Using a weighted Voronoi diagram for forest thinning proposal and skidding trail layouts for teak plantations in Thailand

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Photo 1.
The agricultural tractor is equipped for forest work with a front pusher and a rear frame for attaching cable chokers. The frame above the engine section and the driver's seat provide protection for the machine and the operator only from falling branches. The machine must reach the stump location, and it skids logs to the forest edge landing.
Photo T. Zemánek, 2017.

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RÉSUMÉ

Utilisation d'un diagramme de Voronoï pondéré pour proposer des éclaircies et dessiner les tracés de pistes de débardage dans des plantations de teck en Thaïlande

Le débardage est une des nombreuses causes de destruction ou d'endommagement des peuplements forestiers. Tout système forestier durable exige un tracé des pistes de débardage qui minimise à la fois les dommages causés aux arbres et aux sols et les pertes économiques. Des images de six parcelles de plantations de teck à Thong Pha Phum ont été capturées avec un drone DJI Mavic Pro et traitées avec le logiciel Agisoft Metashape. Le modèle de hauteur de la canopée ainsi créé permet de distinguer les arbres individuels et d'identifier les arbres du sous-étage à éclaircir par le bas à partir d'un diagramme de Voronoï pondéré. Cette approche ne prévoit pas d'enquête sur le terrain et doit donc inclure une évaluation de la santé et de la qualité des arbres, mais elle peut être considérée comme une base pour accélérer le processus de marquage des arbres pour l'éclaircissement. Une estimation de la densité des arbres à l'aide de la méthode par noyau a été obtenue par rastérisation. Compte tenu de l'espacement irrégulier des tecks, une approche subjective a été utilisée pour dessiner un tracé des pistes de débardage en privilégiant la réduction des distances de débardage et des dommages potentiels causés aux sols et aux arbres restants. Cette étude pourrait contribuer à améliorer l'accès aux peuplements forestiers en améliorant la qualité du débardage et en réduisant les dommages causés aux arbres sur pied et au bois lui-même.

Mots-clés : diagramme de Voronoï pondéré, estimation par noyau, aéronef sans pilote, drone, exploitation forestière à faible impact, *Tectona grandis*, photogrammétrie, SfM (structure acquise à partir d'un mouvement), Thaïlande.

ABSTRACT

Using a weighted Voronoi diagram for forest thinning proposals and skidding trail layouts for teak plantations in Thailand

Timber skidding is one of the many causes of destruction or damage to forest stands. Any sustainable forestry system requires a suitable skidding trail layout that minimises damage to trees and soils as well as economic losses. Imagery of six teak plantation plots in Thong Pha Phum was captured with a DJI Mavic Pro unmanned aerial vehicle and further processed with Agisoft Metashape software. Single trees could be distinguished in the canopy height model thus created, and understory trees for thinning from below were identified from a weighted Voronoi diagram. This approach does not include a field survey and therefore needs to include an assessment of the health and quality of the trees, but it can be considered as a basis for accelerating the process of marking trees for thinning. Rasterisation was applied to produce an estimate of tree density based on Kernel Density Estimation. Given the irregular spacing of the teak trees, a subjective approach was applied to plot a skidding trail layout, with the emphasis on shortening skidding distances and reducing potential damage to soils and remaining trees. This study could help to improve access to forest stands by improving the quality of skidding and reducing damage to standing trees and to the timber itself.

Keywords: weighted Voronoi diagram, Kernel Density Estimation, unmanned aerial vehicle, drone, reduced impact logging, *Tectona grandis*, photogrammetry, SfM (structure from motion), Thailand.

RESUMEN

Utilización de un diagrama de Voronoi ponderado para planificar claras de bosque y diseñar canales de desembosque en plantaciones de teca en Tailandia

El desembosque de la madera es una de las principales causas de destrucción y daños en las masas forestales. Conviene tener un diseño de canales de desembosque adecuado en un sistema forestal sostenible, ya que puede minimizar los daños a los árboles y las pérdidas económicas. Se capturaron datos de imágenes para seis parcelas de plantación de teca en Thong Pha Phum mediante un vehículo aéreo DJI Mavic Pro controlado remotamente, y posteriormente estos datos se procesaron con el software Agisoft Metashape. Los árboles individuales se distinguen en el modelo de altura de dosel creado, y los árboles para clara que están por debajo del dosel se identifican mediante el diagrama de Voronoi ponderado. Este enfoque no incluye una vigilancia de campo y, por consiguiente, requiere una evaluación de la salud y calidad de los árboles, pero se puede considerar como una base para acelerar el marcaje de árboles para clara. Se realizó una estimación de la densidad de árboles en la imagen de mapa de bits creada con la estimación de densidad de Kernel. Considerando irregular el espaciado de la teca, se aplicó un enfoque subjetivo en el diseño de canales de desembosque, haciendo hincapié en acortar las distancias de desembosque y reducir el posible daño a los árboles restantes y al suelo. Este artículo puede contribuir a aumentar la efectividad en el acceso a las masas forestales, mejorando la calidad del desembosque y reduciendo los daños a los árboles en pie y a la propia madera.

Palabras clave: diagrama de Voronoi ponderado, estimación de densidad de Kernel, vehículo aéreo controlado remotamente, dron, aprovechamiento forestal con reducción de impacto, *Tectona grandis*, fotogrametría, SfM (structure from motion), Tailandia.

Introduction

Wood, as a natural material, is highly valued. Its use is ecological, and it is considered to be a renewable raw material. Demand for wood products such as paper, furniture, and construction materials is growing, but on the other hand, increasing demand for wood products does not have to mean increasing damage to ecosystems. As a result, as society becomes more aware of the environment, the demand for precise forestry is also increasing. That means the forests should be grown sustainably, with possible improvement in every aspect of forestry. One significant cause of destruction or damage to forest stands is timber skidding (Pukkala 2016). This can be mitigated by pre-planning and careful control over the skidding operation, together with the principles of Reduce Impact Logging (RIL) (Putz et al. 2008). Well-arranged skidding trails can shorten the time required for wood extraction and minimise potential damage to the timber (Kooshki et al. 2012).

Irregular skidding should be avoided, resulting in excessive erosion and severe land disturbance (Buckley et al. 2003). Kooshki et al. (2012) indicate that optimum skid trail density is closely related to timber harvested volume. Further, the layout of skidding trails is strongly affected by topography, property lines, equipment limitations, and economic constraints. Usually, they are designed perpendicularly to the terrain contour line. The skidding trail pattern generally consists of parallel trails of various spacings. In addition, the pattern depends also on the technology used. Two main patterns are common, affected by available technology - branching trails, suitable for forest tractors and parallel trails, used for forwarders (Garland 1983). Gumus and Turk (2016) designed a new Direct Skid Trail Pattern (DSTM) pattern. This method of timber extraction involves creating straight and direct skid trails from the logging site to the landing area. This pattern is introduced to minimise the distance and time required for skidding operations, which can reduce fuel consumption, operational costs, and potential damage to the forest stand.

