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Predicting Tree Felling Direction Using Path Distance Back Link in Geographic Information Systems (GIS)

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Abstract

Directional felling is a felling method practised by the Forestry Department in Peninsular Malaysia as prescribed in Field Work Manual (1997) for Selective Management Systems (SMS) in forest harvesting. Determining the direction of tree felling in Peninsular Malaysia is conducted during the pre-felling inventory 1 to 2 years before the felling operation. This study aimed to predict and analyze the direction of tree felling using the vector-based path distance back link method in Geographic Information Systems (GIS) and compare it with the felling direction observed on the ground. The study area is at Balah Forest Reserve, Kelantan, Peninsular Malaysia. A Path Distance Back Link (spatial analyst) function in ArcGIS Pro 3.0 was used in predicting tree felling direction. Meanwhile, a binary classification was used to compare the felling direction estimated using GIS and the tree felling direction observed on the ground. Results revealed that 61.3% of 31 trees predicted using the vector-based projection method were similar to the felling direction observed on the ground. It is important to note that dynamic changes of natural constraints might occur in the middle of tree felling operation, such as weather problems, wind speed, and unpredicted tree falling direction.

Key Words: reduced impact logging, directional felling, prediction, vector-based projection, GIS-path distance back link

Introduction

Currently, forest harvesting in Peninsular Malaysia is practising Selective Management System (SMS), which was implemented in 1978. SMS allows a selection system for non-dipterocarp and dipterocarp tree species with a minimum cutting limit is 45 cm diameter at breast height (dbh) and 50 cm dbh, respectively. In forest harvesting, reduced-impact logging (RIL) is widely anticipated to maximize conservation values and the extent of damage to residual stands and soil. Directional felling means felling a tree in a predetermined direction to facilitate the skidding process, to avoid damage to residual stand and allow a safe escape path for fellers (Marsh et al. 1996; Sist et al. 1998; Cedergren et al. 2002; Krueger 2004; Mohd Zaki et al. 2013). According to Nikooy et al. (2013), the direction of tree fall is one of the influencing factors on the production rate in the skidding process. It is important, especially for larger trees that make skidding operation easier and faster. It can also have an impact on the quality of timber and re-

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sidual stand.

Practically, directional felling is determined during pre-felling (Pre-F) inventory. The primary concern among loggers is minimum felling error, especially in selective logging systems. In this respect, the predetermined felling direction depends on foresters' skill to set guidelines for choosing a felling direction. In the Manual of Forest Road Specifications for Peninsular Malaysia 1999, the implementation of directional felling should be directing the canopy of tree fall toward the skid trail to ease the extraction process. Therefore, the proper planning and locating of skid trails are vital since it makes the job more productive, and economically feasible and could facilitate directional felling. According to Cedergren et al. (2002), the felling of trees and the hauling of logs to landing sites are the two major direct sources of logging damage. Damage to trees is unavoidable during the felling phase, however expertly felled, the log must fall somewhere, and must, somehow, be hauled to a landing.

The directional felling technique has been studied by several researchers (Srivastava 1982; Pinard et al. 1995; Johns et al. 1996; Cedergren et al. 2002; Nikooy 2007; Nikooy et al. 2013). Pinard et al. (1995) found that fellers could fell trees whiting 10° of marked direction but did not record whether this angle reduced damages. However, it must be assumed that damages to the surrounding trees could be minimized if it is possible to fall a tree in a predetermined direction. In addition, directional felling in combination with other measures such as the use of planned skid trails can minimize damage. Nikooy et al. (2013) conducted a study of directional felling in the Caspian Forest, Iran. Only 52% of 135 trees were felled within 20° of the specified direction. Following these rules, a subsequent study by Cedergren et al. (2002) found that 78% of harvested trees could be felled within 20° of the desired path, and only 10% of them fell above 60° outside the desired lay. He also found that 94% of selected trees for retention could be saved. Meanwhile, Mohd Hasmadi et al. (2013) found that 12 out of 66 trees were felled in the right direction determined from pre-F inventory and other trees were not in compliance where the angle of felling varies from 10° to 23°.

