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Impact of forest management activities on forest aesthetics using photogrammetric point cloud

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Abstract Public concern over clearcutting in the United States during the 1970s led to significant changes in natural resource policies, particularly in forest management. One aspect that came under scrutiny was forest aesthetics. This study aims to assess the impact of different harvest designs on stand aesthetics using photogrammetric point clouds (PPC). To evaluate the effectiveness of PPC for forest visualization, two stands in the McDonald-Dunn Research Forest at Oregon State University were selected due to their potential to negatively impact the visual quality of the surrounding scenery during harvesting. The number of trees, their heights, volume, and area were analyzed using both univariate and multivariate methods. Regardless of the analysis type (i.e., univariate and multivariate), the designs were consistently differentiated by the percentage of the area harvested. Canonical Discriminant Analysis revealed that designs tailored to the terrain, such as "strips" and "islands," effectively occluded the visibility of forest operations, showing negative discriminant values. More complex harvest designs, aimed at screening forest operations with innovative mechanisms like an inundation model, also demonstrated the most negative discriminant values in visibility metrics. Because reduced ground exposure is only a proxy for visual impact, and not a direct measure of aesthetic preference, the visibility metrics are interpreted here as indicators of the potential to screen operations rather than as measures of scenic quality. The study found that, for the two stands examined, removing up to 75% of the trees could markedly reduce, and in some layouts nearly eliminate, the visibility of the harvest from the surrounding landscape. Because these results derive from two simulated case-study stands, they should be regarded as a promising decision-support approach.

Keywords: photogrammetric point clouds, harvest visibility, univariate analysis, multivariate analysis, Pacific Northwest.

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Introduction

Public concern over clearcutting in the United States during the 1970s led to significant changes in landmark natural resource policies, such as the US National Environmental Protection Act and the Forest Management Act (Bell 2001, Sheppard et al. 2004). These concerns arose from a type of even-aged management known as "clearcutting" (Palmer et al. 1995, Gobster 1999). The stark visual contrasts between cut areas and adjacent forests generated negative public perceptions of the practice (Palmer et al. 1995, Pâquet and Bélanger 1997, Chamberlain & Meitner 2012). The public, who were essentially the owners of these public lands, demanded natural-looking landscapes and high-quality scenery (Anderson 1995, Gobster 1999).

The 1992 World Convention on Sustainable Development, held in Rio de Janeiro, established Sustainable Forest Management criteria and indicators, mandating public involvement in the review process during forest management decision-making (Bell 2001). Consequently, effective communication tools became essential for forest managers and landscape planners. Initially, two-dimensional (2D) geographic information system (GIS) outputs and artist renditions were used to assess the impact of forest management on surrounding scenery (Orland 1994). However, due to the lack of detail and realism in 2D tools for visualizing timber harvests, three-dimensional (3D) forest visualization emerged, offering a more detailed explanation of visual impacts (Orland 1994, McGaughey 1998).

Early attempts at 3D forest visualization employed a wide array of techniques and methods to create virtual forests on computer screens. The quality of these visualizations was heavily dependent on computer architecture, with advancements in technology closely tied to the rendering quality (Orland & Uusitalo 2001). Various software programs were developed to render 3D forest activities using stand data, including Smart Forest (Orland 1994, McGaughey 1998, Orland and Uusitalo 2001), Vantage Point (Bergen et al. 1998), VRML (Lim & Honjo 2003), 3D Nature (Stoltman et al. 2004, Song et al. 2006a), CALP (Meitner et al. 2005), WCS (Lewis & Sheppard 2006), and OpenGL (Falcão et al. 2006). The primary goal of these imaging products was to create realistic visualizations by incorporating actual forest data (Orland 1994, Bergen et al. 1998, Lim & Honjo 2003). Inclusion of tangible 3D data into forest renderings eliminated the subjectivity inherent in traditional artist renditions used in the review process (Orland 1994). The trend towards better computer hardware facilitated the creation of larger virtual forests (Lim & Honjo 2003) and improved the realism of computer-rendered forests (Bergen et al. 1998, Lim & Honjo 2003, Yu et al. 2003, Meitner et al. 2005, Falcão et al. 2006, Song et al. 2006a).

Traditionally, hiding or screening harvest activities with strips or edge shaping became common techniques for mitigating the visual impacts of forest operations in sensitive areas (Gobster 1999, Bell 2001, Picard & Sheppard 2002a, 2002b). However, virtual forests addressed a pressing need not only to visualize forests for communicating impacts but also to generate and view multiple harvest designs beneficial for managers and planners. Ribe (Ribe 2005) examined how different cut patterns and retention levels on vista views interacted with public perceptions in 3D simulations. Song and others (Song et al. 2006a) visualized 3D timber harvesting activities using clearcut, strip cut, and patch cut methods. Chamberlain and Meitner (Chamberlain & Meitner 2012) assessed how the shape of cut blocks affected public perceptions.

As computer hardware and software advanced, assessing the impacts of forest operations on the environment began to incorporate viewsheds, a GIS technique that uses viewpoints, observers, and line-of-sight (LOS) vectors on a digital terrain model (DTM) to identify areas where the ground is obscured to the observer (Dean 1997, Maloy & Dean 2001). Although viewshed analysis is not new to forestry, it has been employed in several studies, particularly for assessing clearcuts (Dean & Lizarraga-Blackard 2007), land cover screening (Palmer 2016), incorporating vegetation in landscape assessments (Llobera 2003, Domingo-Santos et al. 2011), and forest planning in mountainous locations (Lee et al. 2019). Chamberlain and Meitner (Chamberlain & Meitner 2009) argued for the need to incorporate GIS techniques with viewshed principles to create timber harvest designs as a decision support tool for forest managers and planners. Chamberlain and Meitner's (Chamberlain & Meitner 2009) work used algorithms and elevation models to automate harvesting designs under specified scenarios, resulting in 3D visualizations that screened timber harvests. More recently, studies have assessed how harvest designs are perceived from aerial viewpoints (Liu et al. 2018).

The evolution of 3D visualization has been significantly enhanced by incorporating Light Detection and Ranging (LiDAR) technologies in forestry applications. Song and others (Song et al. 2006b) noted that LiDAR serves not only as a form of active sensing but also as an advanced geometric modeling visualization technique. LiDAR can capture forest measurements, individual tree measurements, and forest structure in a cost-effective manner (Evans et al. 2006). Fujisaki and others (Fujisaki et al. 2007) utilized LiDAR purely for forest visualization in an immersive virtual environment, which has the advantage of portraying 3D forests with trees in stands that are true to scale.

The popularity of LiDAR in forestry applications has driven technological advancements, culminating in the use of Unmanned Aerial Systems (UAS) equipped with LiDAR sensors to capture high-quality 3D point clouds for forest inventory (Evans et al. 2006, Wallace et al. 2012, 2016, Tomaštík et al. 2017). These advancements have practically rendered traditional photogrammetry obsolete in forestry. However, high-resolution imagery captured from UAS can be processed using Structure from Motion (SfM) algorithms, a combination of computer vision and photogrammetry, to produce point clouds (Tang & Shao 2015). Although photogrammetric-derived point clouds are not as robust as LiDAR point clouds (Lisein et al. 2013), advances in SfM software and UAS drones allow photogrammetric point clouds (PPC) to accurately estimate forest biophysical features (Tomaštík et al. 2017).

Although LiDAR remains the more accurate and canopy-penetrating sensor, it is costly, acquired only opportunistically, and unavailable for many ownerships. UAS photogrammetry, by contrast, is inexpensive, repeatable on demand, and sufficient for the comparatively coarse requirements of harvest-visibility analysis, where the outer canopy envelope rather than sub-canopy detail governs what a distant observer can see. For visualization purposes the trade-off in point density and canopy penetration is therefore acceptable, and PPC widens access to data-driven visual planning for managers who lack LiDAR coverage. A limited number of studies have attempted to integrate UAS-based PPC and GIS viewshed technology with timber harvest design to aid forest managers and landscape planners during the decision-making process. The importance of this integration lies in its reliance on data, which ties visualization to measurements proven to be accurate and realistic (Garms et al. 2020). Therefore, research is needed to bridge the gaps between timber harvest design using viewshed analysis (Chamberlain & Meitner 2009) and emerging technologies like UAS SfM point clouds, which are already in use as decision support tools for forest operations (Magliocchetti et al. 2015).