After forest operations, soil compaction and damage to residual trees are common adverse effects caused by machinery used in the forest stands (Moskalik and Sadowski 2000). When planning the layout, the length of the timber assortments, intended for skidding, is crucial for creating a layout. Maximum suggested angles for connecting skidding trails to skidding roads must be abided by. Improper connections can cause damage to standing trees by contact with skidded timber (Gumus and Turk 2016). Neruda (2013) recommends the following angles listed in table I.

Table I.
Suggested angles of skidding (Neruda 2013).

Assortment transported		Angle of skidding
Bolts	4 m	arbitrary up to 90°
Logs (trees/stems)	8 m	maximum 65°
Logs (trees/stems)	12 m	maximum 45°
Trees, stems	20 m	maximum 25°

The theoretical mean skidding distance, which served as the first forest road-spacing scheme, was presented by Matthews (1942). Forest road planning was focused on achieving the lowest possible cost efforts (Chung and Sessions 2001). With growing attention to ecological consequences, a multicriteria evaluation method came into focus, also considering ground condition and soil type, hydrographic and elevation aspects (Jusoff 2018). Some authors incorporate specific information from aerial photogrammetry, field surveys, and digital terrain models (Chung and Sessions 2001; Kooshki et al. 2012).

Nowadays, new opportunities appear to optimise roads and skidding trails. This is mainly due to the development of airborne laser scanning (ALS) technology. Laser scanning provides precise data for creating a digital terrain model

Photo 2.
The skidder is equipped with a front pusher and a single-drum winch with a cable choker. It skids logs from the forest edge landing to the roadside landing. The cabin provides protection for the operator in the event of machine rollover or cable breakage.
Photo T. Zemánek, 2017.

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(DTM) under forest canopies (Vega-Nieva et al. 2009). Apart from DTM, ALS also provides estimates of tree variables such as height, basal area, volume, biomass, growth, etc. (Næsset 2002; Hansen et al. 2017). The accuracy of these estimates may vary depending on the site conditions, tree species composition, stand structure, and the density of ALS data (Næsset 2014). This information is suitable not only for forest inventory but also for skidding trail network optimisation (Sterenczak and Moskalik 2014). Acquiring ALS data requires investment and planning. Therefore, these data are not cost-effective on small scales or in developing countries (Koch 2015).

The combination of technological progress and the availability of unmanned aerial vehicles (UAVs) has made them attractive for forest monitoring due to their flexibility in acquiring high-resolution optical imagery, as well as the ability to collect LiDAR (Light Detection And Ranging) data, offering very high levels of detail, particularly when captured at low flight altitudes (Puliti et al. 2015). They were demonstrated in different temperate forest stands (Ota et al. 2015), forests in boreal areas (Chen et al. 2017), and tropical forests and woodlands (Zahawi et al. 2015). Except for the forest health analysis, such as the detection of bark beetle infestation using UAVs equipped with multispectral or hyperspectral cameras (Brovkina et al. 2018; Näsi et al. 2018), the UAV incorporation into forest inventory holds a central role (Iglhaut et al. 2019). UAV photogrammetry suits the relevant tree parameters, such as height, density, and biomass (Puliti et al. 2015). Most inventory studies require highly accurate DTM to normalise UAV photogrammetric data, which limits their application primarily to developing and newly industrialised countries (Kachamba et al. 2016). Some authors in these countries use DTM generated from the UAV data themselves or Shuttle Radar Topography Mission (SRTM) data (Kachamba et al. 2016). Generally, the differences between ALS-based and image-based canopy height models are minimal. However, the derived point clouds diverge for closed canopies. The image-based models describe the canopy surface well, whereas the laser beams penetrate through the canopies, allowing for some reflections from the understory (White et al. 2015).

Naturally inspired techniques or technologies that simulate natural phenomena are used in many industries (Rinaldi 2007). Voronoi diagrams, which, e.g., perfectly describe the structure of cracks in the ground or wings of insects, are a weighted version successfully used in graphics and geography, as in predicting human behaviour in cities (Mu 2004). Although the use of Voronoi diagrams in forestry is not entirely new (e.g., Daniels 1986), their application as a competition index has gained renewed interest and shows great potential in recent studies (Aakala et al. 2013; Krejza et al. 2015). This paper merges a new approach to selecting thinned trees in weighted Voronoi diagrams with the well-known technology of UAV and deals with the layout of skidding trails in irregularly spaced teak plantations.

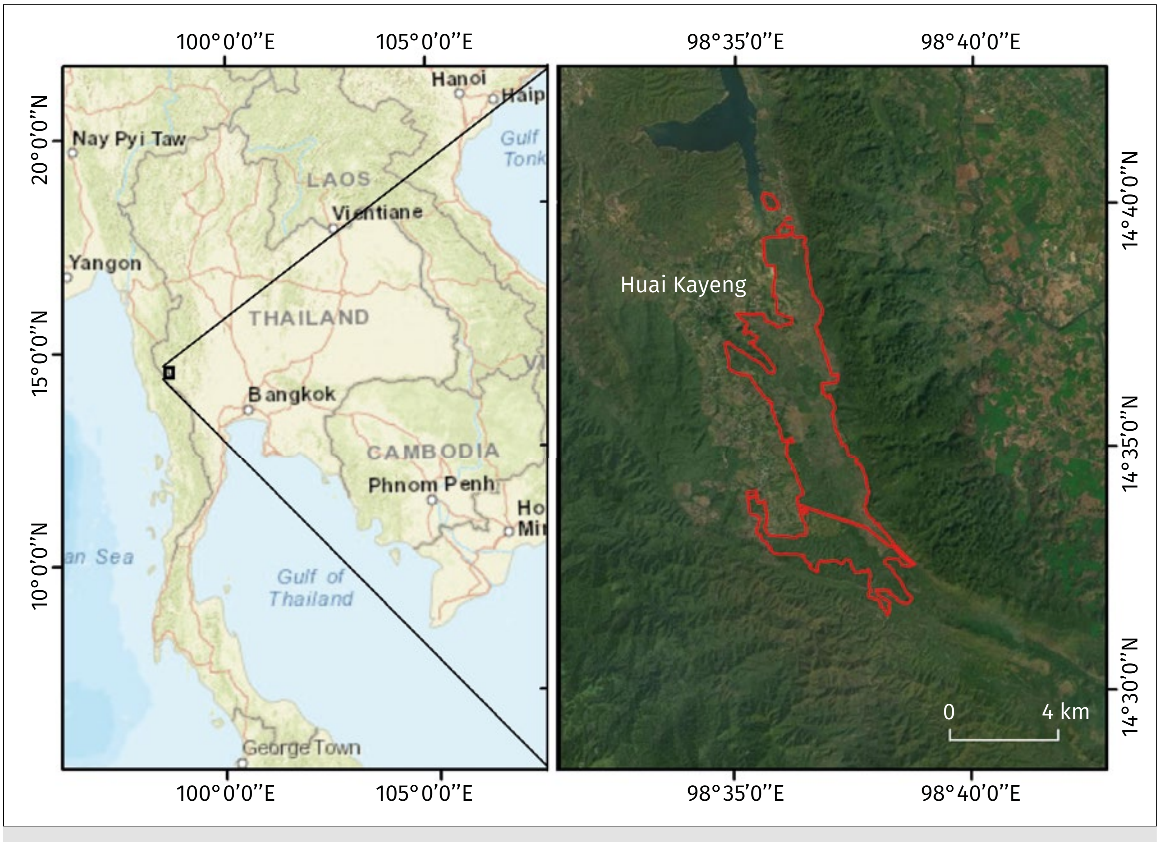


Figure 1.
Location of the Thong Pha Phum plantation.

