptus land use (visual exposure in steradian).
^b Ratio of visible cells of each logging section to total visible cells in the Eucalyptus stand.
^c Ratio of visual exposure of each logging section to the total viewed solid angle within the Eucalyptus stand (see Fig. 9).

section A2 contains 51.48% of the visible cells and accounts for 83.18% of the viewer's field of view within the stand.

Comparing the values of Tables 3 and 4, we can see that Alternative B is less unbalanced both in terms of distribution of visible areas and in terms of visual exposure.

The map of visual exposure can be useful for locating, in each clearcutting section, high impact actions such as the construction of logging roads and platforms. Moreover, at the areas of higher visual exposure in each clearcutting section, we can adopt special measures for visual impact remediation such as leaving some standing tree groups or lines uncut.

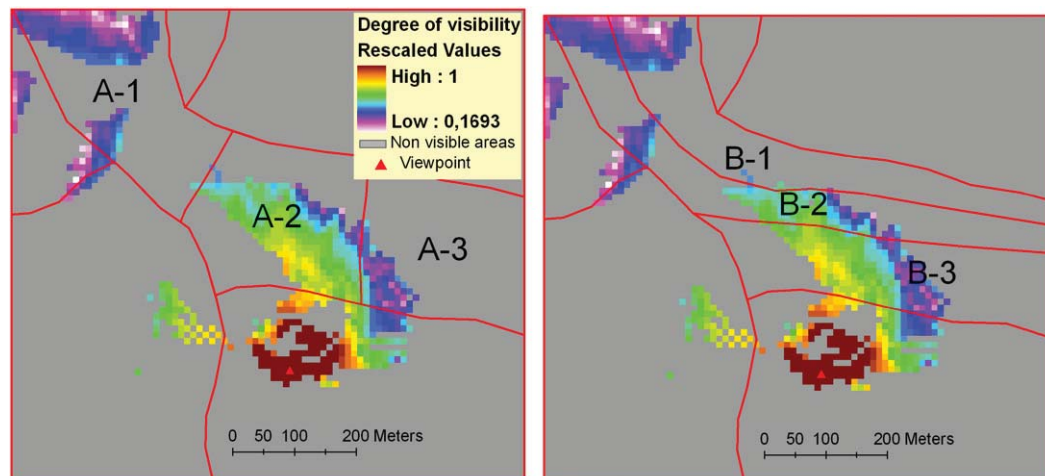


Fig. 8. Visual exposure of the study area from one viewpoint, for each parcellation alternative.

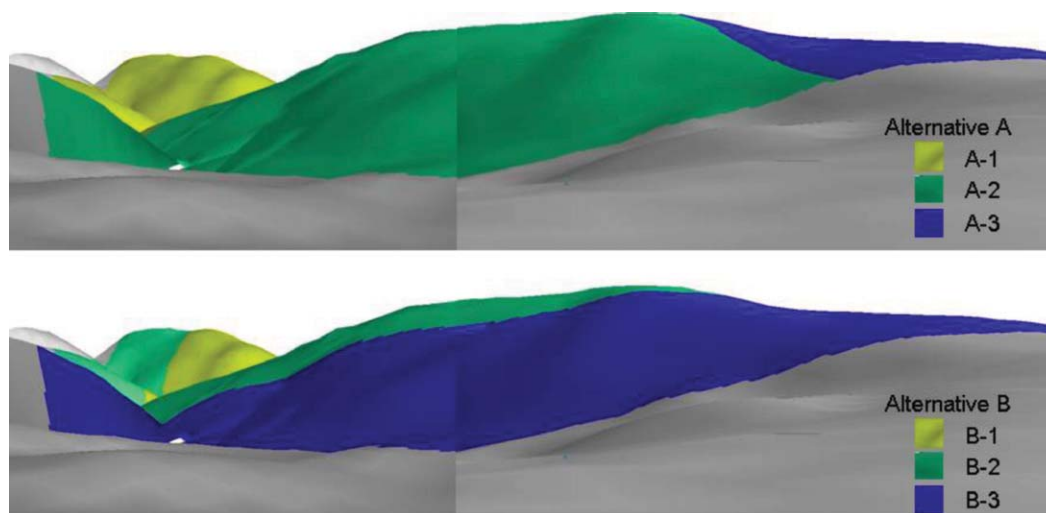


Fig. 9. Approximated 3D views of the study area from the viewpoint showing clearcutting sections in three different colors for Alternative A (above) and Alternative B (below). The visual exposure is proportional to the surface area in the image.

Table 4
 Distribution of the viewshed and visual exposure for parcellation of Alternative B.

Logging section	Area (ha)	Viewshed area (ha)	SUM VE ^a (sr)	% Visible ^b	% VE ^c
B-1	5.99	0.99	0.0062	18.33	5.47
B-2	6.09	2.16	0.0334	40.00	29.70
B-3	6.20	2.25	0.0730	41.67	64.83
Total	18.28	5.40	0.1126	100.00	100.00

^a Total values of viewed solid angles within the Eucalyptus land use (visual exposure in steradian).

^b Ratio of visible cells of each logging section to total visible cells in the Eucalyptus stand.

^c Ratio of visual exposure of each logging section to the total viewed solid angle within the Eucalyptus stand (see Fig. 9).

4. Conclusions

In this paper we propose an algorithm and a GIS tool that provide maps of visual exposure for the terrain within a viewshed. The maps are generated from DEMs for single or multiple observation locations.

Previous algorithms for this purpose obtain relative values of visual exposure within a viewshed, but they do not calculate it in solid angle units (steradians). The solid angle is the surface area covered by a given object on the retina of the observer. The proposed algorithm and its GIS tool obtain the solid angle of each visible cell of the DEM.

Solid angles for each cell are calculated by dividing the square into two triangles, and applying to them the efficient standard algorithm of Van Oosterom and Strackee (1983), for solid angle calculation. The triangle vertices are fitted to the terrain by calculation of their height as the average of the height of the four DEM cells that share each vertex, thus avoiding the intermediate steps of calculating slope and aspect.

For easier viewing of the visual exposure values in maps, we propose a re-scaling algorithm that places all values in the range 1–0.1.

In principle there are no restrictions to the distance range where the tool can be applied, but we find that it should be most useful within the medium-distance view as defined by Higuchi (1983), that is approximately between 140 and 6000 m.

We consider that the algorithm will be useful in landscape planning, forest management, and the visual impact evaluation for any project that does not deal mainly with vertical structures (build-

ings, electricity pylons, etc.) because these cannot be accurately represented by the DEMs. The evaluation of visual exposure of vertical elements from a single viewpoint can be efficiently performed by use of 3D software. The tool also quantifies the visual exposure of multiple viewpoints, which can be complementary to the use of such software.

As stated by Stoltman et al. (2007), visualization tools provide useful aid to forest managers and restoration ecologists. The visual exposure layer can easily be included in multipurpose forest management models, so as to decrease the potential visual impact of harvesting, planting design, habitat improvement, and so on.

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