Despite parallel advances in low-cost UAS photogrammetry and in GIS viewshed analysis, the two have rarely been integrated operationally, so that data-rich photogrammetric point clouds describing actual stand structure are seldom coupled with harvest-visibility analysis to design and formally evaluate alternative cuts. However, aesthetic response is socially constructed and visibility is only a proxy for visual impact (Gobster 1999, Koike et al. 2024, Averbeck et al. 2026).

The proposed research aims to assess the utility of photogrammetric point clouds developed from UAS to create a forest visualization technique that can simulate timber harvest designs, generate forest and visualization metrics from a viewshed visibility perspective, and produce a formal analysis of the performance of timber harvest designs in visually sensitive locations. Specifically, the main objective of the study is to identify layouts that reduce harvest visibility while remaining operationally and financially feasible using a formal quantitative framework built on UAS photogrammetric point clouds. The approach is presented using a study case built on two visually sensitive stands.

The novelty of the work lies in coupling PPC-derived stand structure with viewshed-based visibility metrics within a single numerical based workflow. The importance of this work lies in producing a tool that could help forest managers and landscape planners lay out timber harvesting operations in visually sensitive locations. The utility of the proposed tool focuses on maintaining the social license to practice forestry by accounting for the visual resources often impacted by forest operations.

Materials and Methods

Study area

The study area is located in the McDonald-Dunn Research Forest (Figure 1), owned by Oregon State University. The study focuses on two stands, referred to as Stand A (44°38'10.504"N, 123°17'18.21"W) and Stand B (44°37'44.683"N, 123°18'21.485"W), to assess the impact of visualization on forest harvest. Douglas-fir (*Pseudotsuga menziesii* var *menziesii*) and grand fir (*Abies grandis* ssp. *grandis*) are the predominant overstory species in both stands, with a small component of bigleaf maple (*Acer macrophyllum*). Stand A is nearly nine times larger than Stand B, with higher tree density but shorter trees (Table 1). We selected the two stands to capture the impact of land area, tree size and tree density on the harvesting strategies as well as on the ground visibility from afar.

Table 1 Summary forest inventory of the two stands (TPH denotes trees per hectare; the last four columns give the percentage of points above the 25th, 50th, 75th, and 95th height percentiles).

Stand	Area	Trees	TPH	Height	Volume	Amount of points above the …. percentile [%]			
	ha	count	count	m	m^3	25	50	75	95
A	29.7	7069	238	19	8980	17	11	6	1
B	3.5	498	142.3	31	977	32	21	10	2

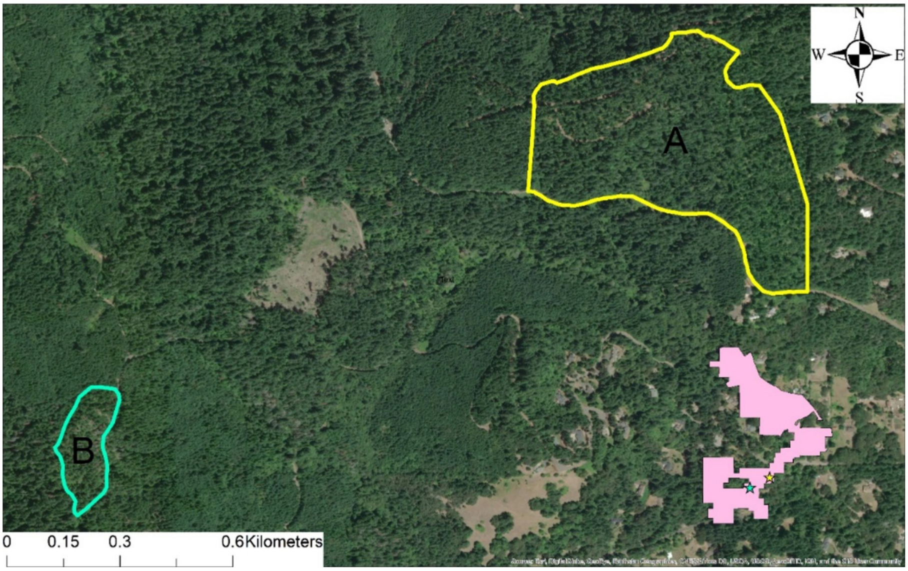

Figure 1 Overall location of the stands A and B inside the McDonald-Dunn Research Forest.

Data acquisition

UAS imagery was collected on 29 August 2019 for Stand A and 5 October 2019 for Stand B. The imagery was captured using a DJI Mavic 2 Pro equipped with a Hasselblad L1D-20c red-green-blue camera, which records 10-bit color images. Flight planning was conducted with the DJI Pilot app flight mapper. The UAS flew at an altitude of 120 meters above ground level (AGL) over Stand A, with 80% front and side overlap, capturing 520 images. For Stand B, the flight altitude was 150 meters AGL, with 85% front and side overlap, capturing 114 images.

Photogrammetric point clouds

Point clouds were generated in Agisoft Metashape (Agisoft 2017) without ground control points (GCPs) using the SfM algorithm. Images from Stands A and B were aligned using all the pixels (i.e., accuracy set to "high"). Initial image pairing was carried out using lower accuracy settings (i.e., pair preselection set to "generic") and overlapping pairs of photos were selected based on camera locations (i.e., the "Reference preselection" option was enabled). We increased the default aligning parameters for key points and tie points to 100,000 and 40,000, respectively.

Dense point clouds were created for Stand A using only 1/16 of the image (i.e., quality set to "Medium"), with depth filtering assuming a lack of meaningful small details (i.e., "aggressive" filtering option). For Stand B, dense point clouds were created similarly to Stand A, except that 1/4 of the image was used (i.e., quality set to "high"). The point clouds generated for Stand A contained 112,610,309 points, while 41,462,169 points were created for Stand B.

Outliers and erroneous points were visually identified and subsequently eliminated in Quick Terrain Modeler (QTM) v8.1.0 (Applied Imagery 2017). Heavily distorted trees found on the edges of the point cloud were removed, as their treetop could no longer be reliably identified. Point cloud normalization was executed in QTM using the QT Basic algorithm with a grid sampling of 10.00 meters.

Visual analysis

To assess the impact of harvest layout on harvest, we have used a four steps workflow, which starts by simulating the harvest layout, followed by a visibility analysis, an individual tree segmentation, and concluding with a formal statistical comparison of the harvest layouts using the attributes describing the forest aesthetic.

Simulated harvests

To assess the impact of harvests on forest visualization, we simulated 15 possible layouts for each stand. The layouts included 5 variations of north-south (NS) cuts, 5 variations of east-west (EW) cuts, 2 clustered variable harvests, 2 inundated modeled cuts, and 1 clear cut. The layouts were created by clipping the points while maintaining a nadir view, with the stand boundary used to separate the trees within the harvest units from those outside the unit. The statistics of the simulated harvests for Stand A can be found in Table 2, and for Stand B in Table 3.

The planned cuts include 10 systematic patterns, specifically NS and EW layouts, which differ from freehand cuts by utilizing grids as guidelines (Figure 2). These systematic patterns were derived from a 20-meter spaced grid, outlining the harvests along the north-south or east-west axis. The strips and islands were created such that the cleared land is oriented towards the town of Corvallis, to ensure maximum visibility of the ground.

The visibility metrics for designs 13 and 14 were computed using an inundation-based procedure, which assumes the observer's eye located at infinity on the ground. Inundation modeling is created by identifying the lowest elevation point of the stand and raising the water level (i.e., observer's eye) to the tops of the initially viewable crowns. The water level is then contoured around the bisections of trees and ground that are on the same plane as the water level. The remaining bisected planes of the tree crowns are used to show the material located behind the first tree crowns, revealing whether the cuts can be screened or hidden (Figure 3).