Materials and methods

The study site is a teak plantation in the western part of Thailand, Huai Kayeng subdistrict, Thong Pha Phum district, Kanchanaburi Province, bordering Myanmar (figure 1). In this area, teak (*Tectona grandis*) and rubber trees (*Hevea brasiliensis*) are grown. For paper purposes, only the teak plantation, with a total of 6 different-age plots, is being considered. The final number of thinning cuts will be determined based on the growth and suitability of each plot over time, taking into account factors such as tree density, growth rates, and stand structure. For the purposes of this study, we assume two thinning operations at 10 and 20 years, followed by the main felling at 30 years. However, if necessary, up to three thinning operations may be performed at 15, 20, and 25 years, with harvesting still planned for 30 years. Determining the number of thinning cuts is important for the analysis, as we need to establish the thinning intensity, specifically how many trees will be harvested. In the Thong Pha Phum plantation, tree felling and timber processing are performed manually. The tree transportation closely follows these stems to the roadside with a ground-based skidding system. Skidded timber is usually 15-20 m long, skidded from the stump to a roadside landing using a farm tractor with logging chokers (photo 2). This type of tractor must come to each felled tree.

All spatial data and maps were created in the WGS 1984 UTM Zone 47N coordinate system. Image capturing was planned and set in a free flight planning app, Pix4D Capture, available for iOS and Android, and performed using the UAV DJI Mavic Pro Platinum. Regarding Thai laws, a maximum flight height of 90 m was used, with 80-85% image overlaps and flight speed regulated to 5 m/s. This low speed was used to amend the electronic shutter, which can cause image distortion.

Images were processed into point clouds, digital surface models (DSMs), and orthomosaics using Agisoft Metashape (Agisoft LLC) software. The common approach involves photogrammetric processing, where images are aligned to generate a sparse point cloud, followed by dense point cloud generation through multi-view stereopsis. The DSM is then created by interpolating the dense point cloud, and orthomosaics are produced by projecting the images onto the DSM (Agisoft 2023). In addition, after image alignment, the incorrect points were deleted from the sparse point cloud using the Gradual Selection tool and Reconstruction uncertainty function.

Points on the ground have been classified in a dense point cloud using the Classify Ground Points tool. The parameters of Max angle (°) were adjusted to 12 and Max distance (m) to 2. The DTM was created based on the ground point class in the Build DEM tool.

Canopy height models (CHMs) have been created by subtracting the DSM from the DTM and used for tree segmentation using the Inverse Watershed Segmentation method (Edson and Wing 2011). The first step was to smooth the CHM using focal statistics, which is crucial for successful identification. Without smoothing, too many trees would be wrongly identified, especially for deciduous species. The focal statistics function calculates the maximum CHM value within a specified circular neighbourhood for each raster cell. The optimum radius was determined experimentally by visually inspecting the accuracy of tree identification against the orthomosaic. The 'best' results, which provided the most accurate representation of canopy shapes and tree positions, were achieved using a radius of 2 m. This radius strongly depends on the canopy radius. Then, the canopy height model was inverted, and hydrological tools, Flow Direction and Flow Length were applied. Zero values were reclassified to 1, and other values were erased. The resulting raster was converted to a polygon vector file. The centroids of polygons representing treetops were generated, and the success of tree detection was visually checked by comparing the identified treetops with the orthophoto. This involved overlaying the detected tree positions onto the orthophoto and visually inspecting whether the identified centroids corresponded to actual treetop locations. The tree height from the CHM was then assigned to each identified tree. Although this evaluation was qualitative, the visual inspection confirmed that the majority of detected trees matched well with the treetop positions in the orthophoto, suggesting a high level of accuracy in the detection process. Inasmuch as the plantation is situated on flat land, a DTM-based skidding trail layout is unreasonable. Hence, the layout was carried out on a proximity thinning and tree density basis, with an emphasis on high extraction productivity and minimum environmental damage. The thinning proposal was performed using weighted Voronoi diagrams (WVD), which serve as a spatial competition index to describe tree neighbourhood structures. In this approach, each tree is assigned a weighted polygon that defines its zone of influence, with weights typically based on tree characteristics such as height or diameter. The WVD provides a way to assess how trees compete for resources like light and space by analysing the overlap and relative sizes of these polygons. Trees with smaller polygons or those surrounded by larger neighbours are considered to be under greater competitive pressure. This spatial analysis informed the thinning process by identifying trees that were most affected by competition, allowing for a targeted removal to improve stand structure and growth potential. (Aakala et al. 2013, Krejza et al. 2015). An inverted tree height was applied as the weight in ET Surface (ET Spatial Techniques), a plugin for ArcGIS. Thinning from below targeted trees are represented by the smallest areas of the Voronoi diagram, based on the assumption that these trees experience high local density and have lower heights. The threshold for the area was not fixed but depended on the thinning intensity. For example, in this study, approximately 33.3% of the trees with the smallest Voronoi areas were selected for removal, ensuring that the thinning process effectively reduced competition in the denser areas. The Kernel Density Estimation (KDE) raster was created by applying the Kernel Density tool to

