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Skid trail network visualizer: A computational tool to generate skid trails created by ground-based timber harvesting machines and facilitate soil disturbance monitoring

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ABSTRACT

A computational tool was developed to reconstruct skid trail networks based on global positioning receivers mounted on ground-based harvesting machines and estimate the number of machine passes. Additionally, this tool has the functionality to identify potential sample point locations by traffic level to monitor and measure soil impacts. The application was evaluated using data from a field test, where the movement of a skidding machine was simulated using an all-terrain vehicle onto which a high-precision global positioning receiver was mounted, which collected real-time corrected data with a 0.2 s capture frequency. To test the effect of receiver accuracy and data capture frequency on the layout of the skid trail and the estimation of traffic level, the original dataset was used to simulate four accuracy levels (0.09 m, 1 m, 3 m, and 5 m) and six capture frequencies (0.2 s, 1 s, 3 s, 5 s, 10 s, and 20 s) resulting in machine position datasets. Results show that the tool could successfully reconstruct skid trails for all cases analyzed. The average difference between the field-mapped and tool-estimated total skid trails lengths was below −0.5 %. The average distance between control points along field-mapped skid trails and the tool-generated skid trails was about 1.41 m, and the average difference between the number of machine passes along field-mapped skid trails and the tool-estimated machine passes was less than one machine pass. Receiver accuracy has a slight effect on the quality of the skid trail layout and does not affect the estimation of traffic levels, and the frequency of data capture has a greater effect on the quality of the layout, although the deviations do not exceed 3 m, which is smaller than the size of the skidding machine itself. Capturing machine positions every 5 s is recommended to generate accurate skid trail networks and balance the volume of data obtained from the global positioning receivers. In addition, the tool's functionality of identifying possible sample points was to measure soil impacts based on the number of machine passes is useful to facilitate monitoring and measuring soil impacts to aid future treatments for site preparation activities.

1. Introduction

During the operational planning of ground-based timber harvesting, typically on terrain with slopes below 35 %, the appropriate layout of skid trails is crucial to ensure high productivity and lower soil disturbance (Labelle et al., 2022). From an economic viewpoint, the location of skid trails directly impacts the traveling times of skidding machines (either skidders or forwarders) consequently affecting their productivity and cost. Among all harvesting activities (felling, skidding, processing, sorting, and loading), skidding is the most expensive and causes the most soil disturbance due to the constant transportation of trees or logs to a log landing (Ghaffariyan 2022; George et al., 2022; Louis and Kizha 2021). From an environmental perspective, numerous studies have reported disturbances caused by the skidding machine on the vegetation, such as changes in the understory structure and composition (Harvey and Brais, 2002; Buckley *et al.*, 2003; Zenner and Berger, 2008; Avon *et al.,* 2012). However, most reported impacts are related to soil disturbance such as rutting, soil displacement, and compaction

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(Froehlich, 1981; Gayoso and Iroumé, 1991; McNabb, 2001; Han *et al.*, 2009; Cambi et al., 2015). These impacts have the potential to cause soil erosion by causing sediment production and movement and thus can impact water quality (Gayoso and Iroumé, 1995; Rab, 1996; Kolka and Smidt, 2004). Even severe, and prolonged impacts can cause a loss of soil productivity to growth trees (Wronski, 1984; Zenner and Berger, 2008). The magnitude of these impacts is related to multiple factors such as soil type, soil moisture content at the time of the operations, terrain slope and the type of skidding machine (McNabb, 2001; Gayoso and Gayoso, 2009; Cambi et al., 2015). However, independent of the terrain, vegetation, and skidding machine characteristics, it is observed that the magnitude of the impacts is related to the traffic level and most soil disturbances occur during the first several machine passes (Adams and Froehlich 1981; Gayoso and Iroumé 1991; Wang et al., 2005). Derived from these observations, one of the most common and important recommendations is to concentrate the traffic of the skidding machines along a few planned skid trails (Andrus and Froehlich, 1983; Garland, 1997; Han, 2007).

In Chile, there are about 2.4 million ha of forest plantations that in 2021 supplied 43.4 million m^3 of wood to the Chilean timber industry (Kahler et al., 2022). Considering an average of 500 m^3 ha^{-1} at rotation age, it is estimated that around 90 thousand ha are harvested annually, from which about 60 % (54 thousand ha) are in areas with slopes below 35 % that are harvested with ground-based systems that use skid trails (Pincheira, 2023). Chilean regulations recognize skid trails as potential generators of environmental impacts, being explicitly mentioned in the Soil, Water and Wetlands Regulations approved by Supreme Decree No. 82 of 2010, which prohibits placing skid trails in riparian and other water protection zones. Moreover, the area covered by skid trails is considered impacted and mitigation measures to disrupt surface runoff flows must be implemented after their use. On the other hand, the General Regulations of Decree-Law No. 701 of 1974, mentions that details about skid trails must be included in technical studies (cutting permits), in the description of the soil, and the control measures of potential erosive impacts in the affected areas (CONAF, 2021). In regulations such as the best management practices and forest certification manual, there are also several recommendations for mitigating soil disturbance along skid trails (Dykstra and Heinrich, 1996; Aust and Blinn, 2004; Gayoso and Gayoso, 2009; FSC, 2015). These recommendations include prevention and mitigation measures such as i) reducing the length of the skid trail network, ii) placing skid trail along contour lines and avoiding steep slopes, iii) avoiding stream crossings, wet areas, and fragile soils, and iv) installing surface water diversion structures.

As the area covered by skid trails is considered the area impacted by the skidding machines, it is often assumed as an appropriate indicator of soil disturbance (Gayoso and Iroumé, 1993). Traditionally, the area impacted is estimated through post-harvesting field measurements by tracing the visible skid trails (Gayoso and Gayoso, 2009). Using this methodology, in Chile Gayoso et al. (1991) reported that 40 % of the area was impacted by unplanned skid trails in clearcutting operations in *Pinus radiata* (D Don.) plantations. Internationally, for example, Zenner *et al.* (2007) found in a mesic northern hardwood stand, in which a harvesting treatment removed between 50 to 100 % of the canopy cover in Minnesota, USA, 31 % of the area was covered by skid trails. As field measurements take significant time and resources, in the last two decades at the international level, these measurements have been automated using global positioning systems (GPS, GNSS) receivers mounted on the skidding machinery. The information collected includes three-dimensional coordinates from which it is possible to reconstruct skid trails and estimate the impacted area (Carter et al., 1999; Veal et al., 2001; McDonald et al., 2002; McDonald and Fulton, 2005; Taylor et al., 2006). For example, McDonald et al. (2002) found that the impacted area estimated with GPS equipment was 18 % lower than visual field estimates. These differences may have occurred due to the difficulty of estimating the impacted area visually on the field or to errors in the accuracy of GPS receivers.