Contour lines created from the lowest elevation in 50-meter increments are used as guidelines for hiding or screening the harvests. To ensure integration within the forest landscape, the metrics describing the harvest layouts include information on whether strips or polygons are connected to the surrounding forested area (Table 2 and Table 3). It should be noted that by assuming the observer's eye is above the ground, the areas subject to analysis are conservative, meaning they consider more area as observable than in reality. The inundation procedure was implemented in Quick Terrain Modeler (QTM).

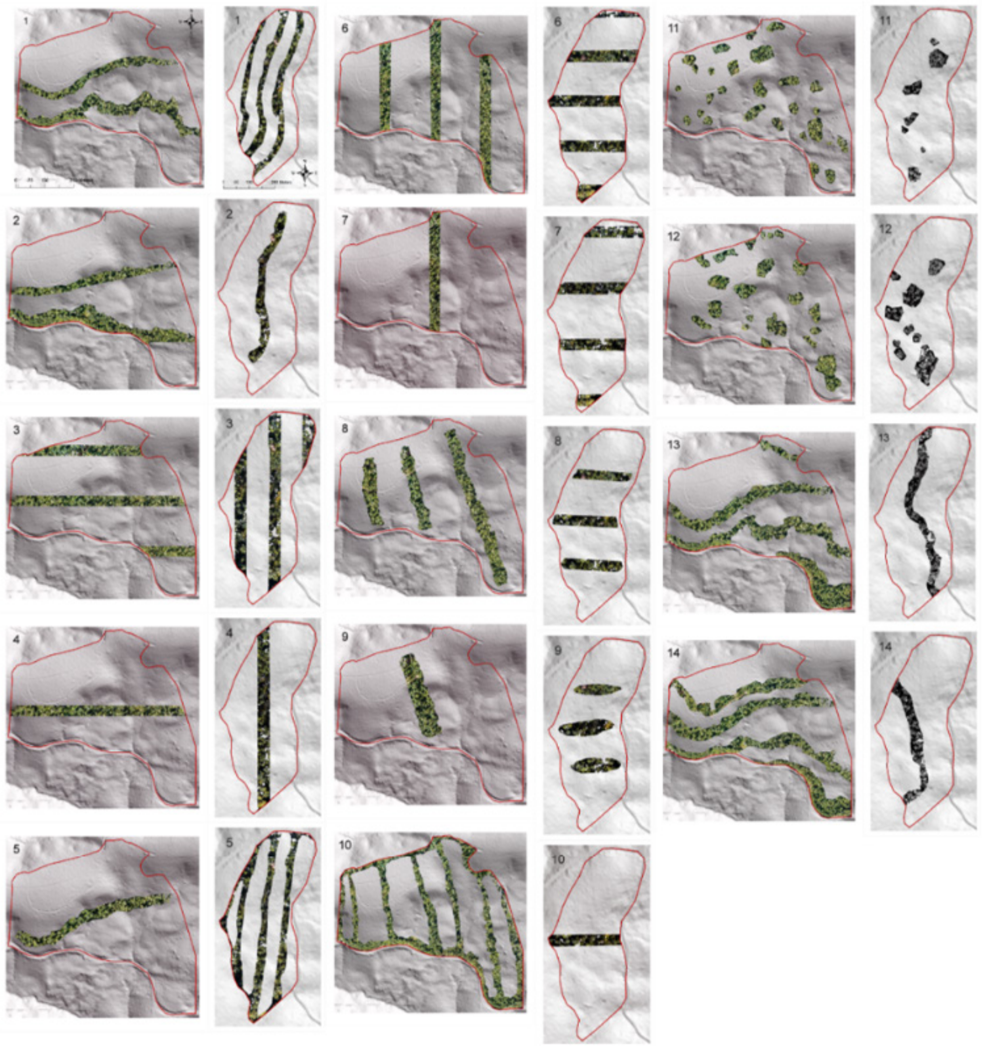

Figure 2 Harvest designs for the simulated cuts. Each harvest design is identified by a number, with stand A at the left and stand B at the right.

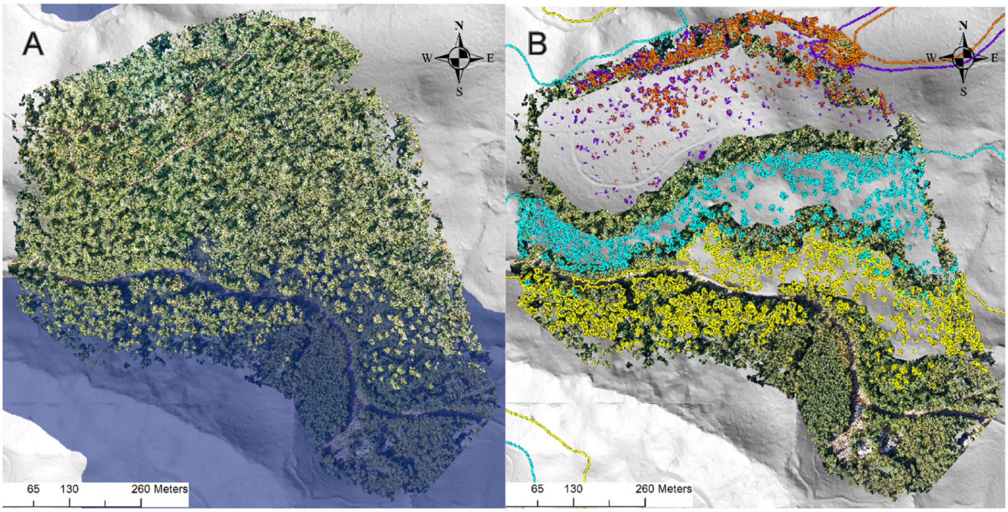

Figure 3 Stand A overlaid on the DTM showing the inundation model process. Image a shows the flood analysis tool flooding the model and contouring the points at the water level. Image B shows the cut 13 with four inundation contours from bottom to top colored (yellow, teal, pink, and green) that were used to pattern the harvest scenario.

Table 2 Simulated scenario harvests for stand A that include the cut numbers, type, if the cuts have connectivity, if a grid contour was used, and a brief description of the harvest layout. Note this stand utilizes the contour lines type to capture terrain.

Layout	Type	Connectivity	Grids	Description
1	EW/Contour	Yes	No	Two strips created with the contour lines method
2	EW	Yes	No	Two strips free hand
3	EW	Yes	Yes	Three strips with 160 m spacing
4	EW	Yes	Yes	One central strip
5	EW	No	No	One central free hand island strip
6	NS	Yes	Yes	Three strips with 160 m spacing
7	NS	Yes	Yes	One central strip
8	NS	No	No	Three free hand island strips centered in the middle of the stand
9	NS	No	No	One central block strip island
10	NS	Yes	Yes	Five island strips with a surround buffer around the entire boundary
11	Variable	No	No	“Clumpy groupy” structure in variable polygon shapes that retain large trees and surrounding structure.
12	Variable	No	No	“Clumpy groupy” structure in variable polygon shapes that retain more structure than cut 11.
13	Inundation	Yes	No	Utilizes bottom to top inundation flooding to contour cuts
14	Inundation	Yes	No	Utilizes top to bottom inundation flooding to contour cuts
15	Clearcut	No	No	Removal of all points in the unit

Table 3 Simulated scenario harvests for Stand B that include the cut numbers, type, if the cuts have connectivity, if a grid contour was used, and a brief description of the harvest design.

