Preparation of Allometric equation using Terrestrial Laser Scanners and Unmanned Aerial Vehicle

Submitted by:

Geo Three D. Modelling Pvt. Ltd

Kageswari Manahora-9,kathmandu

Submitted to:

Karnali Province Government

Ministry of Industry, Tourism, Forests and Environment

Forest Research and Training Center

Birendranagar, Surkhet

June 2023

TABLE OF CONTENTS

LIST OF FIGURES

1 INTRODUCTION

1.1 General Background

A forest is a diverse ecosystem made up of a lot of trees, shrubs, plants, and animals (Lefsky et al., 2002). Forests play a crucial role in supporting biodiversity, regulating the climate, providing ecosystem services, and offering resources for human use.Forests are vital to climate regulation through their influential rolein the global carbon cycle (Stovall et al., 2018).

Pinus *wallichiana*, commonly known as the Himalayan pine or Bhutan pine, is an evergreen tree native to the Himalayan region, including Nepal. It is recognized for its towering height, reaching up to 30 to 60 meters, and its distinctive bluish-green needles arranged in bundles of five. The species thrives in high-altitude environments, typically between 1,800 and 3,900 meters above sea level. Pinus *wallichiana* holds significant ecological importance and serves as a valuable timber resource, making it an intriguing subject for investigation.

Pinus *roxburghii*, also known as the Chir pine or longleaf pine, is another notable pine tree species native to the Himalayan region, including Nepal. This evergreen species exhibits a straight trunk and a conical crown, growing to heights of 30 to 45 meters. The bark is thick and reddish-brown, while the needle-like leaves are dark green and arranged in bundles of three. Pinus *roxburghii* is commonly found in the lower Himalayan region, thriving at elevations ranging from 500 to 2,000 meters above sea level. It holds significant commercial value, being utilized for timber production, pulpwood, and resin extraction.

The process of methodically gathering, examining, and interpreting data about the make-up, dynamics, and composition of forests is known as forest inventory (Verburg et al., 2011). It involves assessing various aspects of the forest, such as tree species, size, age, density, biomass, and health. For forest management, conservation planning, estimating carbon sequestration, producing timber, and conducting ecological research, a forest inventory is a useful tool (Bustamante et al., 2016).

Techniques for conducting forest inventories have changed over time to accommodate the growing demand for accurate and effective data collection (Blaschke, 2010). Traditional methods involved manual field sampling, where foresters would measure tree attributes such as diameter at breast height (DBH) and tree height using specialized tools. These methods were often limited in scale and accuracy due to the labor-intensive nature of data collection.

However, with the advent of advanced technologies, such as remote sensing and geospatial analysis, forest inventory has become more comprehensive and precise. Remote sensing techniques, including aerial photography, airborne laser scanning (ALS), and satellite imagery, enable the collection of data over large areas and provide valuable information on forest cover, vegetation types, and disturbances.

The inventory of forests has been transformed by the use of terrestrial laser scanners (TLS), which produce detailed 3D point clouds of individual trees (Disney et al., 2018). TLS devices emit laser beams, measuring the time it takes for the beams to bounce back from tree surfaces. This data allows for precise measurements of tree attributes, including DBH, tree height, and crown dimensions.

UAVs can collect LiDAR data or high-resolution aerial images, making it possible to collect data over large areas quickly and affordably (Oliver, 2017). UAVs can capture high-resolution aerial images or LiDAR data, enabling efficient and cost-effective data collection over large areas. These technologies provide detailed information on tree height, canopy cover, and forest structure.

Forest inventory serves multiple purposes, including forest management planning, timber harvesting, biodiversity conservation, carbon accounting, and assessing ecosystem health. It helps stakeholders make informed decisions regarding forest resources, land-use planning, and conservation strategies. By understanding the structure and dynamics of forests through inventory data, researchers and policymakers can develop sustainable management practices that balance ecological, economic, and social objectives.

Accurate tree volume model preparation is crucial for effective forest management, carbon accounting, assessment of ecosystem services, economic considerations, and scientific research. These models provide reliable estimates of tree volume, enabling informed decision-making regarding timber harvesting, sustainable forest practices, and carbon sequestration. They also aid in evaluating forest structure and composition, contributing to the conservation of biodiversity and the provision of ecosystem services. Additionally, tree volume models have economic implications by informing timber resource assessments and economic planning. Finally, these models are fundamental for research purposes, supporting simulations of forest dynamics and modeling the impacts of management scenarios and environmental factors on forest ecosystems.

Overall, forest inventory plays a vital role in understanding and managing forests effectively. It combines field measurements, remote sensing, and advanced technologies to provide comprehensive information about forests, contributing to their conservation and sustainable utilization.

1.2 Objective:

General Objective

- To develop allometric model using databases from TLS, UAV and Field measurement of pinus*wallichiana* and pinus*roxburghii*.

Specific Objective

- To determine form factors and diameter-height ratio.
- To make species specific tree volume models.

1.3 Scope and Limitation

1.2.1 Scope

- The project aims to estimate tree volume models using terrestrial lidar technology, which involves capturing three-dimensional data of the forest using laser scanning.
- The project focus on a specific forest area or region, considering factors such as vegetation type, canopy density, and terrain characteristics that affect biomass estimation accuracy.
- It will involve data collection using terrestrial lidar equipment, processing and analysis of the acquired lidar data, and development of biomass estimation models based on the collected data.
- The project aims to provide accurate and reliable estimates of forest biomass, which is crucial for forest management, carbon accounting, and ecosystem monitoring.

1.2.2 Limitation

- The accuracy of tree volume models using terrestrial lidar can be affected by various factors, including sensor limitations, data processing techniques, and calibration procedures. These limitations may introduce uncertainties in the final biomass estimates.
- The project's scope may be limited by the availability of suitable terrestrial lidar equipment and access to forested areas for data collection. Limited resources and logistical constraints may restrict the project's coverage to specific regions or smaller-scale forest areas.
- The accuracy of biomass estimation can be influenced by the vegetation structure, density, and species composition within the forest. Variations in these factors may introduce biases or limitations in the biomass estimation models.

- The project may not account for temporal changes in forest biomass, as lidar data collection is typically conducted at specific time points. Changes in forest structure and biomass over time may not be captured adequately.
- The accuracy of biomass estimation may be limited in dense or complex forest environments where lidar signals struggle to penetrate through the canopy and accurately measure the underlying vegetation.

1.4 Study Area

Karnali Province (Figure 1) is the largest province of Nepal with an area of30,211 sq km (11664.5 sq mi). The province is surrounded by Lumbini Province in the southeast and south, Sudurpashchim province in the west, and the Tibet Autonomous Region of China in the north. It ranges from 28.16-30.44 N & 80.98-83.68 E. It includes 10 districts of Nepal namely Dailekh, Dolpa, Humla, Jajarkot, Jumla, Kalikot, Mugu, Rukum (west), Salyan, and Surkhet. Out of the total, 38% of the land is covered by a forest in Karnali(Data., 2022). Due to the great variation in topography and climate makes Karnali province a unique region that comprises of various vegetation types, including tropical lowland forest (*Shorearobusta*), temperate oak, forests and conifers in the mid-hills to dwarf rhododendrons and alpine meadows in the higher regions.