Although the area impacted represents the sectors through which the traffic of skidding machines caused soil disturbance, this indicator does not consider the level of traffic, which is strongly related to the intensity of the soil impacts (Gayoso and Iroumé, 1991; Bettinger, et al., 1994; Zenner *et al.,* 2007; Han *et al.*, 2009). Therefore, measuring the number of machine passes is also a variable of interest, but is practically impossible to measure with field observations post-harvesting. Field measurement of the number of machine passes would occur during the harvesting operation, which might alter machine productivity and most importantly, would increase the risk of accidents by placing observers in unsafe zones. Alternatively, the number of machine passes can be estimated from the data collected by the GPS receivers. There are only a few studies conducted to estimate traffic levels from GPS data directly, however, these studies were also able to identify areas with significant rutting and exposed mineral soil (McDonald *et al.*, 1998; Carter et al., 1999; McDonald et al., 2002). When comparing their results with field measurements, these studies reported a similar percentage of area with low to medium traffic levels (<20 machine passes), and 13 % less area with significant rutting and exposed mineral soil.

In Chile, even fewer studies use global positioning technology to represent skid trails, estimate the area impacted, and the traffic level of ground-based harvesting systems (Cordero et al., 2006). However, due to decreasing costs, global positioning technology is being used more frequently in forest operations, and even large forest companies in Chile use low-end global positional receivers mounted on logging machinery to identify areas impacted and improve the overall efficiency of their operations. Despite these efforts to quantify areas impacted, this metric does not consider how soil impacts change with traffic level. This raises the need to quantify soil impacts as a function of traffic level to properly quantify and monitor soil impacts and to guide subsequent remediation, site preparation, and establishment efforts. Additionally, as the cost of global positional technology is related to the quality of the data provided, an important aspect is to evaluate the effect of the accuracy and frequency of the global positional data capture on the representation of skid trails, the estimation of traffic level and the percent of the area impacted.

Consequently, the objectives of this work are i) to develop a computational tool, based on positional data captured through global (GPS/GNSS/GLONASS) receivers during ground-based harvesting operations, to recreate the skid trail network and estimate the level of traffic, and ii) to evaluate the effect of the accuracy and frequency of positional data on the quality of the skid trail network and estimation of traffic levels.

2. Materials and methods

2.1. Computerized tool development

Due to its widespread use in the professional and academic community, the tool was developed as an Add-in for ArcMap, v10.6. The Add-in was programmed using the C# programming language in Visual Studio 2019 after installing the ArcObjects Software Development Kit for.NET. This library made available ArcMap AddIn option as the user graphic interface for this tool. The tool, called skid trail visualizer (STV), was designed to graphically represent skid trails in vector format, and estimate the number of machine passes, length of the network, and percentage of the area impacted based on positional data from skidding machinery during the operation. In addition, it has the functionality to identify the coordinates of systematic sampling points by traffic level placed along the skid trail network to facilitate the measuring and monitoring of soil impacts.

2.1.1. Input data

The STV requires input data in the form of digital layers and general parameters to identify the skid trail and the other estimates. The four digital layers include:

i) Digital terrain model (DTM): layer in raster format representing the elevation above sea level of the area under consideration.
ii) Harvested area: layer in vector polygon format that delimits the surface of the area harvested.
iii) Landing: layer in vector polygon format that delimits the area where logs/trees are transported by the skidder for further processing.
iv) Positional data: layer in vector point format that presents the machine positions collected by global positioning receivers (GPS/GNSS/GLONASS) during harvesting. From the layer attributes table, fields representing: date: in day/month/year format (ie., 10/26/2022), time: in hr:min:sec format (ie., 15:52:38.9), and altitude: value in decimal numeric format representing the elevation (m asl) of each point must be specified. The program internally obtains the X and Y coordinates of each point when reading the data.

General parameters, to be specified by the user, include:

i) Cell size (m): used to rasterize the geographic extent of the positional data. As the location of skid trail segments originates from and ends at cell centroids, a smaller cell size would result in a skid trail network more adjusted to the machine's positions. Suggested values are between 0.5 and 5.0 m (machine length).
ii) Maximum speed (m/s): represents the maximum speed at which the skidder can travel, or the maximum speed it traveled, if there is operational knowledge of the ground conditions where skidding occurred. It is used to filter out outlier positions that may represent errors caused by a poor satellite signal. It is recommended to use values between 4.0 and 7.0 m/s.
iii) Skid trail width (m): represents the approximate width of the skid trails generated by the multiple passes of the skidder. For example, machine width or distance between the outer side of the tires. It is used to estimate the area impacted considering a fixed value along the network.
iv) Segment length (m): represents the desired length of the skid trail segments generated to represent the skid trail network. In the case of segments close to intersections, shorter segments are inevitably generated. A shorter segment length will result in skid trails closer to the machine positions. However, values larger than the diagonal of the cell size should be entered. Values close to the machine length are recommended.
v) Sampling points: indicates the number of sampling points to be identified at each traffic level. The locations of the sampling points are selected systematically based on the distances of each skid trail segment within each traffic level and the total distance of the segments in each level. By default, six traffic levels are identified: 1–5, 6–10, 11–15, 16–20, 21–25, and > 25 machine passes). The default value is zero, but if a value is entered, a layer is automatically created with the locations of the sampling points for each traffic level.