Layout	Type	Connectivity	Grids	Stand B
1	EW	Yes	No	Free hand cut with three strips
2	EW	No	No	Free hand with one island strip
3	EW	Yes	Yes	One central strip
4	EW	Yes	Yes	Three strips with 40 m buffers
5	EW	Yes	No	Free hand with three strips and buffering trees around the edges of the harvest
6	NS	Yes	Yes	Five strips at 60 m spacing
7	NS	Yes	Yes	Four strips at 80 m spacing
8	NS	No	No	Free hand with three strips equally placed in the center of the stand
9	NS	No	No	Free hand strip with three cigar shaped cuts
10	NS	Yes	Yes	One central strip
11	NS	No	No	“Clumpy groupy” structure in variable polygon shapes that retain large trees and surrounding structure.
12	NS	No	No	“Clumpy groupy” structure in variable polygon shapes that retain more structure than cut 11.
13	Inundation	Yes	No	Utilizes bottom to top inundation flooding to contour cuts
14	Inundation	Yes	No	Utilizes top to bottom inundation flooding to contour cuts
15	Clearcut	No	No	Removal of all points in the unit

Visibility analysis

The visibility analysis identifies areas across the landscape from which points at predefined locations can be seen. In this study, the landscape considered covers 2881.3 hectares and is located east and south of the two stands, where most of the local population lives or commutes. For the visibility analysis, the area was represented by a Digital Terrain Model (DTM) created from LiDAR acquisitions in 2008, producing images with 1-meter resolution. While stand B was entirely described by the PPC, stand A required merging pre-existing LiDAR data flown in the McDonald-Dunn Forest in 2008 to close gaps in the areas with sparse point cloud. Because the reduced number of points occurred close to the ground, no bias in height of the dominant and codominant trees was introduced by merging the PPC with lidar point clouds.

To identify the viewpoints within the possible harvest layouts, we use Digital Surface Models (DSMs) produced from the point clouds obtained after the simulated harvest were implemented. The DSM was subsequently merged with the DTM, producing a surface with 1-meter resolution (Figure 4). The resulted surface represents the heist elevation of the forest ecosystem, which in some locations is the ground and in others the top of the trees. The visibility analysis was conducted for five points within each stand, considered the most likely to be seen following harvest. The five viewpoints per stand were not arbitrary: they were placed at the locations within each unit that the preliminary terrain analysis identified as the most exposed to the inhabited and commuter areas east and south of the forest, so that the analysis represents a conservative, worst-case visibility scenario. The areas from which the harvests can be observed were identified assuming that the eye is located at 1.6 m above ground and the harvest can be seen from at most 5.5 km. The observer height of 1.6 m approximates average standing eye level and is consistent with values used in comparable viewshed studies (e.g., 1.7 m in Orlof et al.-type analyses), while the 5.5 km cut-off corresponds to the foreground-to-middleground distance beyond which a harvest of this size ceases to be a discernible element of the scene. The Visibility Analysis was carried out in QGIS (Sherman 2020).

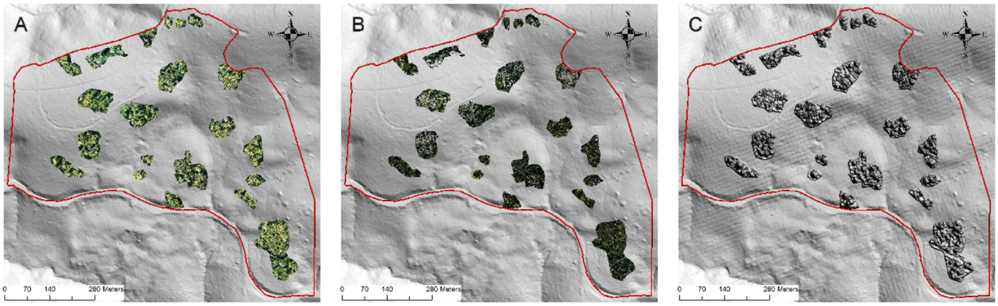

Figure 4 Stand a cut 12 overlaid on the DTM. A) the point cloud on top of the terrain, B) the converted point cloud to a gridded surface, and C) the DTM and gridded surface merged into a final DSM with 1 meter resolution.

To formally evaluate the impact of the harvest layouts on forest aesthetics, in addition to the inundation metrics, three other measures were used: the overall visible area (expressed in hectares) for each of the five viewpoints in the two stands, the critical areas with low visibility (CAL), and the critical areas with high visibility (CAH). The critical areas are regions surrounding the roads inside and outside the McDonald-Dunn Research Forest: CAL within 3 meters from the roads inside and CAH within 5 meters from the roads outside the McDonald-Dunn Research Forest. These road-corridor buffers were chosen because roads concentrate the viewers whose perception underpins the social acceptability of forest operations (Dean and Lizarraga-Blackard 2007; Lee et al. 2019); the narrower 3 m buffer inside the forest reflects the closer, slower vantage of forest users, whereas the 5 m buffer on the public roads outside captures the wider sightlines of passing traffic. We acknowledge that these distances are pragmatic operational thresholds rather than perceptually validated limits, and that the three visibility measures (visible area, CAL, CAH) quantify what can be seen, not how it is judged. Visibility is therefore used throughout as a proxy for potential visual impact and not as a measure of aesthetic preference.

The differences among the harvest layouts were assessed using three common forest inventory measures: volume, total height, and number of trees. The photogrammetric point clouds allow for the estimation of the vertical distribution of matter and important physiological attributes, as commonly encountered in gap modeling and leaf area index computations. To avoid scaling issues associated with the difference in magnitude of the variables, the vertical distribution of matter was expressed in percentiles. Besides the forest inventory attributes, the amount of ground visible from afar was also computed, a variable specifically for visibility analysis.

Tree segmentation

The impact of harvest layouts on feasibility of the forest activities was estimated by computing the volume of each tree. For this purpose, we segmented individual trees in both stands. First, using a trial-and-error approach, we found that the PPC for Stand A was better segmented using the Li et al. (Li et al. 2012) algorithm whereas Stand B had superior results using the mark-controlled watershed algorithm (Meyer and Beucher 1990), as implemented in the lidR package (Roussel and Auty 2019) of the R project (Gentleman and Ihaka 2014). The normalization of the point cloud required by the tree segmentation algorithm was performed using a ground surface with 10-meter resolution, which was executed in QTM, proven to supply accurate digital surface models. The two algorithms were selected to match the contrasting structure of the stands rather than for convenience: the multi-storied shelterwood of Stand A, with an even spread of large dominants over dense regeneration, was best resolved by the local-maxima, spacing-based method of Li et al. (2012), whereas the closed, even-aged canopy of Stand B was better delineated by the marker-controlled watershed, which is less sensitive to within-crown maxima. Finally, we assessed the performance of the tree segmentation algorithms by visually identifying the location of each treetop. The manual delineation of treetops and the recording of the coordinates of the tallest point of each tree were carried out in QTM. Matching the detected treetops against the manually interpreted ones allows segmentation accuracy to be quantified as precision, recall, and F1 for each stand. Because a different algorithm was applied to each stand, segmentation accuracy is not strictly comparable between stands, which is a methodological limitation, but of inconsequential importance as the objective of the study is not tree segmentation but ground visibility.

Analysis of the harvest layouts

To assess the impact of the harvest layouts on forest aesthetics, measured through the visibility of the ground from afar, we used two statistical perspectives: univariate and multivariate. The univariate analysis is relatively robust to many assumptions (such as heteroskedasticity) but has a limited interpretability because it focuses on one variable at a time. For a complete picture of the stand aesthetics as affected by the harvests, we used multivariate analysis, which considers multiple variables simultaneously.

Univariate Analysis

The main variables of interest for most forest management applications are the harvested volume and the corresponding residual volume. From an ecological perspective, some variables of interest are the harvested area and the total height of the residual trees. Irrespective of the variable, we used analysis of variance (ANOVA) to test the impact of the harvest layout. The statistical unit of analysis is the simulated harvest layout, with the 15 layouts per stand treated as the replicates and the two stands analysed separately to avoid confounding their contrasting size, age, and structure. Because the layouts were generated on the same two point clouds, they are not fully independent; the resulting pseudoreplication limiting the inference to these stands and is treated as exploratory rather than confirmatory. The ANOVA formulation depends on the inquired variables, specifically the class variable. Therefore, a set of four ANOVAs were developed:

1. One focused on the spatial distribution, expressed in terms of connectivity, of the harvested volume (Equation 1):

$$Volume_{harvested} = connectivity \tag{1}$$

where connectivity had two values: connected or disconnected.