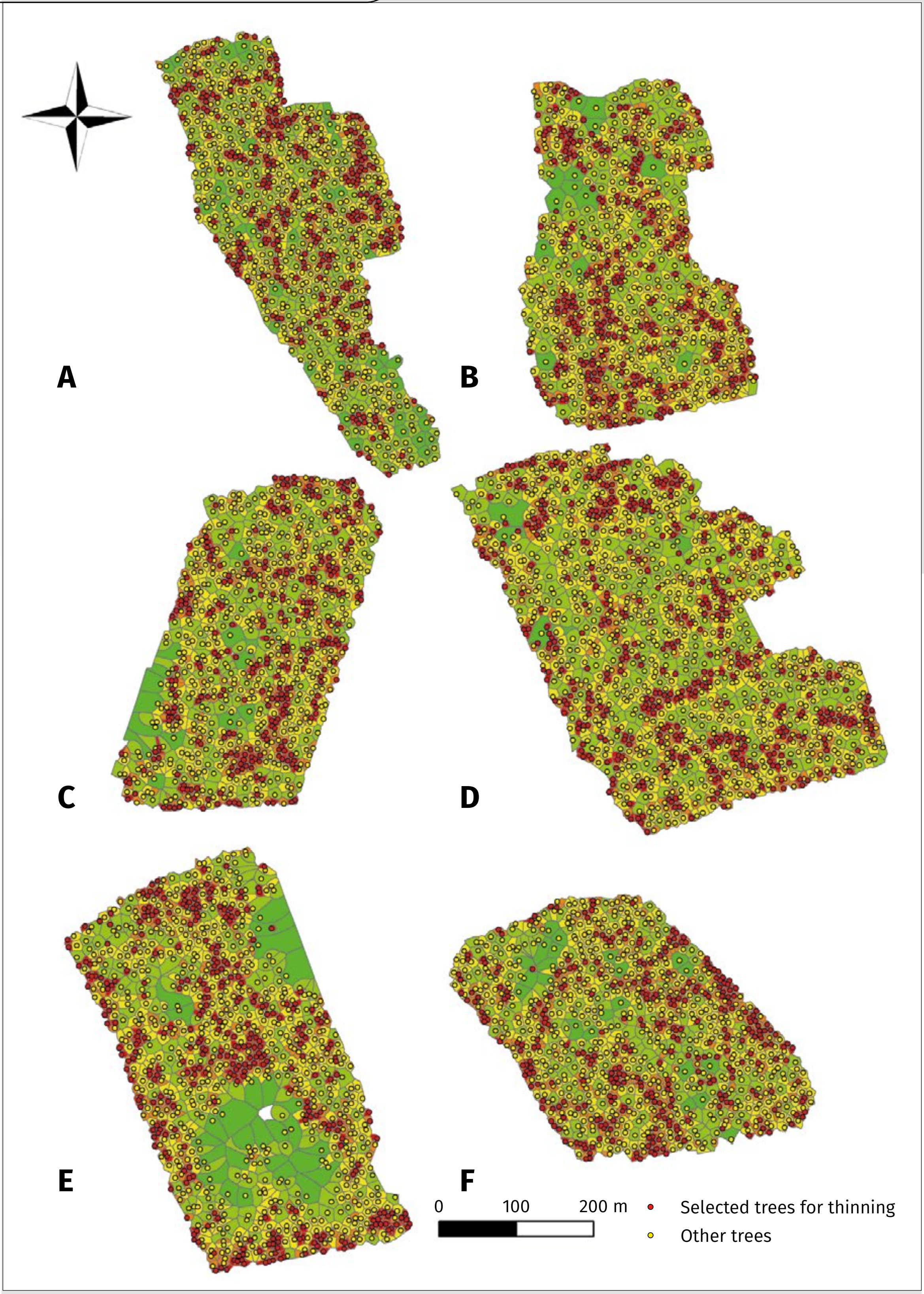
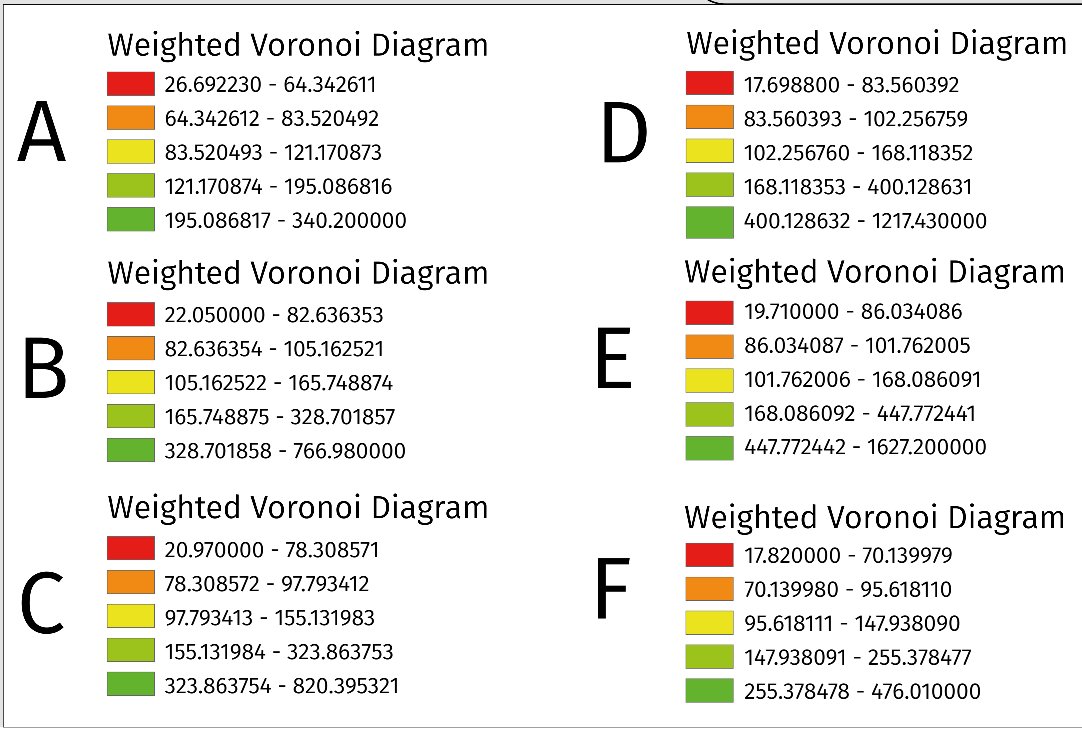


Figure 2.
Thinning proposal based on weighted Voronoi diagrams for each study area (A-F). The colors represent the size of the weighted Voronoi polygons in square meters. The areas are divided into five categories based on a geometric interval. The range of values varies for each area (different geometric intervals). Therefore, these colors are not displayed in the legend, as they would not fit on page.



the point features representing the trees, using the default search radius (bandwidth) determined by a spatial variant of Silverman's Rule of Thumb (Silverman 1986; ESRI 2023). This process calculates a magnitude-per-unit area for each tree, resulting in a smoothly tapered density surface where values are highest at the tree locations and decrease with distance, reaching zero at the specified search radius. The resulting KDE raster serves as a base-map layer for designing the skidding trails layout, with trails proposed to avoid areas of high tree density. When laying out the trails, routes were planned from forest hauling roads or existing skidding trails to thinning centres, with a priority placed on limiting the maximum deflection angle to 25° to ensure efficient skidding of timber 15 m or longer. The Segment Deflection option was used to maintain this angle during the creation of new trail features.

Results

The weighted Voronoi diagrams were classified into 5 classes based on polygon area using geometrical interval classification, with different classification thresholds applied to each study area. The largest polygons (indicating areas with low local tree density) were coloured green, while the smallest polygons (representing high local tree density) were coloured red. The raster datasets for Kernel Density Estimation (KDE) were displayed using stretched colour range symbology, with stretching applied by two standard deviations.