2.1.2. Data processing

The data processing that guides the skid trail generation and metrics estimation are:

i) Data verification: it is verified that the geographic extent of the different digital layers matches, the user selects columns from the attribute table of the positional data with the required format, and the general parameters correspond to values with the required format.
ii) Outlier filtering: positional data collected with global positioning receivers often contain outliers that represent errors due to physical interference, poor connection quality, low satellite count, and intrinsic receiver characteristics. Consequently, the tool incorporates a routine that filters outliers based on the maximum velocity parameter (Fig. 1). The routine calculates the velocity for each section formed by two consecutive positions of the machine using its three-dimensional coordinates and time stamps. Then, it consecutively inspects if there are sections with a velocity greater than the maximum velocity parameter. If a section *i* with a speed greater than the maximum speed is detected, two possible cases are identified; when there is an outlier position and two consecutive sections with speeds greater than the maximum speed (Fig. 2A, blue box in Fig. 1), or when there is an outlier position and one section with a speed greater than the maximum speed (Fig. 2B and 2C, red box in Fig. 1). For the first case, the routine eliminates the outlier position common to both sections and recalculates the velocity of the new section formed by the start position of section *i* and the end position of section $i + 1$. For the second case, either the start or end position of section *i* must be deleted. To select which one to delete, a set of four sections ($i - 1$, i, $i + 1$, $i + 2$) is created and both alternatives are evaluated by recalculating velocities and choosing the option that provides the smallest standard deviation of velocities of the three resulting sections (Fig. 1). Afterward, the velocity inspection returns to the previous section ($i - 1$), to allow iteratively eliminating multiple positions, if necessary, in the positional dataset.
iii) Rasterization of positional data: to facilitate the identification of skid trails, the extent of the area covered by the positional data is rasterized using the cell size parameter (Fig. 3A), and all cells containing at least one machine position are identified (Fig. 3B). Depending on the machine travel speeds and the cell size, skid trails represented in the raster may have discontinuities. Consequently, the tool draws straight lines between adjacent positions and identifies the cells containing the lines, thus avoiding discontinuities in the skid trail network (green cell in Fig. 3C). In addition, there might be empty spaces along the tracks (red cells in Fig. 3C), which are filled in to generate a continuous skid trail network without small circuits (Fig. 3D).
iv) Skid trail network thinning: the raster resulting from the previous step can generate skid trails of different widths (Fig. 3D), so its width must be homogenized to draw single skid trail segments between two points along the network and facilitate identifying their location. Thus, the STV uses the Zhang-Suen image thinning algorithm (Zhang and Suen 1984) to generate the skid trail network with a width of one cell (Fig. 3E).
v) Generation of skid trail segments in raster format: starting from the top left corner of the raster, the first cell of the grid with a machine position with one adjacent cell also with machine position data and is identified and marked as the start of a skid trail segment. Then, to find the end of the skid trail segment, the tool moves along adjacent cells by counting cell widths and cell diagonals until that accumulated length exceeds the segment length parameter value. The process continues identifying the starts and ends of segments along of skid trial and finishes at either an intersection or the end of the skid trail network. Undoubtedly, the last segment along a skid trail has a length smaller than the segment length parameter value (Fig. 3F).
vi) Generation of skid trail segments in vector format: the coordinates of the centroids of the start and end cells of each skid trail segment, identified in the raster, are used to generate straight lines representing skid trail segments in vector format (Fig. 3G). This process, especially at intersections, tends to generate short segments of a length equal to the width or diagonal of a cell, which might not represent actual skid trails segments (Fig. 3H). For such cases, a removal of skid trail segments with lengths smaller than the diagonal of the cell (Fig. 3I).
vii) Estimation of the number of machine passes: Once the skid trail network has been mapped in vector format, the number of machine passes per segment is calculated assuming that the route

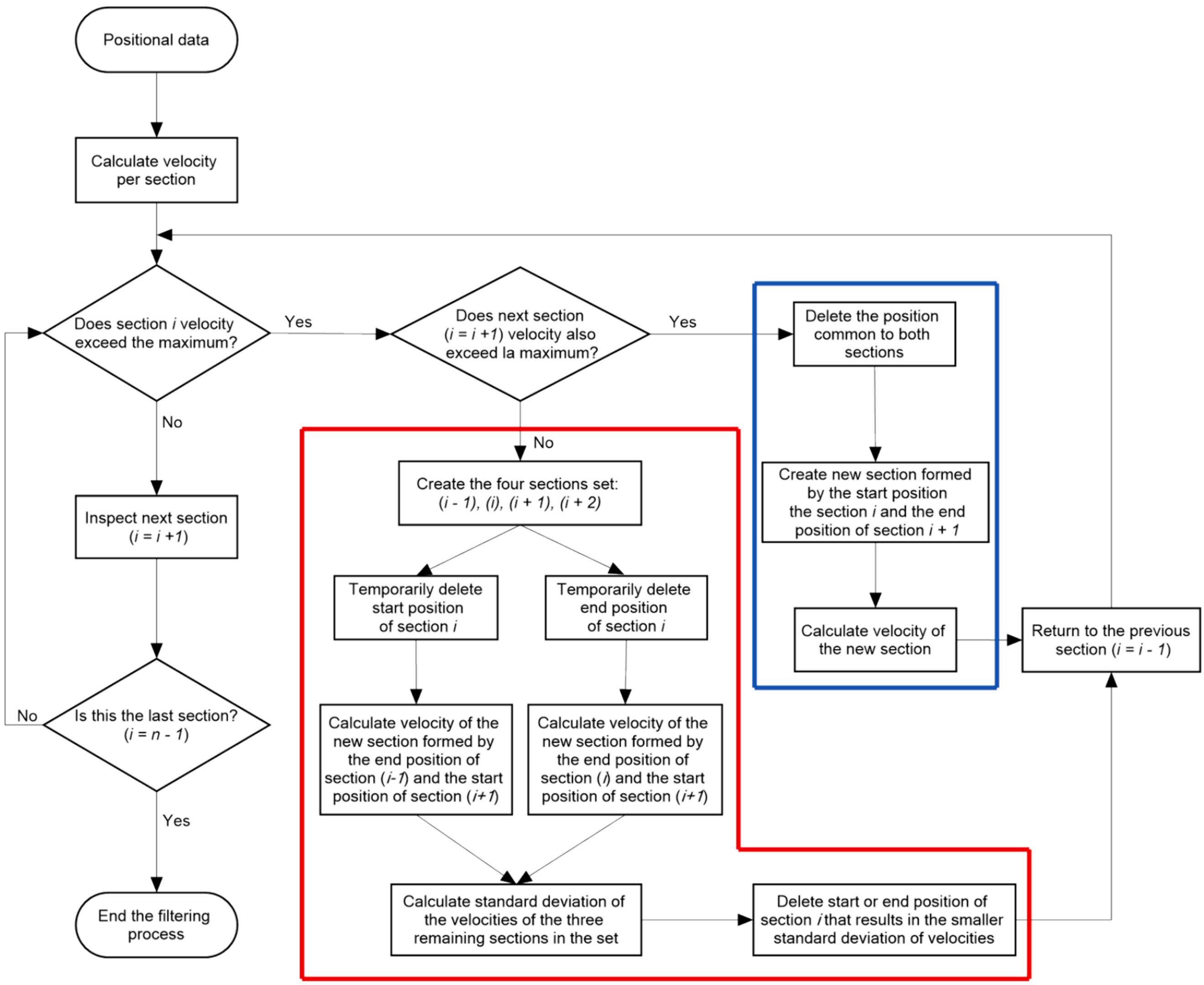

Fig. 1. Flow chart of the logical process used to filter outlier positions.