Balancing the quality of the felling tree in terms of volume and potential impacts on the following trees (such as gap creation, broken felled trees, residual damage, etc.) while considering the safety during felling works require thoughtful planning during pre-determining the direction of the tree felling. Moreover, directional felling facilitates skidding since the extraction distance can be shortened (Marsh et al. 1996). The safety of forestry workers, which is a major problem in tropical forestry (Blombäck 2002), can also be enhanced by using the directional felling technique. Laying out the direction of tree felling to the exit points such as feeder roads and log landings is implemented manually by the forestry department, which is based on tree distributions and road networks plan map. Some constraints for a safe felling direction and feller safety are probably overlooked as extra time is needed for repeated evaluation and assessment of finding the safer direction. Additionally, inadequate spatial forest area and stand distribution information during the pre-determining of the felling direction will cause an error in felling work.

Geographic Information System (GIS) provides plenty of beneficial techniques and captures huge information on forest areas. GIS is a computer-based information system used to digitally represent and analyze the earth's surface's geographic attributes (Chang 2008). The GIS demonstrates the advances in the information system and the various methods of decision-making, analysis, and optimization, which highlights the importance of research on forest operations with different variables and methodologies (Grigolato et al. 2017; Rahmawaty et al. 2020). In fact, GIS gives detailed information on spatial forest areas, including terrain attributes, and makes a quick evaluation and analysis for safe felling direction. Therefore, the predetermined tree felling direction can be projected using GIS. Additionally, any potential impact on vegetation and feller safety could be predicted preceding the timber harvesting operation. Thus, this study aimed to predict and analyze the direction of tree felling using the path distance back link method in GIS and compare it with the felling direction observed on the ground. The "path distance back link method" in GIS is an operation that determines the connectivity between locations based on the shortest path distance. This method involves calculating the distances between neighbouring. The backlink refers to the identification of the previous or upstream node or cell that leads to the current node or cell in the shortest path (Ou et al. 2022).

Materials and Methods

Study area

This study was conducted at Kompleks Perkayuan Kelantan Sdn. Bhd. (KPKSB) located in the Gua Musang District, Kelantan State, Peninsular Malaysia (Fig. 1). KPKSB was established in 1979 and began its operation as a logging company in 1980 with a total of 5,747 ha of concession area in Kuala Krai South. Data were collected at 144.0 ha in Compartment 30 of Balah Forest Reserve at latitude 5°18'4049 N and 101°45'29.52 E. A total of 5,744.12 m feeder roads were constructed in the harvestable block connected by 24 temporary log landings. The highest elevation in the compartment is recorded at 1,313 m with a slope gradient ranging between 0.6° to 40°.

Data collection

The map of the harvesting plan was obtained from the GIS Unit of the Forestry Section in KPKSB. This unit was responsible for preparing timber harvesting area planning maps, road maps, and tree-tagged maps. The given map shows the spatial features of the operation unit attributed with a 20 m elevation interval. Harvesting operation was described to be conducted within 500 m to 1,000 m elevation, and a buffer zone was demarcated to be 20 m away from the stream. Skid trails were planned and constructed within a maximum limit of 300 m subjected to prescriptions listed by the forestry department. During operation, unexpected stream weather may occur, such as heavy rain, and sudden changes to the scheduled plan may exist for workers' safety and reduce possible negative impacts. The operation may remain inactive until forest roads are getting dry, and fellers will resume their work once the working environment has been certified safe by forest managers.