The resulting thinning proposals for each study area are presented in figure 2, where the colour-coded weighted Voronoi diagrams illustrate the spatial distribution of tree density. Figure 3 displays the proposed skidding trails layout, overlaid on the KDE raster, which highlights areas of varying tree density. Additional map features for both figures are described in their respective legends.

To compare and present the advantages of the proposed layout, a different parallel pattern of skidding trails was created (figure 4). This type of pattern is regular and is typically used for forwarders (Garland 1983). The average width of the working field is 30 m to the axis of the 3.5-meter-wide skidding trails, meaning the total working field width from one roadside to the next is 26.5 m. From each skidding trail, the tractor would drive into the stand at a maximum distance of 13.25 m. Although the Dijkstra algorithm, as used by Sales et al. (2019), is a well-known method for optimising paths based on cost minimisation, it was not applied in this study because the primary goal was to assess the practical and operational efficiency of a parallel layout commonly used in forestry practice. However, future work could include a comparison with the Dijkstra algorithm to evaluate potential differences in efficiency and impact. In this study, 82.47 ha were captured and further evaluated. The total number of detected trees on all plots is 5,882. With a thinning intensity of 33.33%, the total number of proposed trees for all plots is 1,959. Currently, the road network covers 6,876 m, with a proposed increase up to 16,899 m (table II).

In figure 5, a new method for skidding trail layouts is compared with a conventional parallel pattern that uses existing trails. Using the new method, the length of the skidding trails was reduced by an average of 19.7%. The only exception is area E, where the length was increased by 6%.

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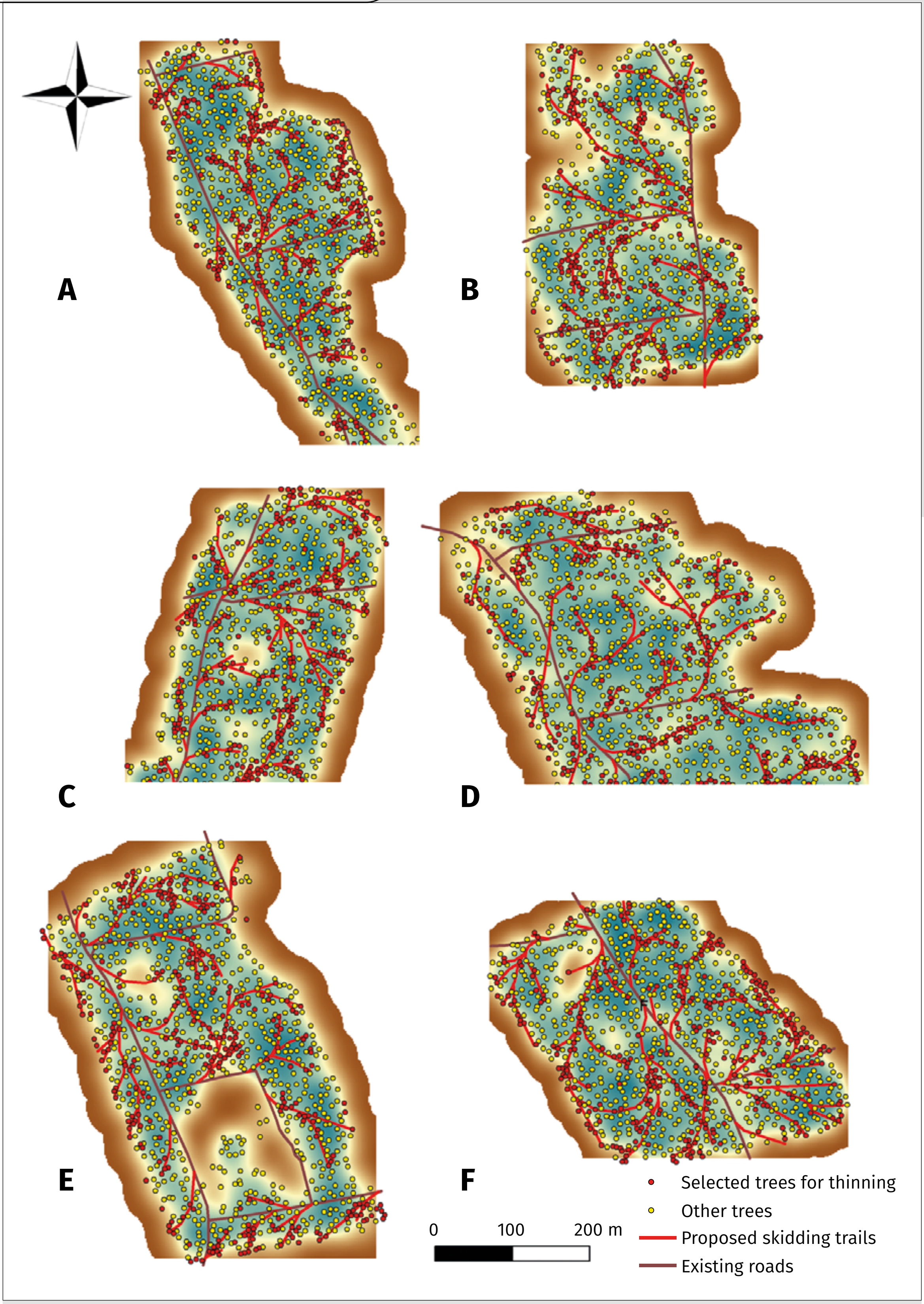
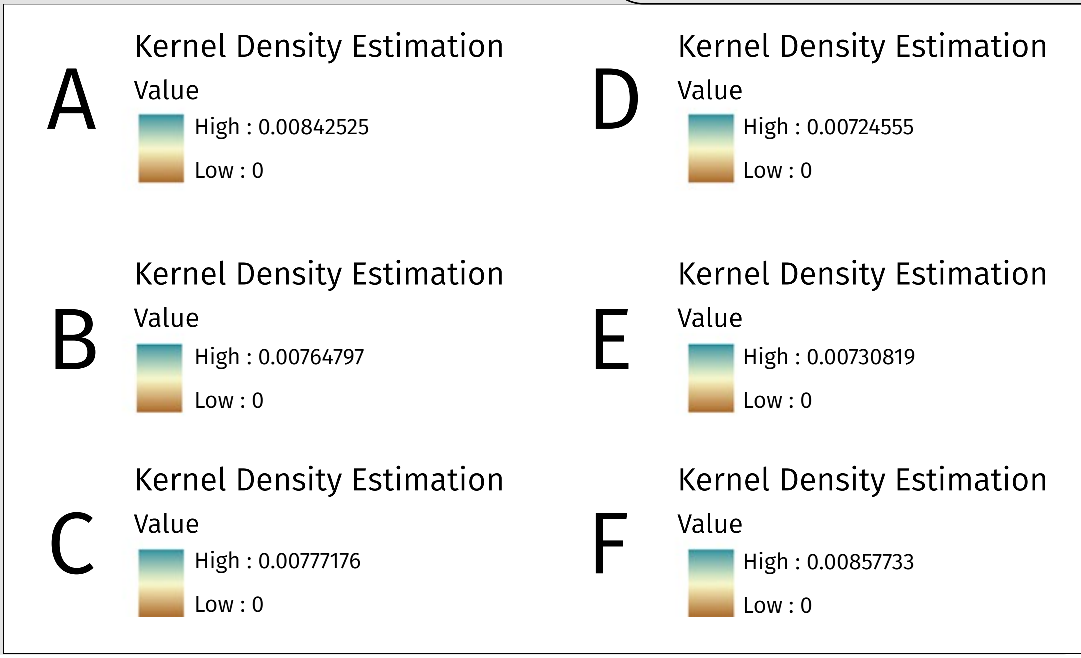
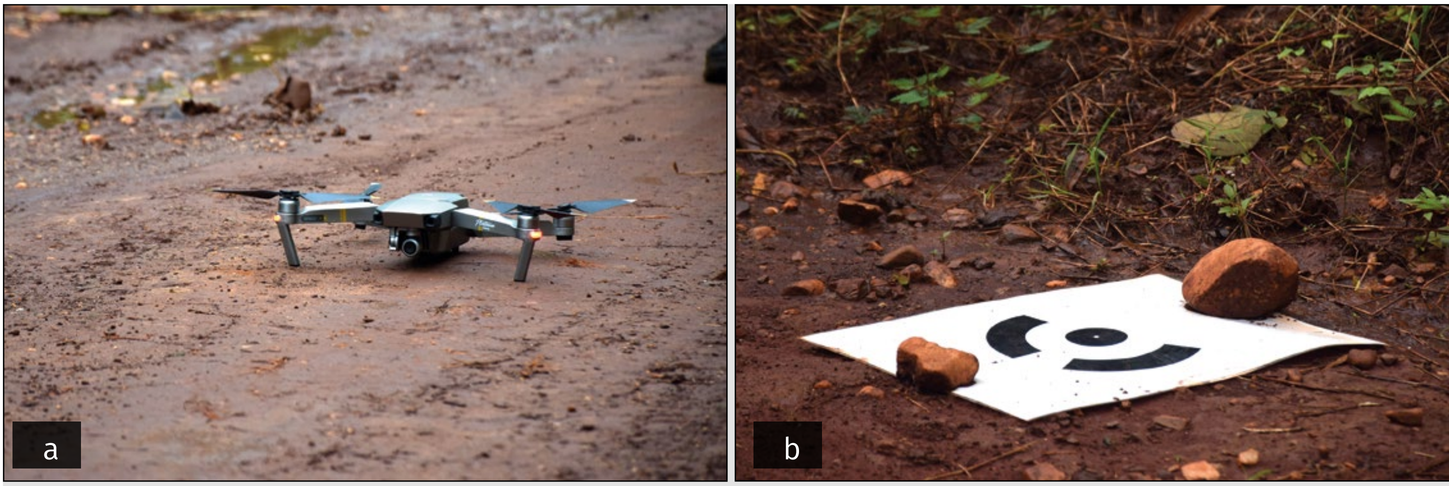