2. One focused on the magnitude of the harvested volume concerning the number of trees harvested (Equation 2):

$$Volume_{harvested} = percentage\ of\ hervested\ trees \tag{2}$$

where the percentage of harvested trees was expressed as a class variable with four levels: <60%, 61–70%, 71–80%, and 81–90%.

3. One focused on the harvested area as a function of the number of harvested trees (Equation 3):

$$Area_{hervested} = percentage\ of\ harvested\ trees \tag{3}$$

4. One focused on the average height after harvesting as a function of the number of harvested trees (Equation 4):

$$Height_{residual} = percentage\ of\ harvested\ trees \tag{4}$$

When significant differences were present (i.e., type I error less than 5%), the multiple comparison Scheffe test was used to identify groups among the levels of the class variable.

Multivariate Analysis

Similarly to univariate analysis, the multivariate analysis was used to assess the impact of the harvest on several variables, focusing on those related to volume and aesthetics. Therefore, we started by evaluating the differences in the vertical distribution of matter according to the harvest levels, a surrogate for both volume harvested and visibility, using multivariate analysis of variance (MANOVA). The matter distribution was represented by the ratio between the first three quartiles of the number of photogrammetric points before and after harvest. In addition to the 25th, 50th, and 75th percentiles, we used the 95th percentile, which has been proven by several studies to represent the average height of the dominant and codominant trees (Kane et al. 2010, Hao et al. 2019). The MANOVA equation was:

$$M = \text{percentage of harvested trees} \tag{5}$$

where M is the matrix of the four percentiles of the number of photogrammetric points: 25th, 50th, 75th, and 95th.

Within MANOVA (Eq. 5), we conducted three comparisons to identify the differences, if any, among the harvest intensity concerning the vertical distribution of matter. The comparisons were executed using contrasts [48] that evaluated the first against the second quartile, the third quartile against the 95th percentile, and the first two percentiles (i.e., 25th and 50th) versus the last two percentiles (i.e., 75th and 95th). To support the existence or lack of impact of the harvest levels on the vertical location of matter, we used four tests: Wilk's lambda, Pillai's trace, Hotelling-Lawley Trace, and Roy's Greatest Root (Tabachnick and Fidell 2001).

The distribution of matter is important for economic and ecological perspectives, but the height of the residual trees and their spatial location is important for visibility perspectives. Therefore, we conducted a similar analysis with the vertical distribution of matter but now focused on the four percentiles of the height of the photogrammetric points (Eq. 6). The same four tests were used to assess the impact of harvest level on height: Wilk's lambda, Pillai's trace, Hotelling-Lawley Trace, and Roy's Greatest Root.

$$H = \text{percentage of harvested trees} \tag{6}$$

where H is the matrix of the four percentiles of the height of the photogrammetric points: 25th, 50th, 75th, and 95th.

MANOVA provided an initial insight into the impact of harvest levels on one type of variable (i.e., height or matter), not on a multitude of types. Therefore, we used principal components analysis (PCA) to observe the behavior of all the variables measuring the harvest layouts at once (Rencher 2002): matter, average height, harvested volume and area, and the number of residual trees. The number of significant principal components was selected using the scree plot and a percentage of variance explained larger than 5%, as recommended by Tabachnick and Fidell (Tabachnick & Fidell 2001). The importance of a variable was assessed using loadings, with a minimum threshold for significance of 30% (Tabachnick & Fidell 2001). PCA provides a complete picture of the changes associated with the impact of harvest layouts but does not delineate among the layouts. Furthermore, because none of the variables used in PCA formally assessed the visibility of the harvests, we used Canonical Discriminant Analysis (CDA) (Rencher 1992) to identify similar aesthetics from the obstruction of the ground perspective. The CDA variables included in the visual evaluation were the amount of visible ground, the area with high visibility (i.e., CAH), and the area with low visibility (i.e., CAL). The grouping of the harvest layouts was executed according to the five viewpoints within each stand. To provide an overall perspective of the harvest layouts, the CDA was carried out by including proxy variables for revenue, namely the harvested volume, ecology, represented by the change in total height and cleared area, and aesthetics, described by the visibility. To focus only on aesthetics, a second CDA was carried out, which included only the visibility variables grouped according to the harvest layouts. The same criteria used to select the principal components from PCA were used to select the eigenvectors and the corresponding variables from CDA. The statistical analysis was carried out in SAS 9.4 (SAS Institute 2017).

Results

Stands metrics

For Stand A and B, the point clouds from all 15 designs were used to express the vertical distribution of matter and the visibility of the ground. The four percentiles (i.e., 25, 50, 75, and 95), which count the number of points above the corresponding elevation thresholds (Table 4), represents the distribution of matter for each harvest layout, and serve as a proxy for vertical diversity.

Visibility Analysis

The impact of harvest layout connectivity on the harvested volume differs between stands (excluding the clearcut from the analysis). It is significant for Stand B ($p = 0.03$) but not for Stand A ($p = 0.52$). However, the number of trees harvested varies among the harvest levels for both stands ($p < 0.01$). The Scheffe test exhibited consistent behavior for both stands, grouping harvest levels less than 80% ($p > 0.18$) and distinguishing them from levels greater than 80% ($p < 0.03$), which were not significantly different from each other ($p > 0.53$). A similar conclusion was obtained for the harvested area, which differs with the harvest levels ($p<0.03$). In this case, the separation of levels mirrors the harvested trees only for Stand A, whereas for Stand B, only the harvest level greater than 90% was separated from the rest ($p = 0.03$). Considering that a stand is a forest ecosystem, it was no surprise that the Scheffe test showed that the average height did not vary among the harvested levels ($p > 0.17$).

Resonating with the univariate analysis, which revealed that the harvest designs impact the two stands differently when each attribute is considered separately, the MANOVA showed that the four percentiles are significantly separated based on the harvest levels for Stand A (i.e., for all four tests, the p-value < 0.01) but not for Stand B (i.e., for

Table 4 The number of points, expressed in percentage, above the four selected percentiles.

Design	Stand A (total 112,610,309 points)				Stand B (total 41,462,169 points)			
	> Q25	>Q50	>Q75	>Q95	>Q25	>Q50	>Q75	>Q95
Uncut	17.3%	11.5%	5.8%	1.2%	32.4%	20.9%	9.9%	2.0%
Cut 1	3.5%	2.3%	1.2%	0.2%	8.3%	5.5%	2.8%	0.6%
Cut 2	3.8%	2.6%	1.3%	0.3%	3.5%	2.3%	1.2%	0.2%
Cut 3	3.0%	2.0%	1.0%	0.2%	9.2%	6.1%	3.1%	0.6%
Cut 4	1.7%	1.1%	0.6%	0.1%	5.5%	3.7%	1.8%	0.4%
Cut 5	1.7%	1.2%	0.6%	0.1%	6.7%	4.4%	2.2%	0.4%
Cut 6	3.3%	2.2%	1.1%	0.2%	7.4%	5.0%	2.5%	0.5%
Cut 7	1.4%	0.9%	0.5%	0.1%	5.5%	3.7%	1.8%	0.4%
Cut 8	3.7%	2.4%	1.2%	0.2%	4.6%	3.1%	1.5%	0.3%
Cut 9	1.5%	1.0%	0.5%	0.1%	4.0%	2.7%	1.3%	0.3%
Cut 10	5.9%	4.0%	2.0%	0.4%	2.0%	1.4%	0.7%	0.1%
Cut 11	2.7%	1.8%	0.9%	0.2%	2.3%	1.5%	0.8%	0.2%
Cut 12	2.9%	2.0%	1.0%	0.2%	3.8%	2.5%	1.3%	0.3%
Cut 13	5.5%	3.7%	1.8%	0.4%	4.3%	2.9%	1.4%	0.3%
Cut 14	5.8%	3.9%	1.9%	0.4%	3.0%	2.0%	1.0%	0.2%

all four tests, the p-value > 0.49). When significant differences were present (i.e., Stand A), the contrasts enforced the ANOVA results by separating the first two quartiles from the upper two percentiles ($p < 0.01$). However, the first quartile was distinct from the rest, even from the median one ($p < 0.03$), whereas the 75th and 95th percentiles were not different ($p > 0.05$). For Stand B, the contrasts did not reveal significant differences irrespective of the comparisons (p-value > 0.27).