Field data collection was specifically carried out at proximity 300 m from log landing number two located at 586, 205.80 N and 411, 479.95 E. A tree felling team consists of three persons responsible for harvesting the timbers, and they are a feller and his assistant and an operator who takes the fallen trees to log landing. The direction of tree felling observed on the ground was recorded using a compass. A total of 33 tree falls were observed during the felling operation, and direction was recorded in azimuth bearing, which was converted into an aspect map to make it compatible with the spatial map. Table 1 shows the conversion matrix from azimuth bearing to the direction of the aspect map. For example, the felling direction of a treatment tree was recorded as 15° during the felling operation. By looking at the conversion matrix, 15° was within the north direction, and thus, during the spatial analyses, this treatment tree was treated as falling toward the north direction. Details explanation regarding the direction of felling determination and comparison was presented in section 3.5.3 - the binary classification. In addition, the attribute of the falling trees was recorded, such as tagging numbers, dbh (cm), tree location, and lean tree direction.

Methods

Five main processes were conducted to achieve this study's objective: spatial data creation, constraint map de-

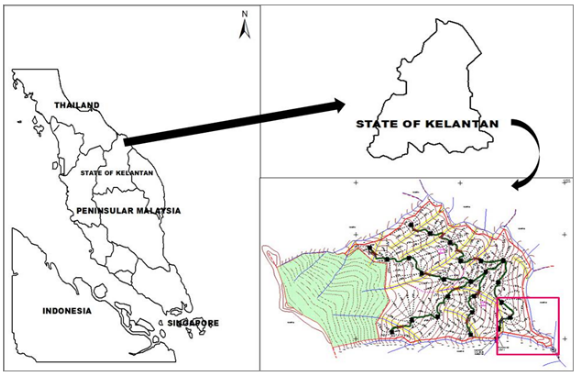

Fig. 1. The red box showing the location of the study area at Compartment 30, Balah Forest Reserve, Kelantan, Peninsular Malaysia.

Table 1. Matrix of slope-bearing conversion from azimuth to the direction of the aspect

Aspect	In degree (°)
Flat	-1
North	0-22.5
	337.5-360
Northeast	22.5-67.5
East	67.5-112.5
Southeast	112.5-157.5
South	157.5-202.5
Southwest	202.5-247.5
West	247.5-292.5
Northwest	292.5-337.5

velopment, grid vector data projection, spatial analysis, and output. The flow chart of the study is illustrated in Fig. 2.

Spatial data creation

Selected layers including slopes, skid trails, and the river were utilized to estimate the appropriate and safe direction for tree felling. These layers were obtained from the forest operation map and topographical map provided by the logging company Kompleks Perkayuan Kelantan Sdn. Bhd. Digitization of these layers was performed using the 'create new shapefile' and 'editor' functions in ArcGIS. To facilitate the digitizing process, all layers were projected to the Kertau RSO Malaya meter coordinate reference system, enabling better overlaying of the layers. A digital elevation model (DEM) was generated to assess the spatial topography of forest areas. The process involved extracting contour lines from a shapefile (*.shp) with 20 m intervals. The 'topo to raster' function in ArcMap was utilized for this purpose, resulting in the development of a 10 m resolution DEM. The resulting DEM provided a visual representation of the availability and distribution of forested areas in a digital format.

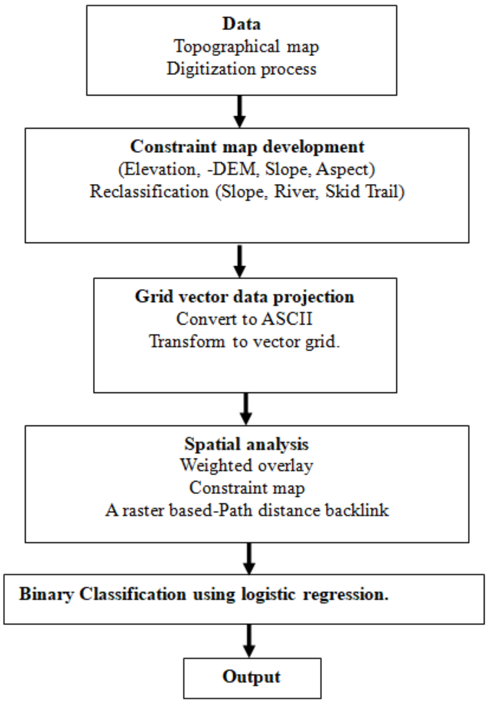

Fig. 2. Flow chart of the methodology applied in this study.