Figure 3.
Skidding trails layouts based on thinning proposal and Kernel Density Estimation for each study area (A-F). The output values represent the calculated density value per square meters for each cell. The color scale is continuous, transitioning from brown to blue. Therefore, these colors are not displayed in the legend, as they would not fit on page. The stretch type is standard deviation with a value of 2 SDs.





Photos 3.
(a) Drone used for imagery and (b) target used as a watermark to orthorectify aerial images.
Photos L. Petrovičová , 2018.

Photos 4.
The Thong Pha Phum plantation.
Photos L. Petrovičová, 2018.

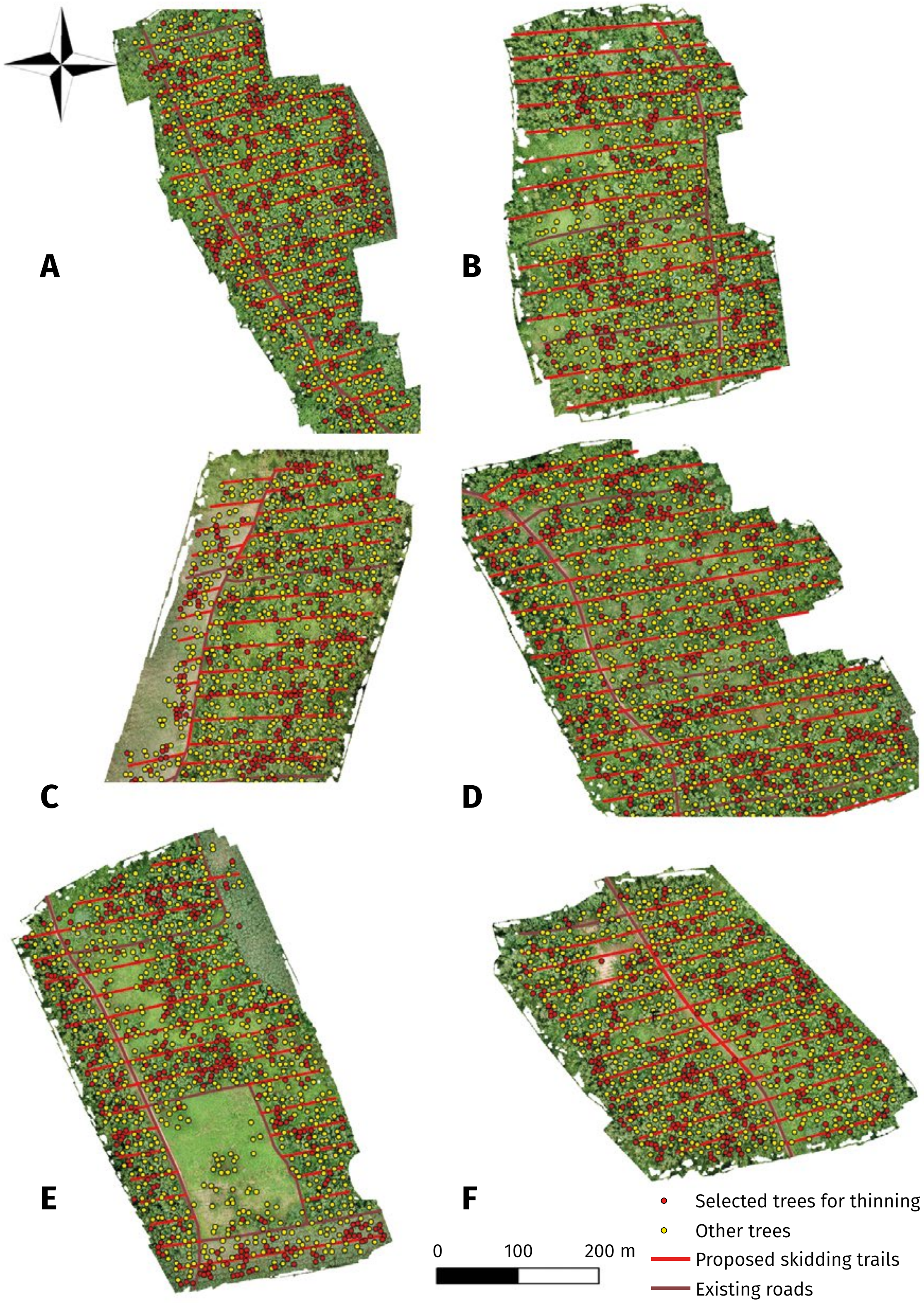


Figure 4.
Skidding trails layouts based on regular parallel pattern for each study area (A-F). The base layer is an orthophoto of the given location.