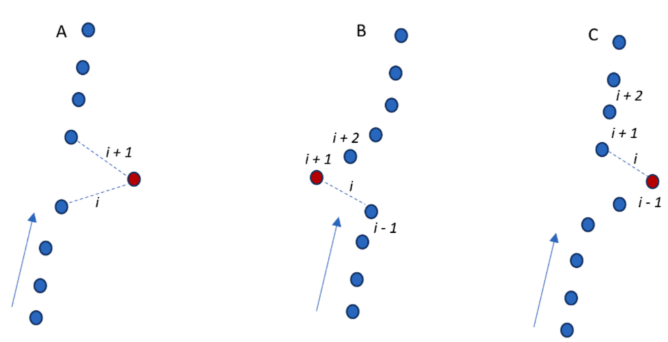

Fig. 2. Examples of the two cases considered in the outlier filtering process.

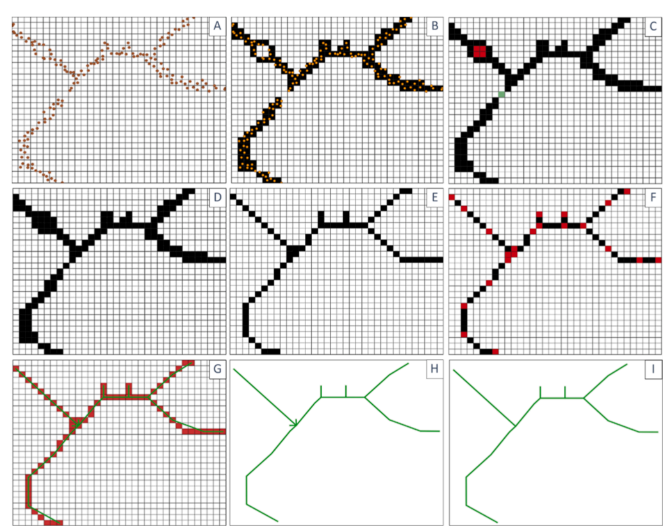

Fig. 3. Diagram of the skid trail generation process used by the computational tool.

followed by the skidding machine during the empty and loaded trip is the same. This process considers the positional data sequentially (temporal order) and the generated skid trail segments in vector format. For each machine position, the closest Euclidean distance segment is identified. Then, following the time sequence of the positions, the machine passes through each skid trail segment is increased by one if the previous position is not associated with the same segment. This avoids duplicating the number of machine passes through a segment due to multiple machine positions associated with one skid trail segment during a logging cycle.

viii) Estimation of the area impacted: the skid trail width parameter is multiplied by the total length of the skid trail network to estimate the area impacted (ha), and the percentage of the area impacted of the total harvested area is also calculated. For simplicity, this calculation considers a constant skid trail width for the entire network independent of the traffic level.

ix) Identification of sampling points: Six traffic levels are identified according to the number of machine passes, with intervals of five, from one to 25, and then greater than 25 (e.g., 1–5, 6–10, 11–15, 16–20, 21–25, and >25 passes). The skid trail segments for each traffic level are identified, sorted according to their internal identifying number, and the cumulative distances of the sorted segments are calculated. Then, the spacing between sampling points is determined by dividing the total distance of the segments by the number of sampling points. Finally, the skid trail segment and the position (x and y coordinates) along the segment where each point is located are identified. The process is repeated for each traffic level to determine the location of all sampling points.

2.1.3. STV results

The STV results include the harvested area (ha), the total length of the skid trail network (m), area impacted (ha), and the percent of area impacted area. In terms of digital layers, the results include a digital layer in vector format with the skid trails (shapefile) where the six traffic levels are identified with different colors according with traffic level. For each skid trail segment, the layer's attribute table includes the coordinates (x,y,z) of the start and end of each segment, the number of machine passes, the average travel speed (m/s) during the loaded and empty trips, the average slope (%) extracted from the elevation of the positional data, the average slope (%) extracted from the digital terrain model, its length (m). Optionally, a layer with the sampling points at each of the six traffic levels is also provided, when the sampling points parameter is greater than zero. The layer's attribute table incorporates the unique identifier number of the point and two additional columns with its coordinates.

2.2. Application of the computational tool

To evaluate the development and application of the tool, a test was conducted in the *Los Pinos* forest tract, property of the *Universidad Austral de Chile*, located 18 km north of Valdivia along Route 202, Los Ríos Region, Chile (73.169211° W and 39.735874° S – Fig. 4). The area used for the test was a 23-year-old *P. radiata* plantation stand of 17.97 ha in size harvested during the summer of 2022. In the summer of 2023, 1,317 m of skid trails used were field mapped. Fifty-four control points (Fig. 4a) were established along the used skid trail network placed at a maximum distance of 30 m or at each change of slope, direction, and intersections. The sub-meter position of each control point was obtained using an EMLID REACH RS2 GNSS receiver in rover mode along a fixed control station with the same type of receiver located in the landing. The location of the control station was pre-determined with under a 1 cm accuracy using a differential post-processing routine and a known base station located 20 km away (data of the station).