Among the selected factors, the slope was considered to control the selection of harvestable trees within the prescribed slope limit for environmentally conscious timber harvesting operations that can be reached by harvesting machines (Norizah 2012). The skid trail was defined to facilitate the extraction process with minimal impact on soils and residual vegetation, while aiming for high productivity. Similarly, the river was taken into account as a measure to safeguard water quality by preventing soil erosion and sedimentation (Mohd Hasmadi 2005).

Subsequently, the selected three layers were rasterized to a 10-m resolution. As each layer contained multiple attributes, the values assigned to each grid cell could vary significantly, ranging from zero to potentially hundreds or thousands. Standardization was necessary to ensure accurate overlaying of these layers. Consequently, the diverse range of values was condensed into three classes, with each class assigned a new value: 1 for highly suitable areas, 2 for moderately suitable areas, and 3 for unsuitable areas. In the context of this study, suitable areas referred to those directing the treatment trees to be felled safely.

The slope map was reclassified into three classes based on the working ability of bulldozers to access felling trees (Mohd Paiz and Wan Mohd Shukri 2003; Norizah 2012) and the safety considerations for fellers working in rugged terrain conditions (Peters 1991; Slappendel et al. 1993). Similarly, the skid trail and river layers were reclassified into three classes based on their proximity to the treatment tree's location. The reclassification of the three selected layers, namely slope, skid trail, and river, to determine the appro-

Table 2. Reclassification made for three selected layers to estimate the appropriate and safe tree felling direction

Spatial layer	Value classes	Verbal description	An attribute of new reclassification
Slope	1	Highly suitable	<20°
	2	Moderately suitable	21-40°
	3	Not suitable	>40°
Skid trail	1	Highly suitable	<50 m
	2	Moderately suitable	50-200 m
	3	Not suitable	>200 m
River	1	Highly suitable	>75 m
	2	Moderately suitable	25-75 m
	3	Not suitable	<25 m

priate and safe direction for tree felling, was conducted in accordance with the guidelines provided by the Forestry Department of Peninsular Malaysia. Further details on the classification of the three layers are summarized in Table 2.

Constraints map development

Each grid cell (i.e., node) in the raster map has a value representing score weight. The values were derived from the attribute of selected layers. All three selected layers were combined using the 'weight overlay' function, and the new layer was called the constraints map. A Constraint map was developed to estimate the possible direction of the fall of a tree in a safe way subject to reducing damage to following trees and gaps of canopy opening, reducing the percentage of broken and/or defects of timber well as for workers' safety. In order to define the suitable area for the felling direction, the three reclassified raster maps were overlaid with the 'weight overlay' function in a GIS. The weight to combine these layers was prorated to simplify the problem formulation and summed up to be equal to 100. The following equation shows how the weights were computed. Thus, a constraints map was developed.

$$[(\text{Slope layer}\times 33.333)+(\text{Skid trail}\times 33.333)+(\text{River layer}\times 33.333)]$$

Therefore, this constraint map was converted to DEM, and the new value created was used to estimate the safe felling direction of treatment trees from their stump site to possible log landing.

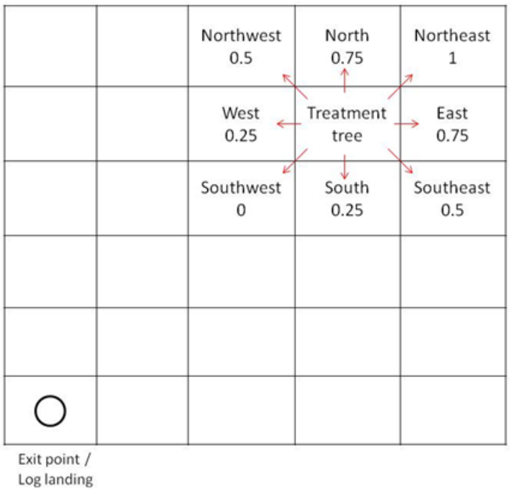

Fig. 3. The principle of predetermining the direction of tree felling with the direction of the aspect map was used as the baseline.