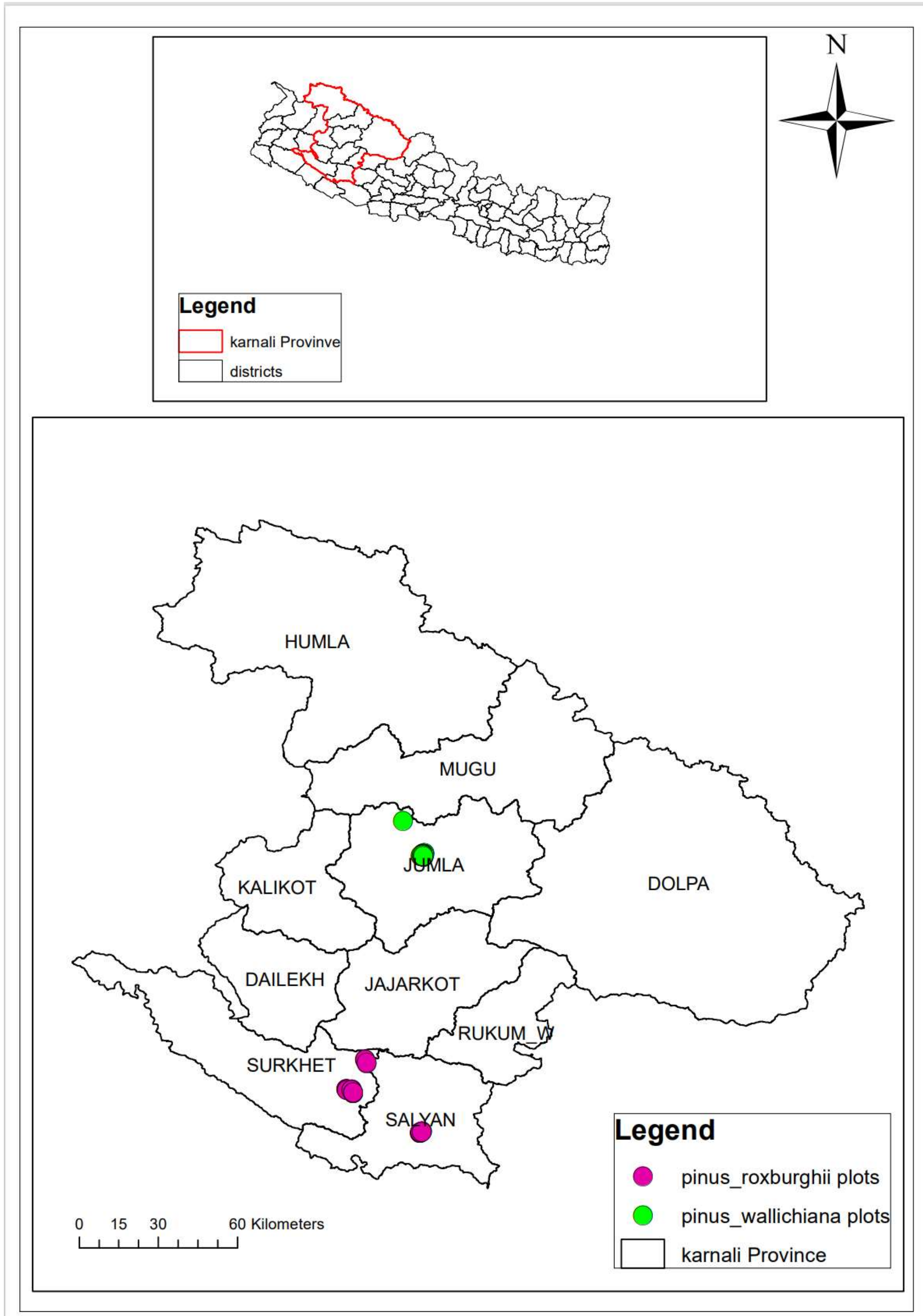

Figure 1: Study area map showing the district of Karnali province from map of Nepal with the sample plots for the pinus_roxburghi in pink color and pinus_wallichiana in green

2 LITERATURE REVIEW

This chapter deals with the definition of various concept regarding Preparation of Allometric equation using Terrestrial Laser Scanners and Unmanned Arial Vehicle we have typically covered various terms related to forest inventory, remote sensing, and the specific technologies involved. Here are some key terms and their definitions:

2.1 Allometric Equation:

An allometric equation is a mathematical relationship that quantifies the proportional relationship between different variables or attributes of an organism or ecosystem. In the context of forest inventory, allometric equations are used to estimate tree attributes such as biomass, volume, or carbon stocks based on easily measurable variables such as diameter at breast height (DBH) or tree height.

Allometric equations provide biomass estimates from tree measurements such as diameter at breast height (DBH), height, and/or wood density. In general, allometric equations is prepared based on the limited data set to show the volume due to which these are for the confined areas. In fact, there are several factors that affect precision of the Allometric equations. Some major factors are stand density, site quality, local climate, soil condition, altitudinal gradient, aspect, inter- and intra-specific competition (Avery and Burkhart, 2000). Allometric equations of one tree species cannot be used for another tree species (Khanna and Chaturvedi, 1982). Traditional methods of data collection for the development of allometric equation relies mainly on destructive sampling however now these days developed countries have been shifted to the use of innovation so as to get rid from destructive sampling.

Almost all of research work involving allometric equation is based on traditional method of data collection. In Nepal, some studies have been carried out to develop the allometric equation of the species however it has been so far to think about the use of modern technology for the development of allometric equation. Further, Karnali Province government is far behind in the preparation of allometric equation of the species even using traditional methods of data collection. Therefore, this study is intended to develop allometric equation of two coniferous species of the karnali province using TLS and UAV and determining the form factors and diameter-height ratio for individual species. In addition with allometric equation, this study aim to develop biomass equation whenever possible.

2.2Tree Volume Model

Tree volume models are mathematical equations that estimate the volume of trees based on easily measurable variables such as diameter, height, and sometimes other factors like crown diameter or wood density. These models are used in various fields including forestry, ecology, and carbon sequestration studies.By utilizing tree volume models, researchers and practitioners can estimate the amount of wood or biomass contained within a tree, which is essential for forest inventory, timber management, and carbon accounting purposes. These models are typically developed through statistical analysis of field data, where measurements of tree dimensions and corresponding volume are collected.The models can take different forms, such as linear, power, or exponential equations, depending on the relationship between the variables and tree volume. The choice of model form depends on the specific characteristics of the tree species and the data being analyzed. Tree volume models provide valuable insights into the growth and productivity of forests, allowing for better management decisions, such as optimal harvesting practices, carbon stock assessments, and monitoring changes in forest structure over time. They can also be used to estimate carbon sequestration potential, helping in the evaluation of climate change mitigation strategies and the development of sustainable forest management plans.

Overall, tree volume models are powerful tools that enable the estimation of tree volume and biomass, contributing to improved forest management practices, carbon accounting, and our understanding of ecosystem dynamics.

2.3Terrestrial Laser Scanners (TLS)

Terrestrial Laser Scanners are instruments that use laser beams to measure distances and capture detailed 3D point cloud data of objects, including trees. TLS technology allows for precise measurements of tree attributes such as DBH, tree height, and crown dimensions.

2.4Unmanned Aerial Vehicles (UAVs)

Unmanned Aerial Vehicles, commonly known as drones, are remotely piloted aircraft equipped with various sensors such as LiDAR or photogrammetry sensors. UAVs are used in forest inventory to capture high-resolution aerial images or LiDAR data, enabling efficient and cost-effective data collection over large areas.

2.5LiDAR (Light Detection and Ranging)

LiDAR is a remote sensing technology that uses laser beams to measure distances and generate precise 3D point cloud data of the Earth's surface. In forest inventory, LiDAR data can provide information on tree height, canopy structure, and biomass.