Along the skid trail network and based on the feasibility of allowing a 4x4 truck to turn around, 24 control points were selected as log pile locations to simulate their skidding to the log landing (Fig. 4b). At these points, 1, 2, and 3 log piles were simulated randomly in a 3:4:3 ratio (numbers in blue in Fig. 4b). In this way, 27 skid trail sections with a predetermined number of loaded machine passes (skidding cycles) were

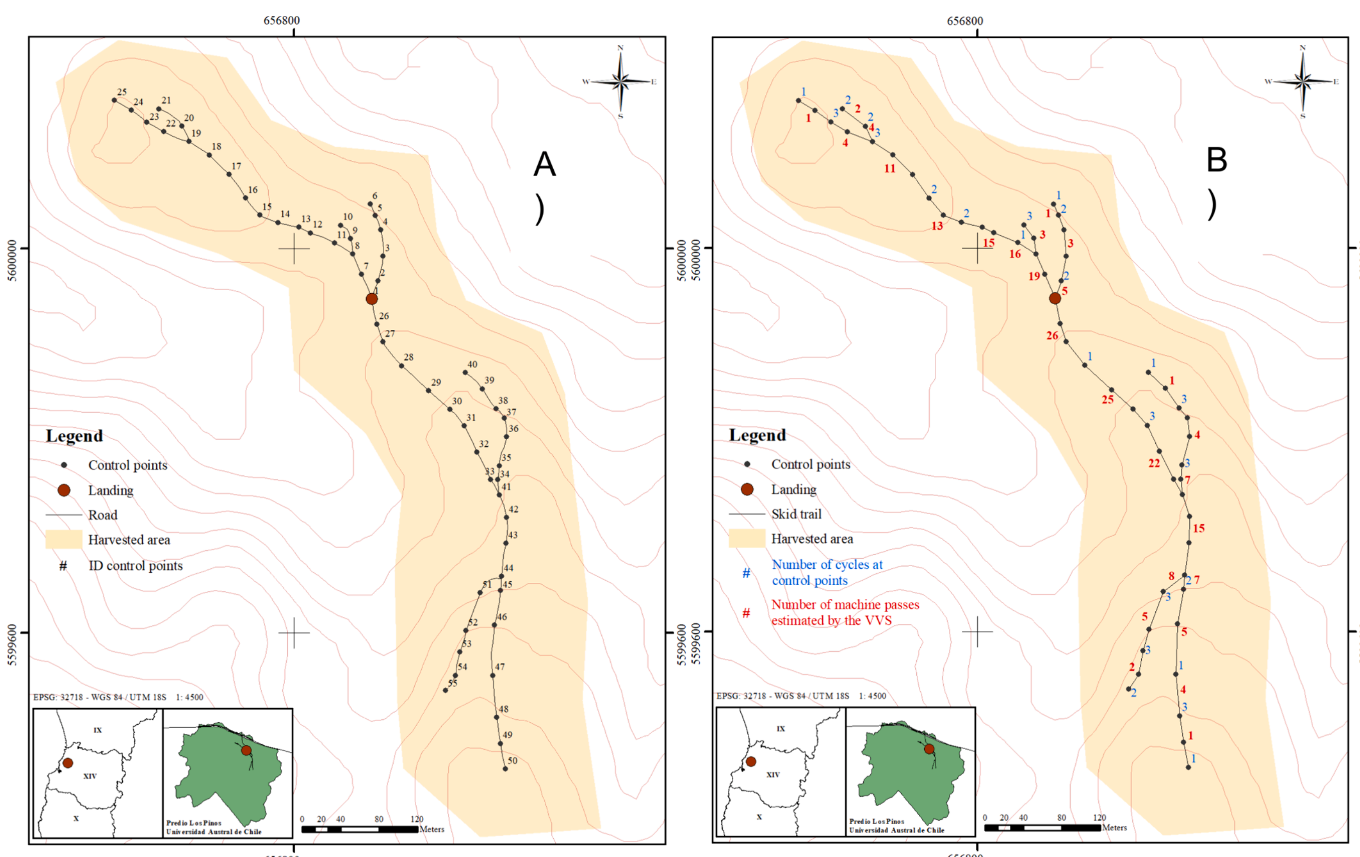

Fig. 4. Area used to test the application of the tool, with the location of the 54 control points (A), and the simulated log pile locations and number of machine passes per skid trail segment (B).

generated to simulate 50 skidding cycles and obtain at least two sections (one on each side of the landing) with more than 25 cycles. The simulated skidding was conducted using 4x4 truck that travelled from the landing to each log pile location simulating the skidding of 1 to 3 cycles according to the number of log piles. The movement of the vehicle was captured using an EMLID REACH RS2 GNSS receiver mounted on the cab of the vehicle in rover mode corrected by a stationary base located at the landing and with a capture frequency of 0.2 s.

2.3. Results evaluation

The first evaluation involved comparing the field-mapped skid trail network composed of 54 control points with the representation of the skid trail network generated by the tool. For this comparison, the Euclidean distance from each control point closest skid trail segment generated by the tool was used to measure the deviation from the field-mapped network. Thereafter, the number of pre-established cycles along the 27 segments, formed by 24 control points considered as log pile locations, and the estimation of the number of cycles made with the tool were compared, for which a standard paired *t*-test was used.

2.4. Accuracy and capture frequency evaluation of the positional data

To identify thresholds of accuracy and data capture frequency needed to represent skid trail networks and estimate the traffic level adequately, the original positional data set obtained from the GNSS receiver mounted on the 4x4 truck during the test was used. First, less accurate positional data was simulated by introducing disturbances to the original coordinates using two random numbers; one number between 0° and 360° to determine the direction offset, and another to determine the maximum offset distance, considering three values: 1, 3 and 5 m. In addition, a lower frequency of data capture was simulated considering only positions from the original data set every 1, 3, 5, 10, and 20 s. Consequently, 24 positional data sets with different precision and capture frequency were generated: 4 accuracy levels and 6 capture frequencies, with 23 simulated data sets plus the original dataset. Finally, the tool was applied to each dataset to evaluate the quality of the skid trail network layout as well as the estimated traffic level.

3. Results

3.1. Application of the computerized tool

After installing STV in ArcMap, it is displayed as a button integrated to the program menu (green circle in Fig. 5) that, when pressed, opens its graphical user interface (drop-down window in Fig. 5). The four required digital layers (DTM, harvested area, landing, and positional data) (red boxes in Fig. 5) and the values for the six general parameters (blue box in Fig. 5) were loaded into the interface. The positional data captured by the GNSS receiver mounted on the 4x4 truck during the trial to monitor the vehicle's movement during logging of the 50 cycles had a duration of 3 hr 11 min and 56 sec. With a position capture frequency of 0.2 sec, a database of 57,581 points was generated (brown box in Fig. 5). As the receiver position was corrected in real time, the average accuracy of the positions captured by the GNSS receiver was 0.09 m.