Grid vector data projection

Once the constraints map was developed, merge analysis was conducted to combine the grid cells of the constraints map with grid cells of the treatment tree and log landing. Prior to that, layers of the treatment tree and log landing were converted to raster layers to have the grid cells value. Later, the new merged grid cells (constraint map, treatment tree, and log landing) were projected into ASCII format. The ASCII file was examined in Excel software, and a set of links between two adjacent nodes was created. How the connection between the two nodes was made was based on graph theory (Foulds 1992). The two adjacent nodes represent 1) from-node and 2) to-node. These nodes have their unique node label (i.e., T1, T2, T3) so that the next analysis to calculate the cost distance from a node to node can be linked to the identified node with the least costs. Along with these two criteria, two additional criteria were added to link, which is from-node to to-node: variable constraints and fixed constraints.

The value of variable constraint was acquired from the value derived from the constraint map, and the fixed constraint value was determined based on the lean direction of the treatment tree, which was recorded from the groundworks and river crossing. The river crossing was set as a fixed value because no skid trail can be constructed by crossing the river. For river crossing, value 1 was given for nodes with no river network, while value 2 was given for nodes that have a river. Fixed values for lean direction were given based on the weight ranging from 0 to 1 at 8 potential

Table 3. Weight ranges values for fixed constraint and justification

Weight range (%)	Justification
0-0.25	Force to fall towards skid trail
0.5	A tree can fall towards a skid trail with high mitigation measures and proper felling method (Mohd Zaki et al. 2013)
0.75-1	Let trees fall towards natural lean to avoid any risks to fellers and the workers to protect against potential negative impact

directions adjacent to the treatment tree node. These eight possible directions were determined according to an oblique angle of 45° in between the treatment tree and log landing as a measure of safe felling direction (Forshed et al. 2008). The direction from the aspect was used as the baseline to determine the direction of tree felling. The example of how the fixed constraint value of lean direction was given at 8 directions as illustrated in Fig. 3 and Table 3 presents the justification given to the specific direction.

Spatial analysis

A raster based-Path distance back link approach was performed to predict the tree felling direction using the link created from the ASCII file. Back link calculation is an algorithm to find the shortest distance between two points introduced by Dijkstra (1959). This analysis was performed with the 'path distance back link' function in the spatial analysis of ArcGIS. The result from the back link calculation then determined the estimated direction of the safe tree felling direction by looking at the fixed constraint value of the first node linked from the treatment tree node to the log landing. It defines the next cell's neighbour on the least accumulative cost path or direction to the least-cost source while accounting for a surface distance along with horizontal and vertical cost factors.

Binary classification

Binary classification is a supervised learning problem to predict whether a piece of the geospatial environment falls into one category or another. The dataset was labelled and needed to train the binary classifier on it. The method used for binary classification is the logistic regression model. Logistic regression is a statistical model that, in its basic form, uses a logistic function to model a binary dependent variable, although many more complex extensions exist. In regression analysis, logistic regression (Tolles and Meurer 2016) estimates the parameters of a logistic model (a form of binary regression). Mathematically, a binary logistic model has a dependent variable with two possible values, such as pass/fail, represented by an indicator variable, where the two values are labelled "0" and "1". The binary classification test was applied to compare the similarities of the felling direction between the predicted felling direction and the on-ground felling direction. If the felling direction for both environments is similar, the test result will be valued as 1 while 0 for different felling directions.