Table II.
Characteristics of thinning proposal, existing and proposed forest road network.

Plot ID	Area (ha)	Number of detected trees	Number of selected trees for thinning	WVD* area threshold for thinning (m²)	Existing road length (m)	Existing road density (m/ha)	Length of proposed trails (m)	Total road density (m/ha)
A	9.82	934	310	80.01	1,266	128.98	2,040	336.81
B	10.32	834	278	86.76	837	81.10	2,123	286.82
C	10.13	841	280	84.24	960	94.75	2,624	353.74
D	16.23	1,299	433	89.55	1,695	104.41	3,486	319.13
E	10.60	955	318	82.00	715	67.44	3,411	389.15
F	14.12	1,019	340	88.43	1,403	99.37	3,215	327.06
Total	**71.22**	**5,882**	**1,959**	**85.17**	**6,876**	**96.01**	**16,899**	**335.45**

*WVD: weighted Voronoi diagram.

Discussion

The presented approach design method does not directly use the digital terrain model but can still be affected by DTM quality. Voronoi polygons weighted by the height of trees, which is detected from CHM normalised by DTM, are used to select trees for thinning. Unlike ALS, the image-based models describe the canopy surface well but lack points for the terrain under closed canopies (White et al. 2015). As a result, the DTM must be interpolated using sparsely distributed points located in forest gaps, which can introduce some errors in tree height calculations. Based on similar studies, DTM interpolation errors in flat terrain are typically within the range of 0.1 to 0.5 m (White et al. 2015; Puliti et al. 2015). Given that our study area is flat, we expect the error to be in this range, and it should have minimal impact on the overall height distribution, as the terrain elevation is relatively uniform. Alternatively, tree height can be estimated using so-called DTM-independent metrics (Giannetti et al. 2018), or these metrics could be directly used as a weight for weighted Voronoi polygons. Nevertheless, this empirical approach could limit the transferability through space and time (Hansen et al. 2017; Iglhaut et al. 2019).

In general, tree detection segmentation accuracy can be challenging for teak and other deciduous trees due to their expansive and overlapping crown structures. A 2 m radius of focal statistics was used for this teak plantation to account for the tree habitus. The algorithm sometimes incorrectly identifies a single teak tree as multiple trees because of the crown expansiveness. While many studies on individual tree detection have focused primarily on conifers, there are also studies addressing crown segmentation for deciduous and tropical trees (e.g., Nurhayati 2015, Ball et al. 2023). However, these studies often involve different species or use specialised techniques that may not be directly applicable to teak plantations, underscoring the need for adjustments in our approach. In addition to planted seedlings, young trees were eventually identified wrongly or not at all. Correction using a smaller radius of the searching radius is possible, but a false increase of detected trees may occur due to the teak crown shape. Other segmentation alternatives are multiresolution segmentation algorithms (Brovkina et al. 2018) or deep learning (Morales et al. 2018). Picos et al. (2020) used a UAV equipped with LiDAR to detect *Eucalyptus* sp., which has problems similar to crown delineation. They added the layer with points located on the stem layer. The same restriction applies to using vegetation indices for detection (Gennaro et al. 2020). When the canopy closure is high, pixels in the vegetation index raster do not differ. A good alternative would be to use terrestrial laser scanning using Simultaneous Localisation and Mapping (SLAM) technology (Holmgren et al. 2019).

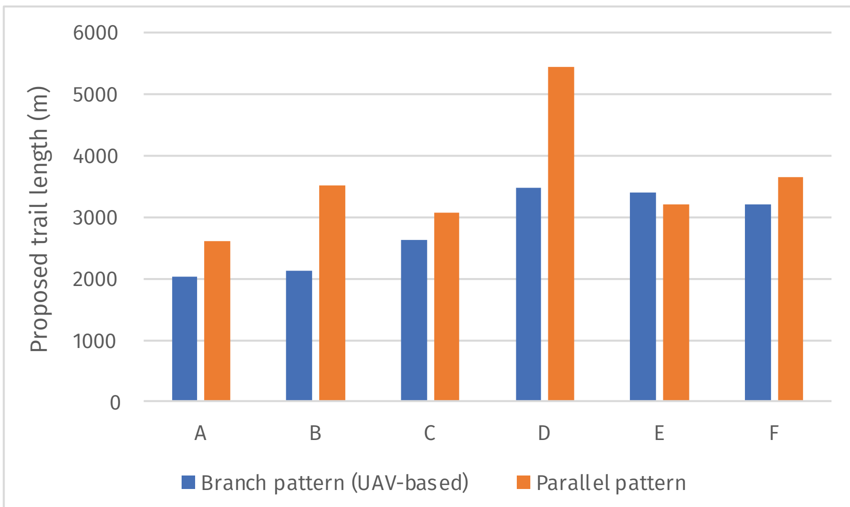


Figure 5.
Length comparison of branch and parallel pattern.