The tool took 5 s to process the data and generate the results (Fig. 6). For the test, the total length of the generated skid trail network was 1334.6 m, 17.67 m longer than the field-mapped skid trail network. Based on the segment length parameter, the skid trail network is formed of 2,267 segments of approximately 5 m. Considering a constant skid trail width of 3.5 m, the area covered by the network was 0.4 ha, resulting in 2.69 % area impacted. This metric is relatively small as only skid trails were mapped and the paths used by the felling machine to forward logs closer to skid trails during the harvesting operation were

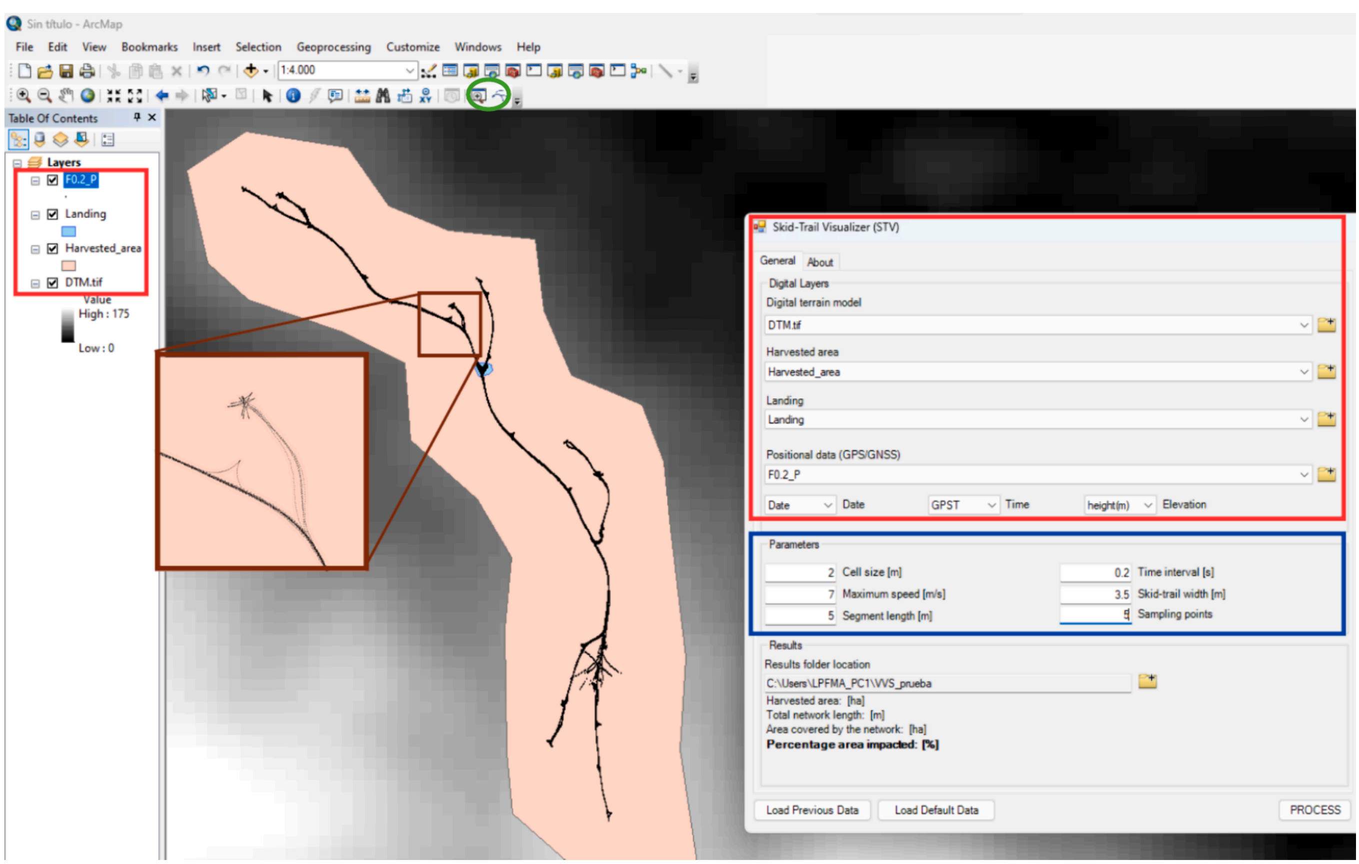

Fig. 5. Input data (digital layers and parameters) loaded into the graphic user interface of the computational tool.