Results and Discussion

Individual tree location on DEM

The visualization of the forest area was achieved by utilizing a Digital Elevation Model (DEM) with a resolution of 10 m. This DEM allowed for the representation of the topographical features of the forest in a digital format. In addition, the positions of the individual trees earmarked for harvesting were overlaid onto the DEM surfaces. This integration facilitated the visualization of tree distribution based on their specific locations and the characteristics of the slopes on which they were situated.

By analyzing the DEM alongside the tree locations, it became feasible to anticipate the direction in which each individual tree would fall during the felling process. The analysis of the distribution of trees to be felled on the DEM encompassed various elevations, spanning from 530 m to 650 m. Notably, the selected tree for felling was situated in an area below an elevation of 600 m above sea level.

Using this valuable information, a planning map was generated to indicate the directional felling directions for the identified individual trees. This map offers a comprehensive overview of the expected felling directions, taking into account the interplay between the DEM results and the specific tree locations. Fig. 4 provides a visual representation of these results, effectively illustrating the spatial relationship between the DEM and the designated trees slated for harvesting.

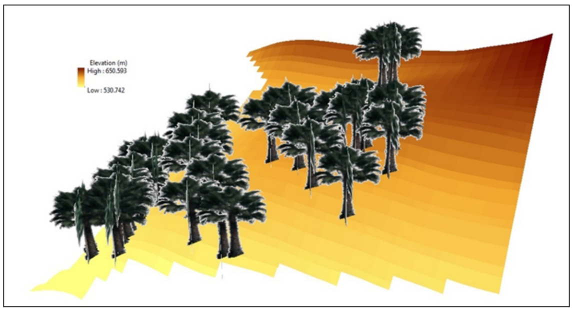

Fig. 4. The distribution of trees to be felled on the DEM was analyzed across various elevations, ranging from 530 m to 650 m.

The range of elevation where the trees were mapped is between 520 m to 660 m. The forest type is classified as hill dipterocarp forest. A total of 31 trees were mapped on the DEM. In the area, *Canarium* spp. (Kedondong) *Cinnamomum* spp. (Medang) and *Bombax valetonii* (Kekabu Hutan) were dominant trees with dbh above 50 cm. In 3D view, some trees had been identified in and near steep terrain areas. In that situation, managers or fellers may need to plan the proper cutting and safety exit if the predicted felling direction is uphill. The tree may fall reversely downhill if the tree canopy is linked to lianas from neighbouring trees. The unpredictable changing of felling direction may course the feller's safety at risk.

Predicting felling direction

The result of the backlink calculation is summarized in Table 4, which provides valuable insights into the predicted felling directions for the trees. The analysis revealed that out of the total number of trees assessed, five trees were directed to fall towards the skid trail, as depicted in Fig. 5. These trees were determined to have a natural lean that aligned with the skid trail direction, making it a suitable and efficient choice for their felling.

Additionally, twelve trees were identified as requiring

Table 4. The summary of felling direction estimated from vector-based back link projection method

No. of tree	Lean direction	Felling direction (observed on the ground)	Predicted felling direction (by using a GIS-back link)
1	S	N	SE
2	S	W	SE
3	S	E	S
4	SE	E	SW
5	E	E	NW
6	SE	E	SW
7	S	S	NE
8	SE	SE	SW
9	E	E	SW
10	SE	E	NW
11	SE	NE	SW
12	SE	NE	SW
13	SE	N	SW
14	NE	NE	NW
15	N	E	W
16	NE	NE	SW
17	E	E	SW
18	NE	NE	N
19	SE	SE	SW
20	SE	SE	SW
21	E	N	NW
22	E	E	W
23	S	E	SW
24	SE	E	W
25	SE	E	SW
26	E	E	NW
27	NE	NE	NW
28	E	E	SW
29	E	N	NW
30	E	N	W
31	N	NE	SW