Terrestrial LiDAR, or terrestrial laser scanning (TLS), has emerged as a valuable tool in forestry applications. It enables the automated measurement of standard forestry inventory parameters and non-destructive estimation of tree-level biomass. Terrestrial laser scanning has been utilized to automate tree diameter and height measurements and capture more complex forest structure characteristics, including vertically distributed leaf area index (LAI) and gap fraction. To derive volume information from terrestrial LiDAR data, two main approaches are commonly employed: voxelization procedures, which convert structured point clouds to cubes, and cylinder-fitting algorithms, which model the tree stem and branches as best-fit cylindrical shapes. These volume estimations are then combined with species-specific wood density to calculate biomass non-destructively. However, the effectiveness of current techniques for biomass estimation from terrestrial LiDAR data varies significantly, with limited applicability across all tree growth forms and a lack of validation against destructive measurements. Moreover, many methods rely on low-noise data, which poses challenges when working with noisier data collected using portable and lower-cost phase-based LiDAR scanners.]

2.6 Software

2.6.1 Global Mapper

Global Mapper is a versatile GIS software that plays a crucial role in working with terrestrial LiDAR and UAV data. With its ability to import and visualize point cloud data, Global Mapper allows users to explore and analyze 3D information captured by terrestrial LiDAR scanners and UAVs. The software offers a user-friendly interface and supports various data formats, facilitating seamless integration of LiDAR and UAV data into GIS workflows. Additionally, Global Mapper provides powerful analysis tools, allowing users to extract valuable information, such as terrain models, vegetation profiles, and building structures, from the collected data. Overall, Global Mapper serves as a valuable tool for professionals in fields such as forestry, environmental management, and surveying, enabling efficient and accurate processing of terrestrial LiDAR and UAV data.

2.6.2 Autodesk Recap

Autodesk ReCap is a robust software application specifically designed for the processing and analysis of terrestrial LiDAR and UAV data. It provides a comprehensive set of tools that allow users to register, visualize, and manipulate point cloud data captured by LiDAR scanners and UAVs. ReCap excels in data registration and alignment, enabling the precise merging and alignment of multiple point cloud scans or flights. It also offers advanced editing and visualization features, allowing users to clean up noisy data, filter unwanted points, and explore the 3D information in a visually engaging manner. One of the key strengths of ReCap is its capability for feature extraction and analysis, enabling users to segment objects, extract vegetation or building structures, and generate digital surface or terrain models. The software also facilitates seamless integration and interoperability by supporting various export formats, making it compatible with other CAD and GIS applications. Autodesk ReCap empowers professionals in industries such as construction, surveying, and urban planning to efficiently process and derive valuable insights from terrestrial LiDAR and UAV data, enhancing their decision-making processes and project workflows.

2.6.3 FAROScene

Autodesk Scene is a powerful software used for the processing, visualization, and analysis of point cloud data collected from terrestrial LiDAR scanners and UAVs. It offers a range of tools and features to efficiently manage and manipulate large-scale datasets. With Scene, users can register and align point clouds from multiple scans or UAV flights, ensuring accurate integration. The software allows for editing and cleaning of the point cloud data, enabling noise removal and filtering to enhance data quality. Visualization options in Scene enable users to generate high-quality visual representations of the point clouds, aiding in analysis and interpretation. Additionally, Scene provides features for extracting specific objects or features from the point cloud data, facilitating modeling and further analysis. The software supports various file formats, enabling seamless integration with other CAD, GIS, and BIM applications. Autodesk Scene empowers professionals in fields like surveying, construction, and infrastructure management to effectively process and utilize terrestrial LiDAR and UAV data for their projects.

2.6.4 Dendrocloud

Dendrocloud is an advanced software solution tailored to the specific needs of foresters, forest managers, and researchers. It focuses on utilizing three-dimensional point cloud capture devices and data processing to enable detailed 3D forest modeling and precise measurements. The software provides essential features such as data import/export, advanced point cloud filters, extraction of high-resolution Digital Elevation Models (DEM) and Digital Surface Models (DSM), classification of point clouds, tree measurements, and professional-quality visualizations. Dendrocloud leverages high-performance engines, parallel processing, and hardware-accelerated 3D visualization to deliver efficient and unlimited processing capabilities for point clouds and grids. Its comprehensive set of features makes it a valuable tool for professionals involved in forest inventory and research, enabling them to accurately analyze and model individual trees and generate detailed visual representations of forest environments.

2.6.5 Pix4D

Pix4D is a leading software solution specifically designed for Unmanned Aerial Vehicle (UAV) data processing and analysis. It offers a comprehensive set of tools and features that enable professionals to transform aerial imagery captured by UAVs into accurate and detailed 2D maps, 3D models, and point clouds. Pix4D utilizes advanced photogrammetry algorithms to process the images captured by the UAV, automatically stitching them together to create a seamless and georeferenced representation of the surveyed area. The software supports various UAV image formats and integrates with popular drones, allowing users to easily import and process the imagery. One of the key features of Pix4D is its ability to generate highly accurate orthomosaic maps. These maps combine the individual images into a single, orthorectified image, providing a precise representation of the area with corrected distortions and uniform scale. Orthomosaics are widely used in applications such as agriculture, land surveying, and infrastructure planning.Additionally, Pix4D enables the generation of detailed 3D models and point clouds. By extracting 3D information from the UAV imagery, users can obtain valuable insights about the surveyed terrain, objects, and structures. This information can be used for volumetric analysis, building and infrastructure modeling, and visualizations.

Pix4D also offers features for data analysis and measurement. Users can extract accurate measurements, such as distances, areas, and volumes, directly from the processed maps and models. This capability is particularly useful for professionals in fields such as construction, mining, and environmental monitoring.Overall, Pix4D is a powerful software solution that empowers UAV operators and professionals in various industries to unlock the full potential of their aerial imagery. It streamlines the data processing workflow, providing accurate and detailed outputs that support informed decision-making and enhance project efficiency.

2.7 Review of Past Studies

“A Systematic Review of the Factors Influencing the Estimation of Vegetation Aboveground Biomass Using Unmanned Aerial Systems” by G. Poley, L. and J. McDermid, G. (2020)

This literature provides a comprehensive analysis of the factors that affect the estimation of aboveground biomass using unmanned aerial systems (UAS). The review systematically examines existing literature on UAS-based biomass estimation, identifying key factors that influence accuracy and precision. These factors include sensor types, flight parameters, image processing techniques, ground calibration methods, and vegetation characteristics. The review highlights the importance of considering these factors in UAS-based biomass estimation to improve the reliability and applicability of such remote sensing techniques. It provides valuable insights for researchers, practitioners, and policymakers involved in vegetation monitoring and biomass assessment using UAS technology.

“Assessment of Forest Biomass and Volume Using Terrestrial Laser Scanning and UAV Photogrammetry" by Wang et al. (2017).

Wang et al. investigate the use of TLS and UAV photogrammetry for assessing forest biomass and volume. They develop allometric equations based on TLS measurements and UAV-derived tree attributes.

“Assessing Forest Structure and Biomass Using Terrestrial Laser Scanning and UAV Imagery" by Martinez et al. (2018)

Martinez et al. investigated the use of TLS and UAV imagery for assessing forest structure and biomass. They developed allometric equations based on TLS measurements and UAV imagery to estimate tree attributes. The outcome of the study highlighted the effectiveness of the combined TLS and UAV approach in accurately assessing forest structure and biomass.

“Estimation of Forest Biomass Using Terrestrial Laser Scanning and UAV Photogrammetry” by Li et al. (2019).

The study aimed to estimate forest biomass using TLS and UAV photogrammetry. The researchers collected TLS data and UAV imagery to derive tree attributes. The outcome of the study was the development of allometric equations for biomass estimation, which demonstrated the potential of TLS and UAVs in accurate biomass assessment.