Different approaches for growth prediction are known. For this study, the weighted Voronoi diagrams method was used. The main reasons for doing so were its undemanding implementation and relative simplicity of calculation. Aakala et al. (2013) evaluate the weighted Voronoi diagrams method as propitious and state that it can display competitive growth simulation using larger and smaller polygons suitably. The results of Aakala et al. (2013) support the low, competitive effects of small trees in dense conditions. However, Krejza et al. (2015) indicate that social area index use is more appropriate; in the study, more factors were considered, namely DBH, tree height, crown projection, and crown length. In this study, only tree height data were available and thus used as the primary factor for assessment. Although a height-diameter function could have been applied for a more detailed analysis, the decision to use only height was based on the lack of reliable field data to accurately calibrate such a function for this specific study area. Additionally, using only height simplified the analysis, allowing us to focus on the primary structural characteristic that could be consistently measured across the entire dataset. If the harvester was used for the thinning operation, the Global Navigation Satellite System (GNSS) could assist in identifying thinned trees, substituting traditional tree marking. In cases where the thinning operation was performed by a chainsaw worker, equipping the worker with GNSS was considered to ensure accurate identification of marked trees. However, signal issues frequently occur under dense canopy cover, and navigation accuracy is heavily influenced by terrain, canopy structure, and GNSS quality. In this study, forest stand characteristics, such as varying canopy density, tree height, and terrain slope, significantly affected GNSS signal reception and accuracy. Some plots had denser canopies or more complex terrain, leading to greater signal interference and reduced positional accuracy. This variability in stand structure contributed to inconsistencies in GNSS-based measurements, which is why we did not conduct field validation of the detected tree numbers, as the level of measurement inaccuracy was expected to be high in densely vegetated areas or complex terrains. Moreover, Johnson et al. (2004) indicate that accuracy may highly depend on the number of available satellites during observation under challenging conditions. Ogundipe et al. (2014) indicate that appropriate results under the dense canopy can be expected only from GNSS with carrier phase measurement, and low-cost GNSS or smartphones operate with significant errors under such challenging conditions. On the other hand, in a more open canopy, GNSS can perform quite sufficiently (Keefe et al. 2019).

One of this study's outputs, a thinning proposal, should be considered as a suggestion, not a strict requirement, mainly because only the height and density of trees were considered in this study. This method cannot reach some advantages of field surveys, e.g., because it does not provide health condition evaluation. The health condition of the teak can be observed during the field survey, and thus, different trees could be classified for thinning. Since the plantation also serves as a pasture for cattle, and passing elephants may occur, there is a significant probability of mechanical damage to the teak. On the other hand, the proposed method can speed up fieldwork and help point out where to aim our interest.

Creating a skidding trail layout is commonly based on terrain topography or DTM, with trails spaced at regular intervals (Sterenczak and Moskalik 2014). However, since the model plantation is situated in flat terrain without elevation extremes, a different approach could be implemented. In this method, the layout was created with a focus on minimising potential damage to standing trees. While automatic design methods such as friction surfaces or the Dijkstra algorithm (Sales et al. 2019) were tested, they did not perform well due to their inability to adapt to the irregular tree spacing and high variability in tree density found in the teak plantation. These methods often proposed skidding trails that intersected areas of high tree density, leading to potential damage to the standing trees. In contrast, the manual approach used in this study involved drawing trails directly onto the tree core density estimation raster output (Kernel Density Estimation), allowing for precise adjustment around areas of varying tree density. This density-based manual method was more appropriate because it provided the flexibility to consider specific stand conditions, avoid densely populated areas, and adjust trail placement according to the unique, irregular tree spacing patterns observed in the plantation. By doing so, it was possible to give different weights to individual design criteria and create a layout that minimized damage while maintaining operational efficiency.

Even so, existing connections between hauling and access roads could be more suitable. The given angle is 90°, contrasting with the abovementioned presumption. It can be assumed that existing hauling roads will not be redesigned and rebuilt. Thus, it can be recommended to skid smaller bolts or logs concerning the suggested length and angle of connection since Neruda (2013) states that skidding whole stems with no harm to standing trees is practically impossible. Consequently, it is strongly recommended to follow RIL (reduce impact logging) principles, which are used to minimise damage to residual trees, such as preventing abrasion, bark stripping, sapwood exposure, root exposure, and root damage. To follow this recommendation, a non-expensive yet adequate precaution can be taken , such as wrapping the stems to prevent abrasion, placing buffers or bumpers created from wooden poles or branches, or installing rubber belts on the stems.

Conclusion

Concerning the technology available and the usual approach of skidding a tree without branches of 15-20 m in length, the suggested skidding trails are connected to access roads at a 25° angle. Neruda (2013) states that this angle is suitable for the mentioned length to eliminate abrading and harm to residual trees. Equally crucial is the consideration of the felling direction. Diagonal felling is strongly recommended in this case, which chainsaw workers should keep in mind. Perpendicular felling to trail or perpendicular deflection angle is possible only when the assortment method is performed up to a maximum length of 4 m. The more extended the timber log is, the smaller the connection angle is allowed (table I).

In this study, a method of skidding trail layout has been developed that combines several technologies. Not only is an economic criterion used, but the proposed method emphasises environmental conditions and minimises damage to standing trees as well. The method uses UAV-based CHM for thinning proposals and the subsequent Kernel Density Estimation of standing trees. The method does not work entirely automatically because the correct skidding trail layout must meet several criteria:

1. The skidding trails are proposed from forest hauling roads or existing skidding trails to centres of thinning, with an emphasis on avoiding locations with high tree density.
2. To minimise the number of travels.
3. The maximum deflection angle should be limited to 25°. This angle is recommended when skidding timber 15 m or longer. If the technology of logging or skidding changed, and short assortments would be skidded, the third criterion would not apply, and it would be possible to introduce one of the automatic algorithms.

Compared to the schematic design of parallel lines, the new method of trail design brings a minor occupation of the area by skidding trails (by 19.7%), which means a higher yield of wood. In addition, the parallel trails are designed for forwarders; the tractors with the logging chokers must drive to each tree being harvested. The difference in trail lengths will, therefore, be even more significant. Parallel lines also have an inappropriate deflection angle of connection to existing paths for long timber skidding, and the time and financial demands for forest stand severance are higher than the new method. The disadvantage of the new method is the worse orientation during the skidding, which can also cause damage to trees. In addition, trails must be created before each thinning.

This study demonstrates that the proposed approach can effectively design thinning and skidding trail layouts, especially in flat terrains. However, several areas for improvement have been identified:

1. **DTM Accuracy**: The method's dependence on DTM accuracy highlights the need for considering DTM-independent metrics in future studies to reduce error impacts, particularly in more complex terrains.
2. **Tree Detection**: Tree detection accuracy for teak could be enhanced by exploring alternative segmentation techniques, such as deep learning or multiresolution algorithms, given the challenges of expansive crown structures.
3. **Integrating UAV-Based LiDAR**: UAV-based LiDAR could offer improved tree crown delineation, especially for species with complex crown structures, although its effectiveness under dense canopies should be further explored.
4. **GNSS Alternatives**: Given the limitations of GNSS accuracy under dense canopies, incorporating advanced GNSS systems or terrestrial laser scanning (TLS) with SLAM technology could offer more precise tree positioning.
5. **Skidding Trail Design**: While the manual layout approach proved effective, integrating semi-automated methods that combine algorithmic efficiency with manual adjustments could enhance adaptability to stand conditions.
6. **Reduced Impact Logging (RIL) Practices**: Implementing RIL principles, such as using buffers or protective measures during skidding, could help minimise damage to residual trees.
7. **Field Validation**: For more comprehensive thinning proposals, field validation that includes health assessments is recommended, as this study primarily relied on height and density metrics.

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Access to data

All datasets used in this research are shared under the Creative Commons Attribution 4.0 International licence at the link: https://doi.org/10.5281/zenodo.8199319

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