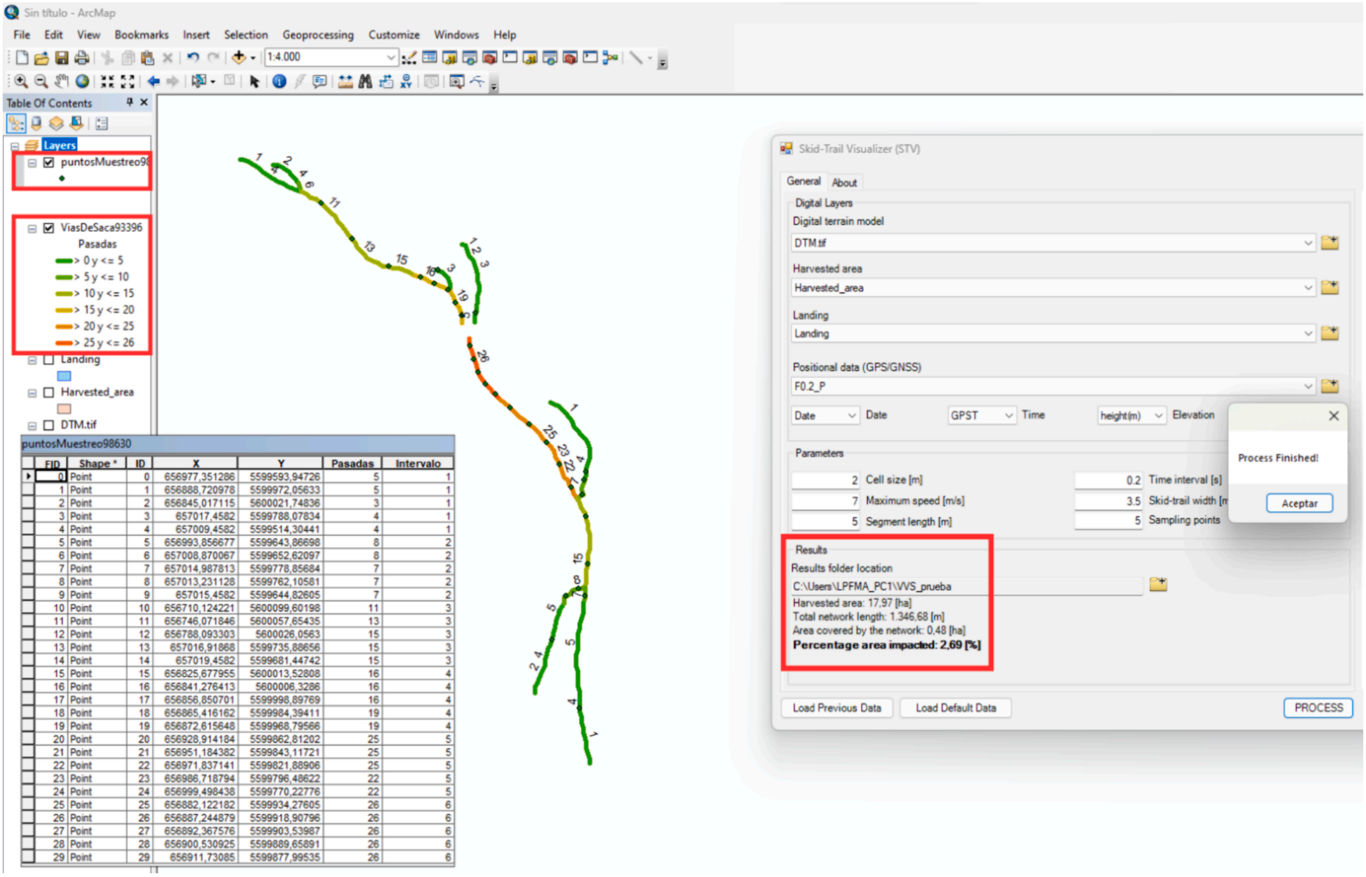

Fig. 6. Results generated by the computational tool.

not considered.

The generated skid trail network layer was automatically loaded onto the ArcMap table of contents with segments classified according to the six traffic levels (Fig. 6). The attribute table of the skid trail network layer contains the start and end coordinates, the number of passes (shown in the skid trail layer labels), and the traffic intensity category to which each segment belongs. Finally, according to the parameter value of five sampling points, a layer with 30 potential sampling points systematically located in each traffic category was generated and loaded to the table of contents.

3.2. Accuracy and capture frequency evaluation of the positional data

As the length of the generated skid trail network affects the area impacted, it is important to understand how data accuracy and capture frequency affect skid trail network length. In general, results show that capture data frequency has a greater effect than the accuracy on the total length of the network. However, the average differences between the field-mapped and tool-estimated total lengths are close to only −0.5 % (5.8 m). The largest difference occurred for capture frequencies of one position every 20 s, being −4.58 % or – 60.4 m (Table 1). Considering total network length differences within 1 % independent of the positional data accuracy, a capture frequency of one position every 5 s seems appropriate. This would result in a database approximately 25 times smaller (2,300 vs 57,851 positions) than the original, which would facilitate data manipulation, especially for more extensive, long-term monitoring. Lower capture frequencies (one position every 10 or 20 s) tend to underestimate the total length.

Regarding the effect on the skid trail network representation, in general for the accuracy and capture frequency values considered, the average deviation distance from the 54 control points to the tool-generated layout ranged from 0.66 to 3.14 m, with an average of 1.41 m (Table 2). Again, results show that the capture frequency has a greater effect than the accuracy of the GNSS receiver on the skid trail representation. For all capture frequency values, decreasing the GNSS receiver accuracy from 0.09 m to a maximum of 5 m only slightly

Table 1
Percentage of total length differences between the field-mapped and tool-generated skid trail network for the accuracy and capture frequency values considered in the analysis.

Accuracy (m)	Capture Frequency (s)					
	0,2	1	3	5	10	20
0.09	1.07	0.84	0.06	0.32	−2.03	−4.58
1	0.20	0.44	0.39	−0.29	−1.58	−3.67
3	1.16	0.68	0.96	−0.33	−1.25	−2.25
5	0.15	−0.17	1.25	0.95	−0.26	−2.78

Table 2
Average deviation distance (st. dev.) between the 54 control points and the skid trail segments generated by the tool for the accuracy and capture frequency values considered in the analysis.

Accuracy (m)	Capture Frequency (s)					
	0.2	1	3	5	10	20
0.09	0.85 (0.89)	0.91 (0.90)	1.05 (0.96)	0.99 (0.78)	1.54 (1.49)	3.14 (2.46)
1	0.81 (0.87)	0.66 (0.66)	0.82 (0.86)	0.96 (0.89)	1.68 (2.07)	3.13 (2.51)
3	1.35 (0.55)	0.85 (0.72)	0.94 (0.97)	1.11 (1.33)	1.26 (1.12)	2.94 (2.34)
5	1.13 (1.51)	1.15 (1.43)	1.00 (0.72)	1.14 (0.90)	1.42 (1.39)	3.01 (2.44)

increases the average deviation distance between the control points and the tool-generated network. On the other hand, for all accuracy levels, the decrease in the capture frequency increased the average deviation distance from about 1 m, for a position every 0.2 s, to about 3 m for a position every 20 s. Considering an average deviation distance close to 1 m desirable, a capture frequency of one position every 5 s seems appropriate.

The accuracy of the global positioning receiver and the frequency of data capture positions did not have a significant effect on the estimation of the traffic level. For the cases analyzed, the difference in the average number of passes did not exceed one pass (Table 3). In one of the cases, the number of passes was slightly overestimated with a maximum of 0.63 passes, and in 29.6 % of the cases, it was underestimated by a maximum of 0.11 passes. The paired sample comparison of the number of passes for the 24 skid trail segments resulted in two p-values < 0.05 for the combination of 5 m accuracy and capture frequency of 0.2 and 1 s, indicating significant differences, but still less than one pass.

4. Discussion

The tool reconstructed skid trail networks and estimated the traffic level accurately for all cases analysed. As for the graphical representation, the length of the networks generated for the 23 simulated cases did not differ by more than 5 % compared with the original dataset, and the average deviation between the control points and the tool-generated skid trail segments did not exceed 3.14 m, indicating high reliability of the results. The tree-like shape of the field-mapped skid trail network is relatively simple, but it is representative of the operations that use planned skid trails, which are widely recommended for ground-based forest harvesting (CONAF, 2021; FSC, 2015). Future assessments could incorporate the use of the tool to recreate unplanned logging roads, which often have multiple circuits and parallel or even overlapping skid trails.