“Integration of Terrestrial Laser Scanning and UAV Photogrammetry for Forest Inventory in Alpine Environments" by Puttonen et al. (2016).

This study focuses on the integration of TLS and UAV photogrammetry for forest inventory in alpinez. The authors develop allometric equations for tree height and volume estimation using TLS and UAV data.

"Quantifying Individual Tree Attributes in Tropical Forests Using UAV-based Photogrammetry and TLS" by Singh et al. (2018).

Singh et al. explore the quantification of individual tree attributes in tropical forests using UAV-based photogrammetry and TLS. They develop allometric equations for estimating tree attributes and compare the accuracy of TLS and UAV-based methods.

“Review of allometric equations for major land covers in SE Asia: Uncertainty and implications for above- and below-ground carbon estimates” by Fung et al. (2016)

The authors investigate the uncertainties associated with allometric equations used in estimating above- and below-ground carbon content in Southeast Asian land covers. The review focuses on major land cover types such as forests, plantations, agroforestry systems, and peatlands. The findings reveal variations in equation parameters, model forms, and data sources across studies, contributing to uncertainties in carbon estimation. Limitations in data quality and representativeness, as well as the inherent variability in tree species and environmental conditions, are identified as sources of uncertainty. The review emphasizes the importance of addressing these uncertainties for accurate carbon estimation in the region and highlights the need for validation efforts, site-specific equations, and consideration of local variations in tree structure and growth conditions. The review concludes by suggesting further research directions to enhance precision in carbon stock assessments, including the incorporation of additional variables.

"Tree Allometric Equations for Estimating Biomass and Volume of Ethiopian Forests and Establishing a Database: Review" by Sebrala, H. et al. (2022)

This literature review focuses on tree allometric equations used for estimating biomass and volume in Ethiopian forests and the establishment of a comprehensive database. Accurate estimation of biomass and volume is crucial for assessing carbon stocks and implementing sustainable forest management practices. The review highlights the significance of allometric equations as practical tools for biomass and volume estimation. It discusses the importance of developing region-specific equations considering the unique tree species composition and environmental conditions in Ethiopian forests. The establishment of a comprehensive database is emphasized to collect and store reliable allometric data for future research and forest management efforts. This literature review provides valuable insights for researchers, practitioners, and policymakers involved in forestry and carbon accounting in Ethiopia.

"Updated generalized biomass equations for North American tree species" by J.C. et al. (2013)

This study focuses on the development and refinement of biomass equations for North American tree species, aiming to improve accuracy in biomass estimation. The study involves a comprehensive review of previous equations, incorporating new data sources and statistical modeling techniques. The updated biomass equations consider tree characteristics such as diameter, height, and wood density for both above-ground and below-ground biomass estimation. The implications of these equations for carbon stock assessments and ecosystem modeling are discussed, emphasizing the importance of accurate biomass estimation in forest management and climate change mitigation. Overall, this literature review contributes valuable insights to researchers, practitioners, and policymakers involved in forest resource assessment and carbon accounting in North America.

3 METHODOLOGY

3.1 Overview

In our Project, we carried out various steps to complete the task with required accuracy and within the estimated time.Despite the projects aim is to prepare only one outcome the data collected has to be processed independently. At first the height and diameter wasmeasured by field-based forest inventory and secondly by remote sensing-based forest inventory. In first method height and diameter was measured by using vertex and diameter tape while in latter method Terrestrial lidar and drone was used in field successively which was then processed to obtain the point cloud and orthomosaics in Autodesk Recap and pix4d subjected to further processing in Autodesk Scene and finally into Dendrocloud to obtain tree height and diameter successively. Finally, height and diameter obtained from both methods were integrated to obtain the biomass which is used to prepare the allometric equation.

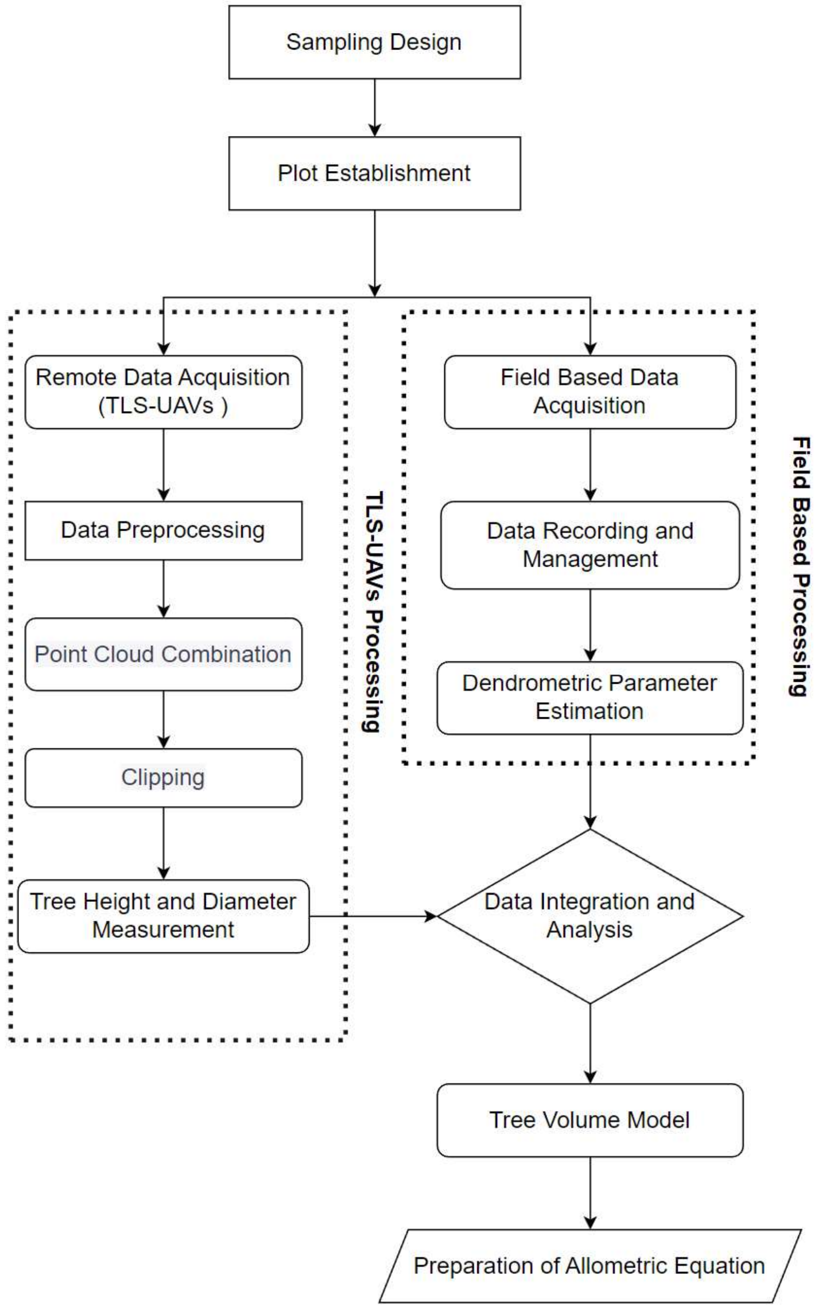

Figure2: Overview of the methodology

3.2 Preparation of Allometric Volume Equation

3.2.1 Sampling Design

Sampling design for forest inventory involves designing a representative strategy to collect data from a subset of forested areas in order to estimate characteristics of the entire forest. The sampling design was basically done in office. Our study area was karnali provinces and we needed to cover major types of trees and from low land terai to mountain region. For our project we selected around 30 plotsfor pinus*wallichiana* and 30 plots for pinus*roxburghii*covering every region.Theseplots were selected from the pool of national forest inventory plot and the plot size was taken about 16 m from the center.The plots were established based on random sampling techniques.In order to prepare the sample plots we selected the sample plots from Forest Research and Training Center of karnali province and then imported CSV file into ArcGIS and finally the plot of 16m radius was prepared. The preflight plan was also prepared in the office taking the plot area.