The principal component analysis (PCA) showed that the first two eigenvectors cover more than 93% of the variation, irrespective of the stand (Figure 5). Moreover, the plots of the two principal components suggest a clear separation of the clearcuts from all the other harvest layouts (Figure 6). For both stands, the variables correlated with the first two eigenvectors are the distribution of matter (i.e., all four percentiles), positively, and the cleared area and trees harvested, negatively.

The canonical discriminant analysis (CDA) provided a similar picture, with the first two eigenvectors cumulating more than 98% of the variation. Different from PCA, for Stand A, the most important variables correlated with the largest eigenvectors were height, followed by visibility and the area seen from outside McDonald-Dunn Research Forest (Figure 7). However, for Stand B, the CDA mirrors the PCA findings, with the four percentiles and the trees harvested being the variables with the highest correlation with the first two eigenvectors (Figure 7). When the clearcut was not included, the first two eigenvectors showed a clear separation of the harvest levels, irrespective of the stand, which was different from the PCA results (Figure 8).

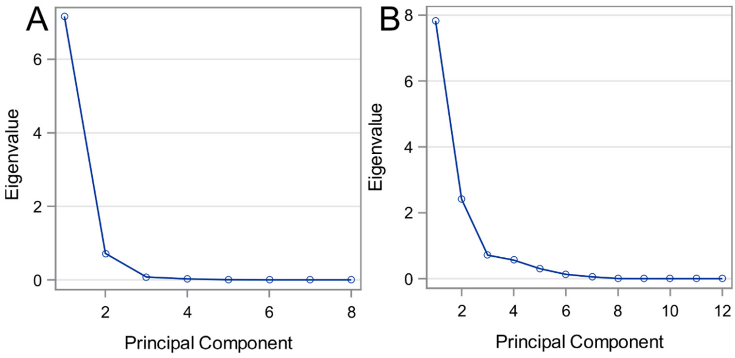

Figure 5 Scree plot. a. Stand A b. Stand B.

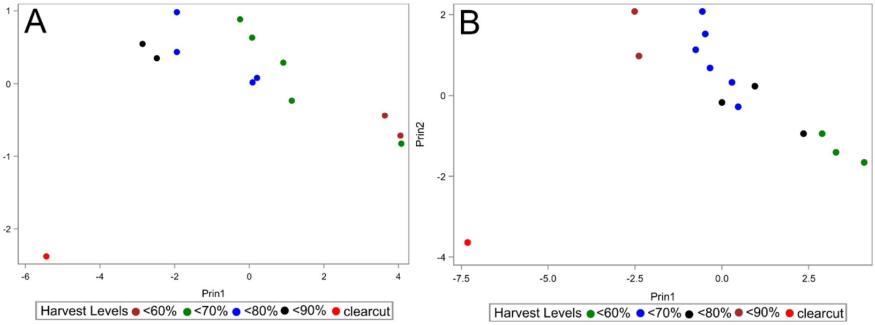

Figure 6 Separation of the harvest levels according to PCA: a. Stand A b. Stand B.

Because most of the analyses suggested that direct visual measures are not significantly influenced by the harvest layout, we ran the CDA by replacing the harvest levels with the harvest layouts and including only the visibility variables (Figure 9). The likelihood ratio test suggested that only the first eigenvector is significant, but for Stand A, the first two eigenvectors explained more than 95% of the variability. Interestingly, the variable with the largest load was the critical areas with low impact (CAL), namely within the McDonald-Dunn Research Forest, which is the opposite of what was expected and as suggested by the CDA executed by considering the clearcuts.

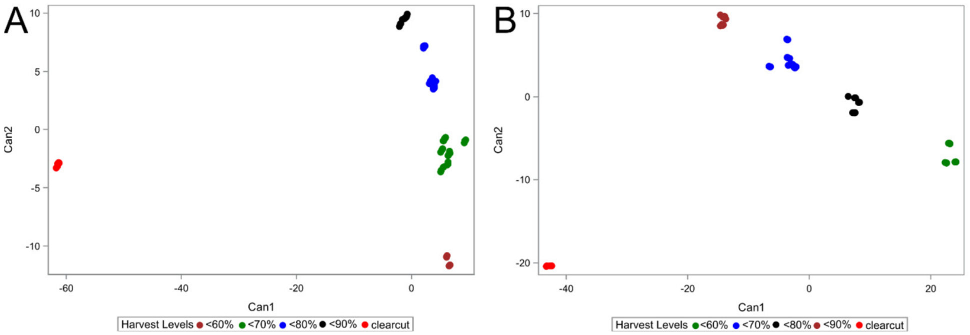

Figure 7 Separation of the harvest levels according to PCA: a. Stand A b. Stand B.

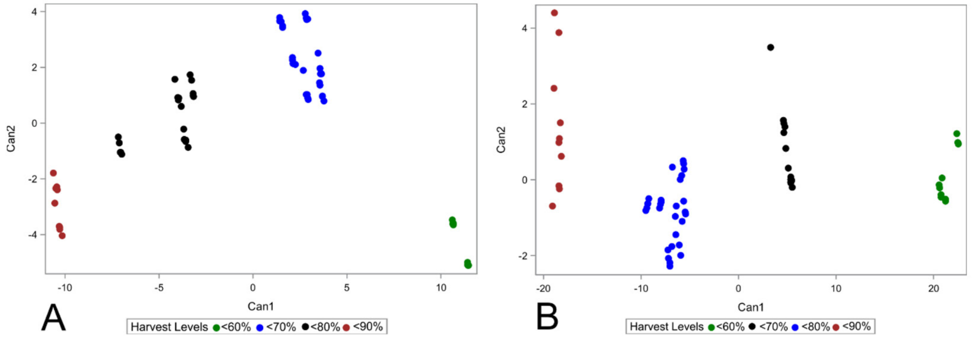

Figure 8 CDA for the harvest levels that do not include clearcut: a. Stand A b. Stand B.

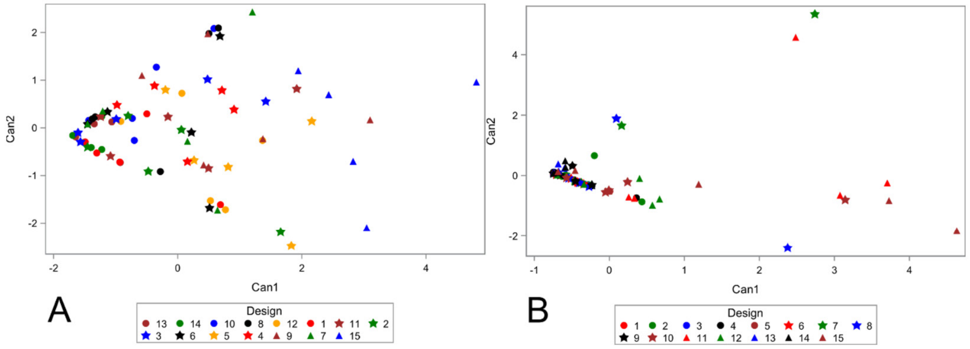

Figure 9 CDA on the harvest patterns and visualization variables: a. Stand A b. Stand B.