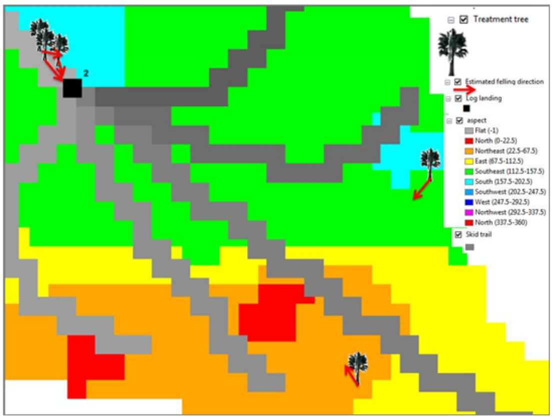

Fig. 5. Five trees were estimated to be forced to fall toward skid trails in the range 0 to 0.25.

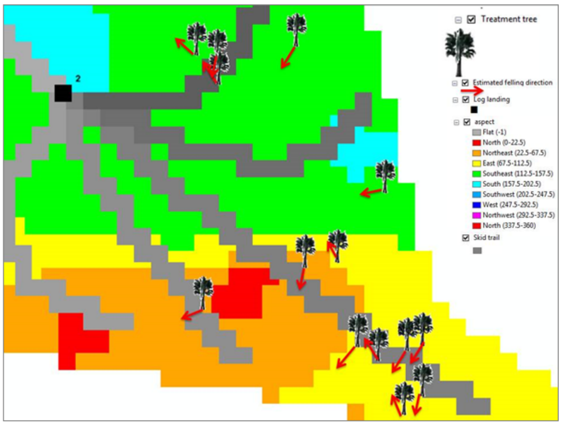

Fig. 7. 14 trees were estimated to be forced to fall toward skid trails in the range 0.75 to 1.

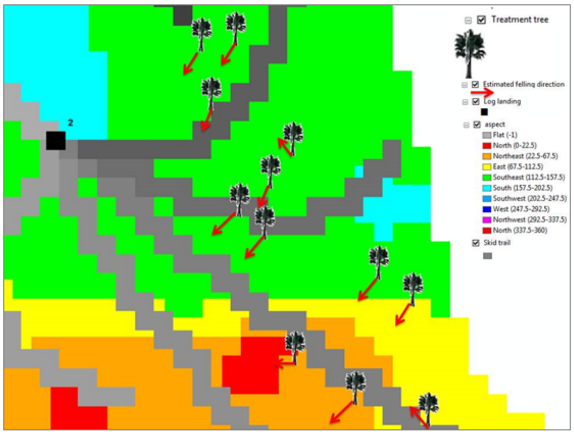

Fig. 6. 12 trees were estimated to fall toward the skid trail direction with high mitigation measures in the range of 0.5.

high mitigation measures to ensure their safe falling towards the skid trail, as shown in Fig. 6. This indicated that these trees had a natural lean in a direction that did not align directly with the skid trail. However, with the implementation of appropriate mitigation measures, such as the use of wedges or mechanical assistance, these trees could be safely directed towards the skid trail.

Furthermore, the analysis revealed that fourteen trees naturally leaned in a direction that facilitated their falling without the need for additional mitigation measures. These trees fell towards their natural lean, as illustrated in Fig. 7. The determination of these felling directions was based on considering a fixed constraint value for the lean direction given to the eight adjacent directions from the treatment tree node, taking into account the slope of the terrain.

By considering these factors, such as the natural lean of the trees and the constraints imposed by the surrounding terrain, the backlink calculation provided an understanding of the optimal felling directions for the assessed trees. This information enables forest managers and fellers to plan and execute the tree felling process in a manner that maximizes safety, efficiency, and resource utilization. However, it is essential to continuously assess and adapt to the dynamic conditions on the ground during the actual tree felling operation to ensure the safety of the personnel involved and to account for any unforeseen factors that may influence the felling direction.