Table 1: Coordinate of 30 sample plots for pinuswallichiana in left andpinusroxburghii in right .

Plot-ID	Easting	Northing	Height	Plot-ID	Easting	Northing	Height
1	614597.928	3242259.367	2506.363	31	589655.296	3153862.236	1684.477
2	614668.704	3243073.914	2640.936	32	589702.555	3153870.863	1653.117
3	607612.198	3255355.155	2983.14	33	589768.023	3153802.011	1657.134
4	614511.078	3241859.733	2487.816	34	589809.584	3153745.798	1659.573
5	614463.566	3241811.297	2493.499	35	589838.22	3153714.89	1669.189
6	614476.526	3241879.64	2506.164	36	589775.099	3153702.545	1693.995
7	614775.348	3243289.923	2675.309	37	589821.14	3153522.416	1677.678
8	614741.121	3243212.511	2673.417	38	591438.743	3153735.12	1523.073
9	614766.574	3243055.992	2665.807	39	591432.964	3153706.745	1531.537
9	614769.026	3243047.01	2660.504	40	591376.058	3153615.1	1569.515
10	614725.517	3243015.494	2651.866	41	591350.292	3153553.724	1588.464
11	614226.409	3242940.419	2579.792	42	591913.504	3152437.383	1503.962
12	614245.643	3242989.766	2584.902	43	591932.144	3152472.5	1490.822
13	614256.196	3242917.81	2579.463	44	591948.577	3152532.629	1470.866
14	614266.599	3242776.026	2564.252	45	591996.166	3152574.656	1445.857
15	614231.187	3242463.308	2531.802	46	591928.005	3152687.399	1402.544
16	614193.69	3242490.275	2538.348	47	591917.314	3152719.827	1397.185
17	614189.954	3242410.271	2547.998	48	595835.635	3164950.507	1198.973
18	614194.545	3242445.221	2545.465	49	595807.219	3165004.251	1181.678
19	614283.665	3242200.722	2530.716	50	595791.788	3164999.761	1182.747
20	614252.919	3242231.007	2535.301	51	596372.186	3163726.598	1277.161
21	614175.801	3242249.339	2548.195	52	596373.086	3163798.533	1246.797
22	614214.155	3242234.778	2540.628	53	614295.538	3137776.601	1064.432
23	613643.423	3242066.191	2651.046	54	614327.413	3137787.206	1068.275
24	613595.754	3242092.807	2659.536	55	614356.64	3137792.505	1071.97
25	613637.242	3242141.908	2641.401	56	614393.6	3137813.163	1071.468
26	613669.116	3242149.764	2632.392	57	614439.265	3137836.73	1068.609
27	613708.843	3242150.393	2626.672	58	615047.958	3138176.778	1053.372
28	614058.666	3242171.908	2570.326	59	615025.612	3138157.167	1059.951

29	614319.396	3242103.939	2527.533	60	614989.53	3138151.94	1046.681
30	614384.502	3242036.635	2527.582	61	614965.006	3138121.231	1045.396

3.2.2 Plot Establishment

This step was basically done at the time of field data collection. At first, we collectively determined the appropriate plot size of 16meter radius from center plot considering the forest type and research objectives. One team member used a GPS device to record the accurate coordinates of the center plot, while others used measuring tapes, compasses, and surveying equipment to mark the plot boundaries on the ground. Together, we placed visible markers at our plot area to ensure easy identification during subsequent visits. We discussed potential sources of bias and avoided atypical areas to ensure a representative sample. Our collaborative effort and use of GPS devices, compasses, measuring tapes, and surveying equipment resulted in the successful establishment of the sample plots, providing a solid foundation for data collection and analysis.

3.2.3 Field-based Data Acquisition

Field measurements was taken to provide a basis for comparing the UAV-TLS data. The field-based data acquisition was done after the plot was approximately established. For measuring diameter, diameter tape was used whereas to measure height vertex was used and the name of species was identified as well. The attributes of trees within 16m radius wererecorded.The diameter of tree was taken at a height of 1.3 m from the ground.

3.2.4 Remote (TLS-UAVs) Data Acquisition

The Remote Sensing data acquisition was done in two steps.At first, drone was flown in the plot right after the field forest inventory was completed.The pre-flight plan was already done at the office. Before The UAV mission, we did preliminary survey or reconnaissance of the project area (plot), for the ground control point (GCP) establishment and flight plan. Since the drone used for this project is RTK (Real-Time Kinematic) GNSS (Global Navigation Satellite System) enabled and there was no need to establish ground control. But for the accuracy assessment as well as for the further process of data acquisition, it can be more helpful. And as per the accuracy requirement, tree height, and terrain topography, the flight was performed successively.

The UAV named DJIP4MultispectralAgricultureUAVwithD-RTK2GNSSstationand/orAutelProII sensor having a wavelength of 450 nm±16nm for Blue (B), 560 nm±16nm for Green(G), 650 nm±16nm for Red (R), 730 nm±16nm for Red Edge (RE), 840 nm±26nm for Near Infrared (NIR) and Visible Light (RGB) with ground sampling distance (GSD) of 5-8 cm was used for this project (DJI, 2022).

Secondly the TLS was operated.The trees were sampleusing the TLS system ensuring variability in tree speciesand the diameter range to ensure consistency in the generated allometric models

Each TLS scan wascaptured in a high-speed mode with a pulse repetition rateof 300 kHz and vertical and horizontal resolutions of 0.05degrees. Since the TLS data captured from one side cannotensure complete tree coverage, each tree was scanned froma minimum of three (03) directions to ensure 360 coveragefor describing a complete 3D tree structure. Along withTLS data collection, basic tree inventory attributes (DBHand height) are measured on the field during the TLS dataacquisition using a measuring tape and.The first scan position was selected at the center of the plot and the other three scans was conductedfrom outside separated by an angle of 120 degrees in order to cover area of center plot with radius of 16m. The multiple-scan approach can reduce the problem of occlusion, which is caused by tree stems, branches, or other forms of understory vegetation near the scanner's location(Sanaa et al., 2022).

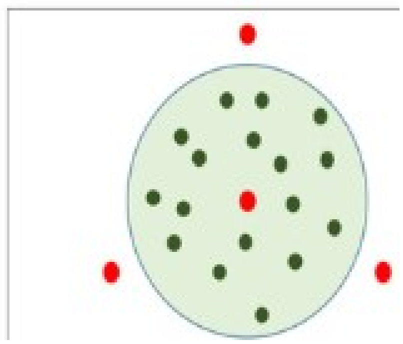

Figure 3: Configuration of the terrestrial laser scanner (TLS) multi-scan (Sanaa et al., 2022)

The acquisition of the TLS data was performed by the FARO®'s latest ultra-portable FocusS Laser Scanner series which enable to capture of fast, straightforward and accurate measurements of complex objects and buildings as well as forest. We will use FocusS 350/350 Plus scanner which has long-range measurements of up to 350m. Also, it contains a measurement Speed: Up To 976,000 Points Per Second/Up To 2 Million Points Per Second (350 Plus) and the error ranging is ± 1mm ("FARO Terrestrial Laser Scanner," 2021).