Discussion

The emergence of remotely sensing UAS platforms that can produce data-rich 3D point clouds with SfM methods in a user-friendly and affordable package, while maintaining accuracy (Tang & Shao 2015), support inclusion of forest aesthetics in forest management decisions. By using PPC in the public review processes for proposed forest operations, this research provides researchers and land managers with a proof that forest aesthetics in highly visible areas can be maintained without sacrificing revenue beyond acceptable levels, allowing forestry professionals to maintain their social license even in visually sensitive areas.

The two stands from McDonald-Dunn Research Forest were chosen due to their proximity to a large number of viewers and the potential for active management that provides both revenue and research opportunities in OSU's College of Forestry. A characteristic of the two sites chosen was their size difference, as Stand A was almost 10 times larger than Stand B (i.e., 29.7 ha vs. 3.5 ha). The size difference is probably one reason for the variability seen in the analysis based on trees harvested, as in Stand A, the mean number of trees harvested was approximately 240/ha, whereas in Stand B, it was almost 30% less (i.e., 167/ha). Even though Stand A exhibited a larger average harvest intensity than Stand B, it did not show a significant loss in connectivity due to the large variability among the harvest layouts.

The significant separation of the four percentiles by harvest levels for Stand A, as shown by MANOVA, can be attributed to a shelterwood cut executed almost two decades ago (i.e., in 1999) that left large diameter Douglas-firs (i.e., on average 38 trees/ha), as well as a smaller hardwood component of 40 cm - 50 cm trees. The efforts placed in regenerating a vigorous second story, comprised mostly of Douglas-fir, combined with the even distribution across the stand of larger Douglas-fir, explain the partition of quartiles; especially the first two quartiles ($p < 0.03$) against the median ($p < 0.03$) and the upper quartiles. It would have been expected that the 75th and 95th percentiles would be significantly different since the larger dominant trees left in the shelterwood harvest would emphasize the separation from the second story, but the variability of co-dominant and dominant trees left after the cut explained the lack of significance observed ($p > 0.27$). The harvest from Stand B did not significantly separate the four percentiles, as the 68-year-old even-aged Douglas-fir stand with smaller remnants of grand fir and bigleaf maple precluded accurate description with PPC of the lower layers, leading to information loss in the dominated and suppressed crown cover.

The PCA for Stand A and B shows similar findings, with harvest layouts associations driven positively by the number of trees harvested and the matter, and negatively by the cleared areas and volume harvested (Figure 6). The CDA painted a similar picture with PCA, as the levels of harvest were clustered in well-defined groups, which is expected as the CDA emphasizes aggregation rather than variability (Sherry & Henson 2005). When looking at the CDA without including the clearcuts (Figure 7), the clustering remains defined even when visual variables are included. However, the visual metrics are not significantly influenced by the harvest layouts any more than the dimensional variables being assessed. Further analysis of a CDA with patterns against the visual metrics (Figure 9) revealed the maintenance of well-defined clusters.

The CDA of patterns against visual metrics in Stand A showed clustering of east-west layouts with negative discriminant scores, except for design 4 (Figure 2), which has one strip connected to the rest of the forest. The negative separation of the E-W cuts can be attributed to the pattern not considering the topography or surrounding features that would hide or screen the cut. Harvest designs planned against the topography showed a more dispersed clustering, with slightly positive correlations with the visibility metrics, as these designs allow for greater visibility of a harvest. Designs that consider topography would hide and screen a cut more effectively than those focusing on time efficiency by disregarding the natural setting. However, an oblique view of the pattern would provide the same screening properties as if viewed on a north-south axis. The clearcut shows the most positive discriminant scores in the CDA, followed by the design with a single N-S large strip in the middle of the stand (i.e., number 9).

The designs that clumped residual trees were clustered, which can be attributed to sufficient remaining structure to reduce visibility. However, the variable nature of the clumps and grouped structures was not enough to reliably provide negative discriminant scores seen in the east-west designs. The designs based on the watershed inundation model that planned cuts behind initial tree lines near areas of most visibility concerns (i.e., numbers 13 and 14) exhibited the most negative discriminant scores (Figure 3). The effort placed in developing such designs is significant compared to the rest, but the most effective results were obtained. The manner in which the inundation model was conceived in this study does not suggest operability but shows that intentional harvest designs planned to mitigate visibility reduce the chances of their observation by most of the public.

The CDA for Stand B revealed similar negative discriminant scores (Figure 9) with the patterns that followed the topography (Figure 2). The clearcut in Stand B does not have a more positive discriminant value than Stand A, suggesting that the stand is less visible in general. Stand A is both larger and more visible than Stand B, making the potential for more positive discriminant values for each harvest design.

Chamberlain and Meitner’s (Chamberlain and Meitner 2009) attempted to automate harvest designs by integrating viewshed techniques based on 3D data (i.e., DTM and raster with forest cover data) with 2D raster maps. Their results showed that automatic “screening” and “hiding” of cuts are possible, similar to this study. However, the automated approach, which is an attractive alternative to the time-intensive work of crafting harvest designs from point clouds, leads to errors. Their approach is one of the few attempts that use 3D information (i.e., DTM and forest height information) in combination with visualization techniques and viewshed analysis to create harvest designs for scenery management objectives but lacks resolution compared to the present study based on point clouds rather than rasters. Meitner and Chamberlain (Chamberlain & Meitner 2012) found that circular shapes with rounded edges were the most preferable. Their results show public preferences for cut block shapes using generated realities, consequently incomplete, whereas this study produces comprehensive 3D data-driven visualizations. Furthermore, while Meitner and Chamberlain's study concentrates on public acceptance of visible forest operations, this study focuses on the efficacy of creating harvest scenarios that are visually pleasant. A similar study by Ribe (Ribe 2005) considered forest operations in highly visible vista views by assessing harvest shapes and the retention left in timber harvests with photo-realistic simulations. They found that aggregated cut blocks were perceived as ugly, no matter the shape, whereas dispersed harvesting practices led to favorable preferences, with green tree retention and irregular harvest shapes improving viewer perceptions of timber harvests, similar to our results. However, lacking the point cloud representation of the forest and the forest inventory data, their study is only informative in understanding how timber harvest operations are perceived, whereas our study expands into the operability and reality of active forest management.

Song and others (Song et al. 2006a) performed 3D timber harvest visualizations, like this research, and used differing designs to create various harvest strategies, such as "before harvest," "clearcutting," "stripcutting," and "patch cutting." However, the simulated strategies were not formally analyzed, as the study focused mainly on the creation of visualizations, unlike this research, where the formal analytical assessment of the visualization is the focus. Fujisaki et al. (Fujisaki et al. 2007) used LiDAR point clouds obtained by aerial laser scanning to create an under-the-canopy immersive virtual 3D stand assessment. The present study expands their results, which showed that point clouds can be used to visualize a forested stand, by incorporating harvests in the visualization process, an aspect not considered by Fujisaki et al. However, we have shown that PPCs are a viable alternative to the expensive LiDAR in forest visualization and can recommend harvesting strategies. PPCs were also used by Magliocchetti et al. (Magliocchetti et al. 2015) in creating a 3D virtual decision support system for harvest operations in mountains with UAS SfM point clouds. However, their study offers an opposite perspective of forest activities compared to Song et al. (Song et al. 2006b), as it focuses on the feasibility of forest harvests without any interest in visualization. The present study brings together both perspectives, operational and aesthetic, and reveals that financially feasible harvests are possible without impacting the aesthetics for most people. The results of this research show that in these two stands harvests removing up to 75% of the trees can be largely screened from the surrounding landscape while also altering the vertical distribution of matter, suggesting a low likelihood that such operations would be detected from the critical viewpoints. Whether this reduced visibility translates into a neutral or favourable aesthetic response, rather than merely a less visible one, remains to be confirmed through viewer-based perception testing.