Comparison of directional felling between GIS-back link and observation on the ground

The analysis involved comparing the predicted felling directions with the observed ground felling direction. Ground observation, on the other hand, entailed physically inspecting the trees and marking them for felling. In this binary classification, it was found that out of the total of 31 trees examined, 19 trees had the same felling direction in both approaches. This implies that approximately 61.3% of the trees displayed consistency in their felling direction between the predicted values and the actual observed values.

The results of this binary classification, detailing the felling direction of each tree, are presented in Table 5. This table provides a comprehensive overview of the comparison between the predicted and observed felling directions, al-

Table 5. Binary classification result of comparison between predicted felling direction by GIS and observed ground felling direction

No. of tree	Binary classification	No. of tree	Binary classification
1	0	17	0
2	1	18	1
3	1	19	1
4	1	20	1
5	0	21	1
6	1	22	0
7	0	23	1
8	1	24	0
9	0	25	1
10	0	26	0
11	1	27	1
12	1	28	0
13	1	29	1
14	1	30	1
15	1	31	0
16	0		
	19/31=61.3%		

lowing for clear visualization and understanding of the agreement between the two approaches for each individual tree.

By examining the comparison between GIS-back link analysis and ground observation, the study can provide valuable insights into the advantages, challenges, and potential opportunities associated with these two methods in the context of directional felling. Understanding the benefits and limitations of each method aids in improved planning, decision-making, safety, environmental impact assessment, and productivity optimization. By integrating these approaches, forest managers can achieve more sustainable and efficient forestry operations (Latterini et al. 2022).

The classification of the felling direction between the estimated and observed ground felling direction was interpreted by using the value given for the fixed constraint of lean direction. For example, (e.g., for tree number 2, from observation on the ground, the felling direction value was 0.5 toward the W direction and estimated by using GIS was 0.25 toward the SE direction); thus, both trees have been identified to have the same felling direction and was given the binary value 1. This tree was classified in the same direction because estimated felling of 0.5 can be directed to fall towards the skid trail within constraint value 0-0.25. However, felling should be conducted with high mitigation measures for the feller's safety and proper felling method should the estimated direction be practised by a feller. If there is a hazard to fellers or workers, felling direction towards natural lean should be practised for this treatment tree. For example, for tree number 7, from observation on the ground felling direction was 0 (at the S direction) and estimated using GIS was 0.75 (at NE direction). Thus, both trees have different felling directions and were given the binary value 0. The estimated felling direction with GIS was directed to log landing by considering the least constraints cost (with back link calculation of shortest path algorithm) without considering the lean direction. Therefore, this confirmed that the GIS application estimates the felling direction based on preferred selected spatial features with the constraint value. While felling was determined according to the tree tagging practice and where the fellers think appropriate to fell the trees as observed during felling work.

Conclusion

Controlling logging damage is crucial to ensure sustainable timber production. One recommended approach to achieve this is through the implementation of directional felling. A valuable tool for facilitating feasible directional felling is the utilization of a digital elevation model (DEM) to accurately map and visualize the spatial distribution of trees in three dimensions. This mapping process plays a vital role in assisting managers and fellers in organizing the systematic and safe extraction of pre-felled trees. This back link GIS analysis yielded an accuracy rate of 61.3%, which closely corresponds with observations made in the field. By incorporating a constraint map, forest managers and fellers have multiple alternatives to estimate the felling direction based on specific preference factors. Enhancements to the tree felling direction can be achieved by considering additional factors during the analysis, such as the distribution of the tree stand, the presence of existing mother trees, and the existence of residual trees. By integrating the visualization of the DEM, tree distribution analysis, elevation assessment, and directional planning map, a comprehensive evaluation of the suitability for tree felling can be conducted. This integration serves to enhance safety, efficiency, and informed decision-making in forestry operations. However, it is important to acknowledge that dynamic changes in natural constraints may arise during the tree felling operation, including unforeseen weather conditions and unpredictable tree falling directions. It is crucial to take these unexpected factors into account and manage them appropriately to ensure the safety and efficiency of the tree felling process.

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