3.2.5 Data Recording and Management

After the data acquisition was completed successfully, the field-based data collected was recorded into computers and other digital device and the data in paper was stored safely. The data was managed plot wise and used for further processing. We reviewed the collected height and diameter measurements for accuracy, consistency, and completeness. We ensured that any outliers or erroneous data points were identified and addressed appropriately.

3.2.6 Data Preprocessing

The data obtained from the terrestrial lidar and drone were downloaded into the compute and subsequent preprocessing was done.

At first, the data collected from drone which was in form of aerial imagery was processed in Pix4D software. The aerial imagery contains the location information as the GPS in drone would automatically tags images with GPS coordinated. However, the location information in aerial images had errors in meter level. So, in order to make it error free the GCP coordinate was added. And finally the adjusted orthomosaic was obtained along with point cloud.

Secondly, the data collected from terrestrial which was in form of 360^0 imagery was processed in Autodesk Recap and adjusted. The data obtained from TLS was in TCP format. These data might contain some kind of radiometric and atmospheric errors. Similarly, during scanning operation in field there might be scan of the field operator and team. These types of errors were removed using Autodesk Scene. Finally, the processed data are obtained in the form of point cloud same as processed from drone in .las format.

3.3.7 Point Cloud Combination

The point cloud data obtained from preprocessing of terrestrial lidar and drone were first ordered in sequence of the plot number and was finally combined together in global mapper. During point cloud combination the point cloud obtained from pix4D mapper and Autodesk Recap were added simultaneously in global mapper and finally a combined .las file was obtained. The point cloud obtained from TLS and Drone were subjected to registration in Autodesk Recap software ensuring accurate spatial alignment for consistent measurements.

3.3.8 Dendrometric Parameter Estimation

Dendrometric parameter estimation from field-based forest inventory involves measuring and analyzing height and diameter data to estimate various forest parameters. Using the recorded height and diameter measurements for each tree, we calculated the relevant dendrometric parameters. We computed the basal area of each tree by applying the formula for circular cross-sectional area based on the diameter. Additionally, we calculated the tree volume using appropriate volume equations based on tree height and diameter. Once the tree-level calculations were completed, we aggregated the dendrometric parameters to obtain stand-level estimates. This involved summing the basal areas and volumes of individual trees within each plot or stand.We conducted statistical analysis on the dendrometric parameters to derive summary statistics, such as mean, standard deviation, and range. These statistics provided insights into the variation and distribution of the estimated parameters within the forest stands.

3.2.9 Clipping

The combined point cloud obtained from terrestrial lidar and drone were subjected to the clipping of the area of about 16 m from the center. The clipping of whole plot was done and was stored as a new file for further processing. In our case we used global mapper for clipping. Furthermore, the error in point cloud was subjected to cleaning and any point cloud other than tree was removed.

3.2.10 Tree Height and Diameter Measurement

The clipped point cloud data obtained was then imported into Dendrocloud software. Dendrocloud is an advanced software solution tailored to the specific needs of foresters, forest managers, and researchers. It focuses on utilizing three-dimensional point cloud capture devices and data processing to enable detailed 3D forest modeling and precise measurements. This software automatically identifies the trees and allows us to calculate the diameter and height of trees. The diameter of trees were obtained from point cloud in Dendrocloud software by applying optimal circle method while the height of trees were obtained using global mapper software.