For the field test, the estimated percentage of the area impacted is relatively small because not all skid trails used in the actual operation were mapped, only those where it was still feasible to drive a 4x4 truck. Additionally, the paths followed by the felling machine to forward logs closer to the main skid trails during the harvesting operation were not mapped. However, the functionality of the tool to estimate the percentage of the area impacted works adequately, which is a useful metric for measuring and monitoring the impact on the ground. Moreover, the tool considers a constant skid trail width which may vary with traffic intensity, whereas skid trails with a higher number of passes may have wider skid trails. However, if the relationship between skid trail width and traffic intensity is known, the impacted area can be easily calculated in the attribute table generated by the tool.

Regarding the traffic level, the differences with the field collected data did not exceed one pass in all cases, with no significant differences, except for the less accurate (5 m) and higher capture frequencies (one position every 0.2 and 1 s) datasets. This is because when positions are collected with low precision the tracing may follow a zigzagging pattern, not only from side to side but also forward and backward. Consequently, it is recommended to consider using capture frequencies according to the precision of the receivers. Capturing positions with short time intervals (i.e., < 5 s) using low-precision GPS/GNSS receivers should be avoided because the data patterns might overestimate the number of passes. Our results suggest using a 5 s data capture frequency, independent of the accuracy levels tested. For example, some of the early work on the subject (Veal et al. 2001, McDonald et al. 2002, and McDonald and Fulton 2005), which used 1 and 2 s intervals, indicated that time intervals greater than 2 s would not negatively affect the capture of skidder motion, since their travels tend to be in straight lines without sharp turns. On the other hand, Cordero et al. (2006) point out that times longer than 10 s are ineffective for accurately determining the path of the machinery.

To test the application of the tool, positions were captured with a sub-metric receiver corrected in real-time with a fixed base to improve its accuracy, obtaining a planimetric accuracy of 9 cm. To simulate the use of lower accuracy receivers (3–5 m), such as those typically mounted on forestry machinery to monitor their movement, we simulated its data by introducing perturbations. This approach may not be representative of data captured with lower accuracy receivers and it would be advisable for future evaluations to use receivers of different quality. However, receiver accuracy does not appear to have a major effect on the layout of the skid trails and the traffic level estimation. Additionally, studies that evaluated the accuracy of GPS equipment in different canopy cover conditions (Veal et al. 2001, Cordero et al. 2006; Wing et al. 2008) conclude that the best accuracy is under open sky environments, such as the conditions in which skidders work, which makes it possible to use lower cost equipment for these operations (Danskin et al. 2009).

Furthermore, several studies using receivers mounted on the harvesting machines capture positions every 30 s (Strandgard and Mitchell 2015). According to our analysis, this data capture frequency does not seem appropriate with results suggesting a frequency of 5 s. Defining the frequency of data capture frequency is important before installing receivers because it affects file size, which might not be a problem for monitoring one machine, but could be an important factor to consider for companies with dozens of simultaneous harvesting sites, such as large companies in Chile, with multiple machines operating at each site, all of which must also be monitored simultaneously.

It is useful to have a tool that facilitates identifying the location of potential sampling points for measuring and monitoring post-harvest impacts, especially as they relate to the number of machine passes. If there are known relationships between the number of machine passes and soil impacts, additional changes can be made to the attribute table to map rutting depth or changes in bulk density or porosity. Mapping the impact of skid trail networks as a function of traffic intensity would be beneficial to aid site preparation treatment activities during site clearance and preparation for the next rotation, thus meeting legal and paralegal requirements. These requirements generate the need to monitor timber harvesting operations, adopt corrective actions for site remediation according to the intensity of the impact detected, and envision additional corrective actions for improvements in future operations if needed.

Finally, although the commercial ArcMap® software is the standard in the forest industry, other freely available geographic information systems (QGIS®, Global Mapper®, Avenza Maps®) and mapping systems (Google Maps® or Bing Maps®) are becoming increasingly popular. Consequently, future versions of the tool can also be implemented in these systems to facilitate its use.

5. Conclusions

The tool developed can successfully reconstruct skid trail networks used by ground-based timber harvesting machines in terms of location, network length, and traffic level. The tool's functionality to estimate the area impacted is useful as a way of estimating the geographic extent of

Table 3
Average difference (*p-value*) between the field-test and tool-generated number of machine passes for the 27 skid trail segments for the accuracy and capture frequency values considered in the analysis.

Accuracy (m)	Capture Frequency (s)					
	0,2	1	3	5	10	20
0.09	−0.16 (0.168)	−0.19 (0.105)	−0.16 (0.177)	−0.10 (0.360)	−0.17 (0.434)	0.03 (0.870)
1	−0.14 (0.253)	−0.10 (0.406)	−0.14 (0.183)	−0.11 (0.423)	0.08 (0.626)	−0.08 (0.706)
3	−0.20 (0.106)	−0.23 (0.069)	−0.17 (0.189)	−0.36 (0.086)	0.03 (0.845)	0.00 (0.985)
5	−0.63 (0.004)	−0.36 (0.023)	−0.28 (0.077)	−0.36 (0.144)	0.11 (0.536)	0.08 (0.614)

impacts to the ground. In addition, it is useful to identify possible locations, on a systematically random and balanced basis, where to measure soil impacts based on the number of machine passes and thus facilitate monitoring and soil treatment for site preparation activities.

The evaluation of the receiver accuracy indicates that it has a slight effect on the quality of the skid trail layout and does not affect the estimation of traffic levels. On the other hand, the frequency of data capture has a greater effect on the quality of the layout, although the deviations do not exceed 3 m, which is smaller than the size of the skidding machine itself. There was also no effect on the estimates of the number of machine passes. From this analysis, a capture frequency of one point every 5 s is recommended to generate a skid trail network with a deviation from control points close to 1 m and to balance the volume of data obtained from the global positioning receivers. Additionally, it is suggested to use capture frequencies according to the accuracy of the equipment, so that higher frequencies (<one every 5 s) are suggested only for receivers with high accuracy.

CRediT authorship contribution statement

Marco Contreras: Writing – review & editing, Supervision, Project administration, Investigation, Formal analysis, Conceptualization. **Christopher Parra:** Writing – original draft, Visualization, Validation, Methodology, Data curation. **Cristian Cárdenas:** Software, Methodology, Formal analysis. **Carlos Hermosilla:** Software, Methodology, Formal analysis. **Ricardo Pastén:** Validation, Methodology, Data curation. **Darío Aedo:** Writing – original draft, Methodology, Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Marco Contreras reports financial support was provided by National Agency for Research and Development. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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