Interpreting these results should formally link aesthetic values with the metrics quantifying visibility. The wider literature on forest aesthetics shows that scenic preference is a socially constructed response shaped by stand attributes rather than by mere exposure: large trees, variation in tree size, a moderate (rather than absent) understory, and the avoidance of visible clear-cuts and harvest residues all raise perceived scenic beauty (Averbeck et al. 2026), while historically the concept itself, dating to von Salisch's Forstästhetik, tied beauty to stand structure and the play of light through the canopy rather than to invisibility alone (Koike et al. 2024). A screened harvest is not automatically a preferred one, and concealment may even conflict with the view, held by some practitioners, that managed forests should not appear to hide what they do (Hull et al. 2000; Sheppard 2001). The layouts that performed best on our visibility metrics, those following the terrain and retaining connected forest structure, also coincide with attributes that perception studies associate with higher scenic beauty, such as retained large trees and irregular, dispersed openings rather than aggregated clear-cuts (Ribe 2005, Chamberlain & Meitner 2012, Averbeck et al. 2026). This convergence is encouraging but indirect, and the visibility metrics should therefore be read as a screening-oriented complement to, not a substitute for, preference-based assessment.

Limitations Associated with the PPC and Visibility Analysis

One of the limiting factors in this study was the lack of ground control points (GCPs) in the flight planning. Accurate measurements resulting from PPC have been used in forestry applications (Iglhaut et al. 2019), and significant errors can accrue when no GCPs are used in the alignment stage of the images (Grayson et al. 2018) with impact on georeferencing (Eltner & Schneider 2015). Sanz-Ablanedo et al. (Sanz-Ablanedo et al.

2018) found that when fewer than 1 GCP per 100 photos is used, the accuracy degrades rapidly. The errors incurred from not using GCPs in the alignment were understood in the design of this study, with the caveat that the forest inventory derived from the PPC is not as accurate as field measurements.

Additionally, a portion of the east side of Stand A has a sparser point cloud, which could influence the viewshed analysis portion of the visibility analysis. To alleviate the lack of PPC density, particularly in the lower portion of the stand, the point cloud was merged with the LiDAR data acquired in 2008. Tree metrics, other than the visibility metrics, were derived solely from PPC.

More fundamentally, photogrammetric point clouds carry intrinsic limitations relative to LiDAR that bound the inferences drawn here. Structure-from-motion reconstructs the outer canopy well but penetrates poorly into and beneath the crown, so point density falls and noise rises in the lower canopy and on shaded slopes (Tomaštík et al. 2017; Sanz-Ablanedo et al. 2018). These properties most likely explain the contrasting behaviour of the two stands: the multi-storied Stand A retained enough penetrable structure for the height percentiles to separate by harvest level, whereas the closed, even-aged canopy of Stand B blocked reconstruction of the dominated and suppressed strata, flattening the vertical signal and masking differences among layouts. Stand structure, rather than the harvest designs alone, therefore drives much of the divergence between the two stands, which cautions against generalising from these two case-study stands to forests with different composition, density, or terrain. The use of a different segmentation algorithm in each stand, although justified by structure, further limits the direct comparison of detection accuracy between them. Broader testing across additional stands and forest types, ideally with co-registered LiDAR for benchmarking, is needed before the workflow can be considered operationally validated.

The study was designed such that each harvest layout would be encountered in both stands, particularly the ones following a pattern. However, the shape and size of each stand preclude the exact mirroring of the layouts. Another limitation in the visibility analysis is the amount of point clouds considered throughout the study. Additional point cloud reconstruction of the forest surrounding the two stands would yield a more robust visibility analysis, which would change the amount of area in the CAL and CAH metrics. Increased forest structure would lower the visibility metrics inside the CAL and potentially the CAH. Not only would the level of visual occlusion increase inside the forest, but the surrounding stands would also limit the visibility of the CAH. A screening of trees does not automatically create a barrier of opaqueness as it is more complex (Dean 1997, Llobera 2003, Liu et al. 2010). Maloy and Dean (Maloy & Dean 2001) found that viewshed analysis results are dependent on the algorithm, the type of DTM raster, and the spatial resolution, which can lead to errors even when inputs are optimal.

Many practitioners believe that managed forests should not hide behind buffers and screens of trees, which would suggest that there is something to hide (Hull et al. 2000, Sheppard 2001). However, exposing the ground to the public tends to be disliked by many people. For forested landscapes that are on vista views or mountain slopes with a greater chance of influencing the surrounding viewshed, this study offers a decision support tool to assist managers in planning operations that occlude cuts without sacrificing financial feasibility. Beyond producing designs, the data-driven, three-dimensional nature of the visualizations can support participatory planning: by letting stakeholders see and compare candidate layouts on the actual stand rather than on abstract maps, such tools have been shown to improve comprehension and to focus discussion, which can help reduce conflict during public review (Meitner et al. 2005, Lewis & Sheppard 2006).

In areas of significant concern, a large buffer of point clouds around the areas of visualization is recommended, as a larger region would be necessary to create the required inputs for viewshed analysis. For harvests that aim to minimize visual impacts, it is recommended that designs follow the natural terrain, with buffers and strips limiting visibility (Figures 8 and 9). More complex designs (Figure 3) that involve ingenuity, time, and effort can help produce superior aesthetics, as seen in the CDA (Figure 8 and Figure 9).

Conclusions

This study aims to assess the impact of harvest designs on stand aesthetics, greatly expanding previous studies in visualizing 3D forests, which were limited by the capabilities of computer hardware to create realistic, data-driven 3D virtual forests and involved a time-intensive process of generating a library of images needed to render trees and terrain. Viewshed analysis was used to assess the visual impacts of harvests and numerous designs evaluating public preference were added to the growing literature that seeks to mitigate the negative aesthetics associated with forest operations. As technology advanced, LiDAR forest visualizations emerged alongside a boom in UAS technology. Chamberlain and Meitner's research on assessing visual impacts using GIS viewshed analysis with 3D forest visualization techniques synthesized a body of literature focused on visual impacts. Our approach uses photogrammetric point clouds to create varying harvest designs and formally assess their impacts with advanced statistical analyses.

To investigate the efficacy of photogrammetric point clouds for forest visualization, two stands (A and B) were located in the McDonald-Dunn Research Forest by Oregon State University. The stands were chosen for their potential to negatively impact the surrounding visual quality of the scenery during forest harvesting. Dense point clouds derived from UAS were created and used as templates to produce timber harvest designs. The number of trees, heights, volume, and cleared area were inputs in univariate and multivariate analyses. Tree metrics were also used in a PCA, which found that designs were consistently separated by the degree of percent harvested. Visibility metrics of the visible area were also used in a Canonical Discriminant Analysis, which showed that designs tailored to the terrain (e.g., structures like "strips" and "islands") occluded the visibility of forest operations with negative discriminant values.

Harvest designs that involved more complexity and aimed to screen forest operations with novel mechanisms like an inundation model showed the most negative discriminant values for visibility metrics. For the two stands examined, the most time consuming designed layouts could largely screen harvests removing up to 75% of the trees. Because visibility is only a proxy for visual impact, this finding indicates a reduced likelihood of detection rather than a confirmed gain in aesthetic quality.

Sparse SfM-based point clouds were enhanced with the LiDAR point cloud obtained from the 2008 flight by merging them with the PPC, creating the required input for the viewshed visibility analysis. While viewshed analysis is informative, formal visual analysis is subject to significant errors, particularly the inability to properly account for the complexity of forest vegetation. This limitation offers a place for future research in creating harvest designs assessed with algorithms that emphasize the penetration that vegetation exhibits.

Additional research into how a photogrammetric GCP point cloud differs from the no-GCP visualization approach would be enlightening. Assessing the visualization performance of the combined PPC and LiDAR would be fruitful and would create a more holistic image of how effective point clouds can be used as a decision support tool for forest managers in designing harvest blocks.

Overall, the workflow presented here should be regarded as a promising decision-support approach rather than a fully validated operational solution. Because the findings rest on two simulated case-study stands and on visibility as a proxy for visual impact, they are not directly transferable to other forest types or to actual public response. Priorities for future work are therefore to validate the visibility metrics against stakeholder perception studies, to test the workflow across a wider range of stand structures and terrains, and to benchmark PPC-based designs against LiDAR-based equivalents.

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