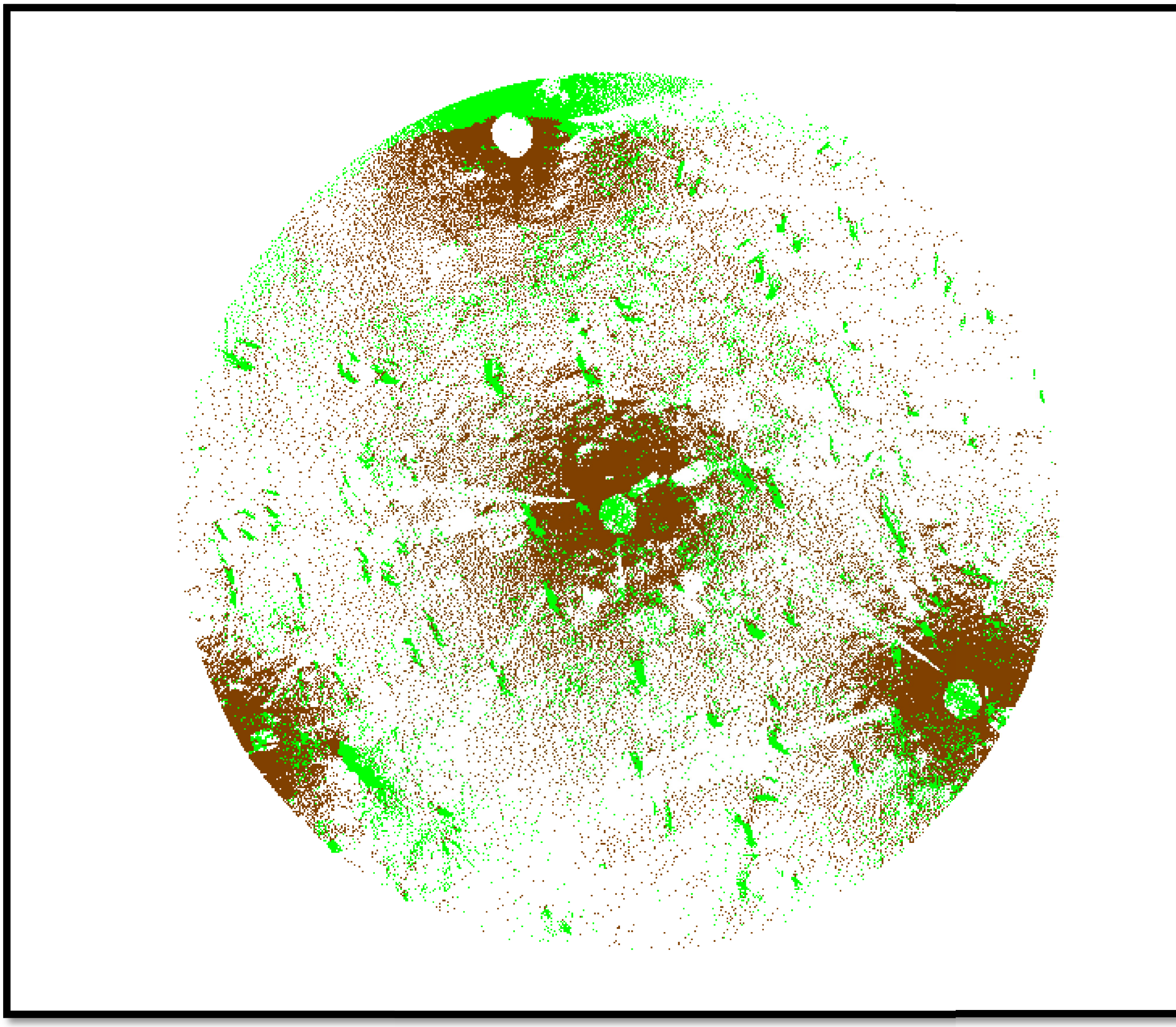

Figure 4: step-1 clipped plot of radius16m-clip the file being in .las format

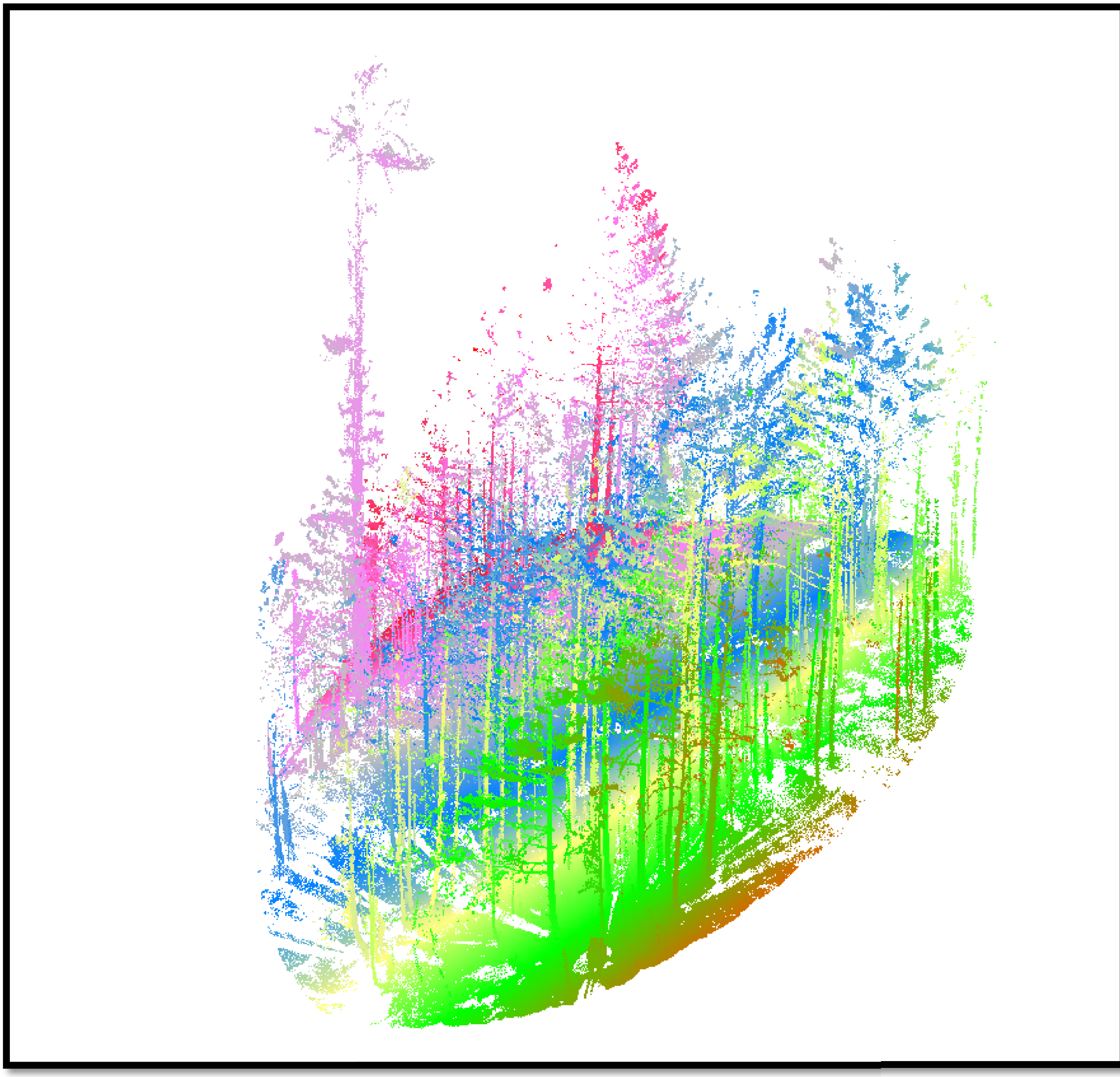

Figure 5: importing point cloud in dendrocloud

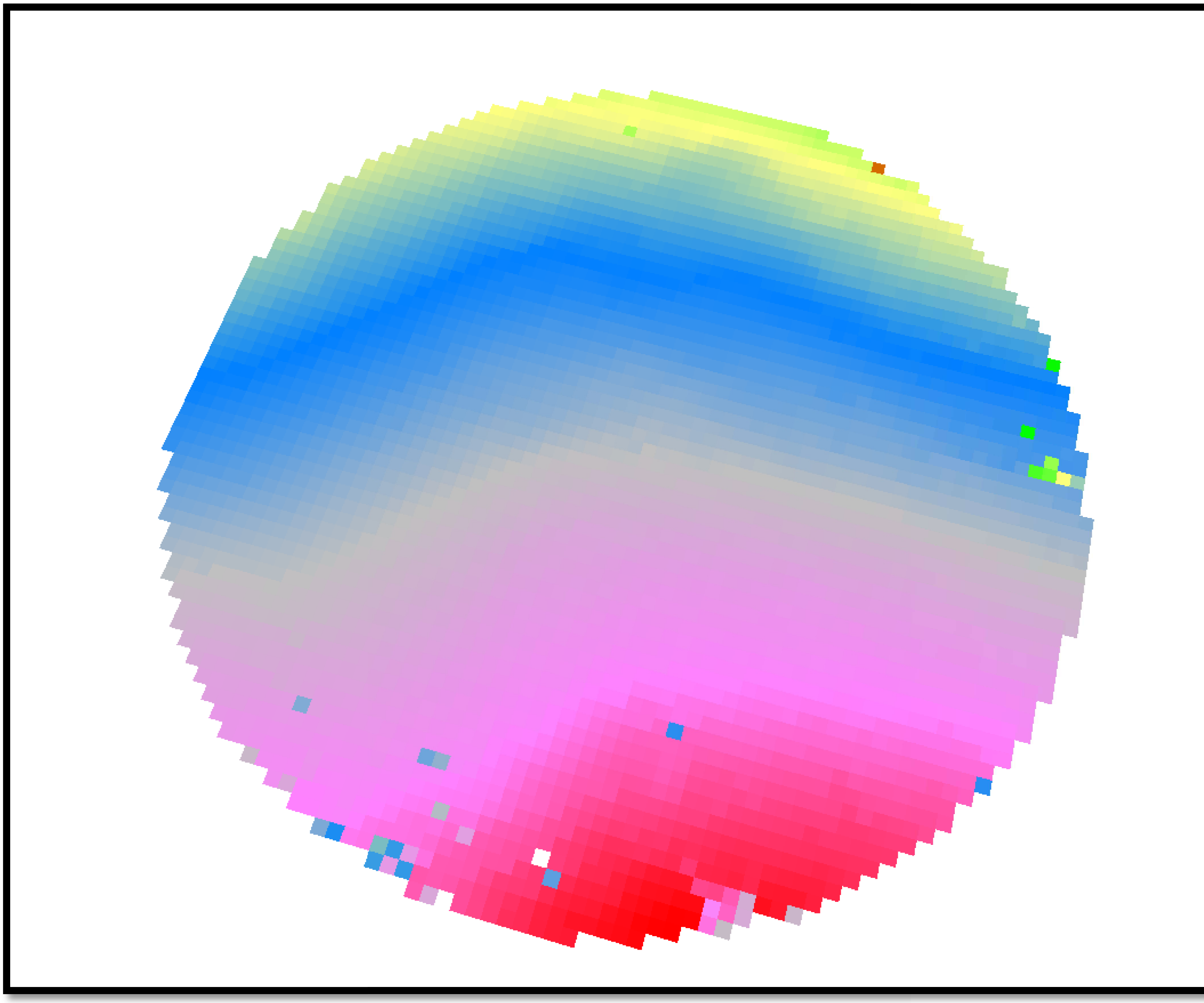

Figure 6:step-2creating DTM from the minimum z value of the plot (ground points) with 0.5m resolution

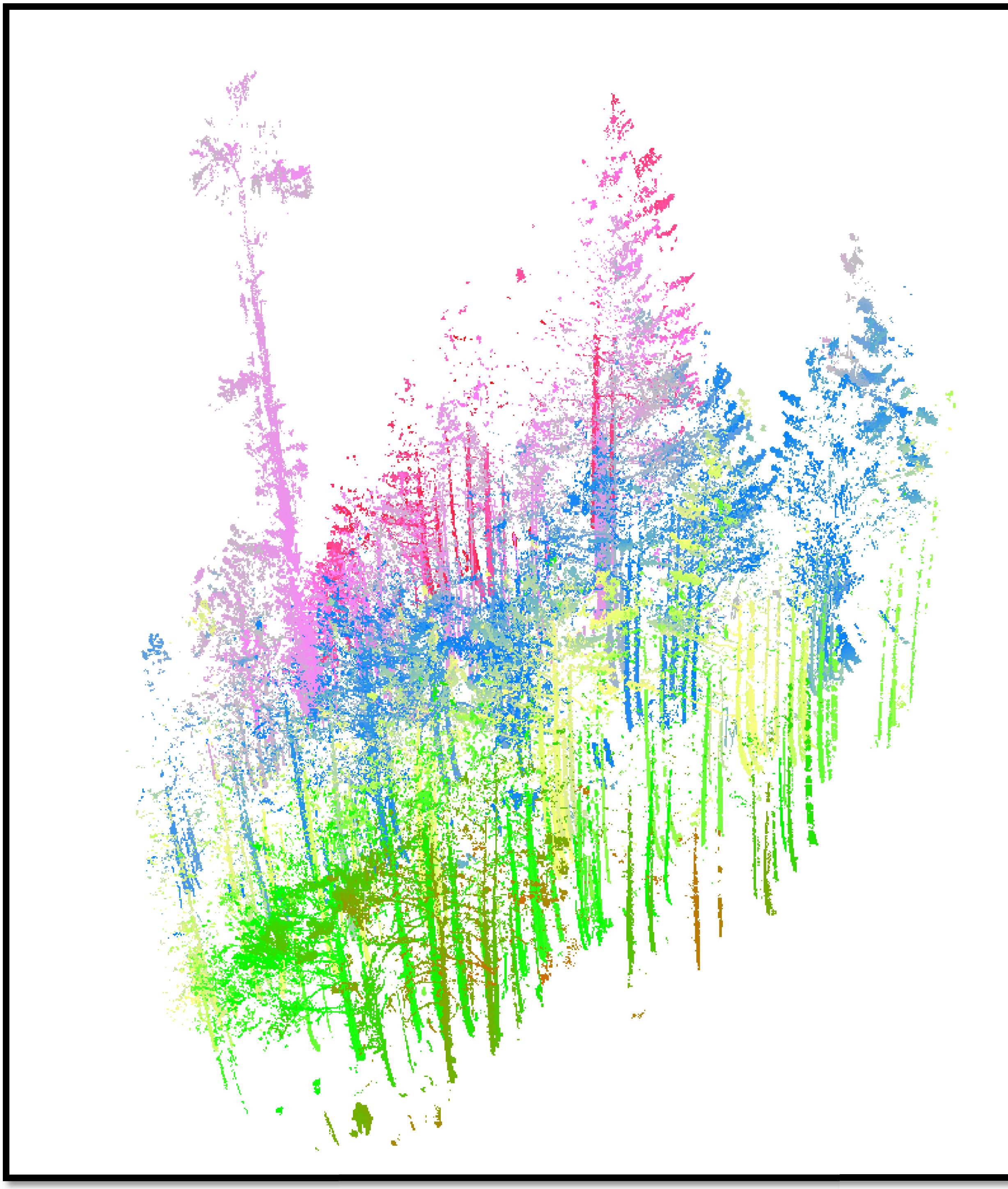

Figure 7:step3-extraction of tree point cloud by using surface cross-section

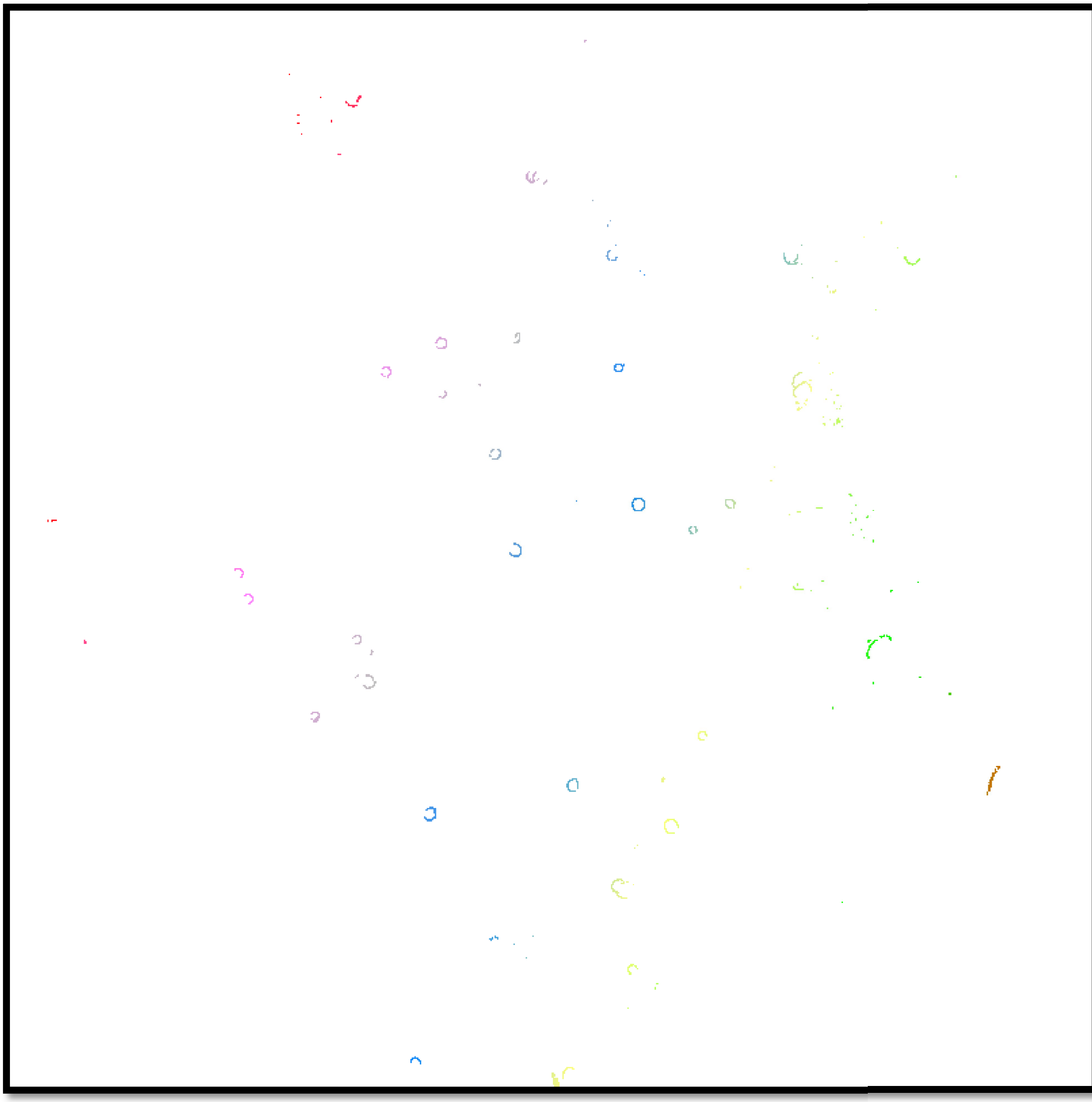

Figure 8:step4-cross-section or section diameter of trees at height 1.3m (dbh)

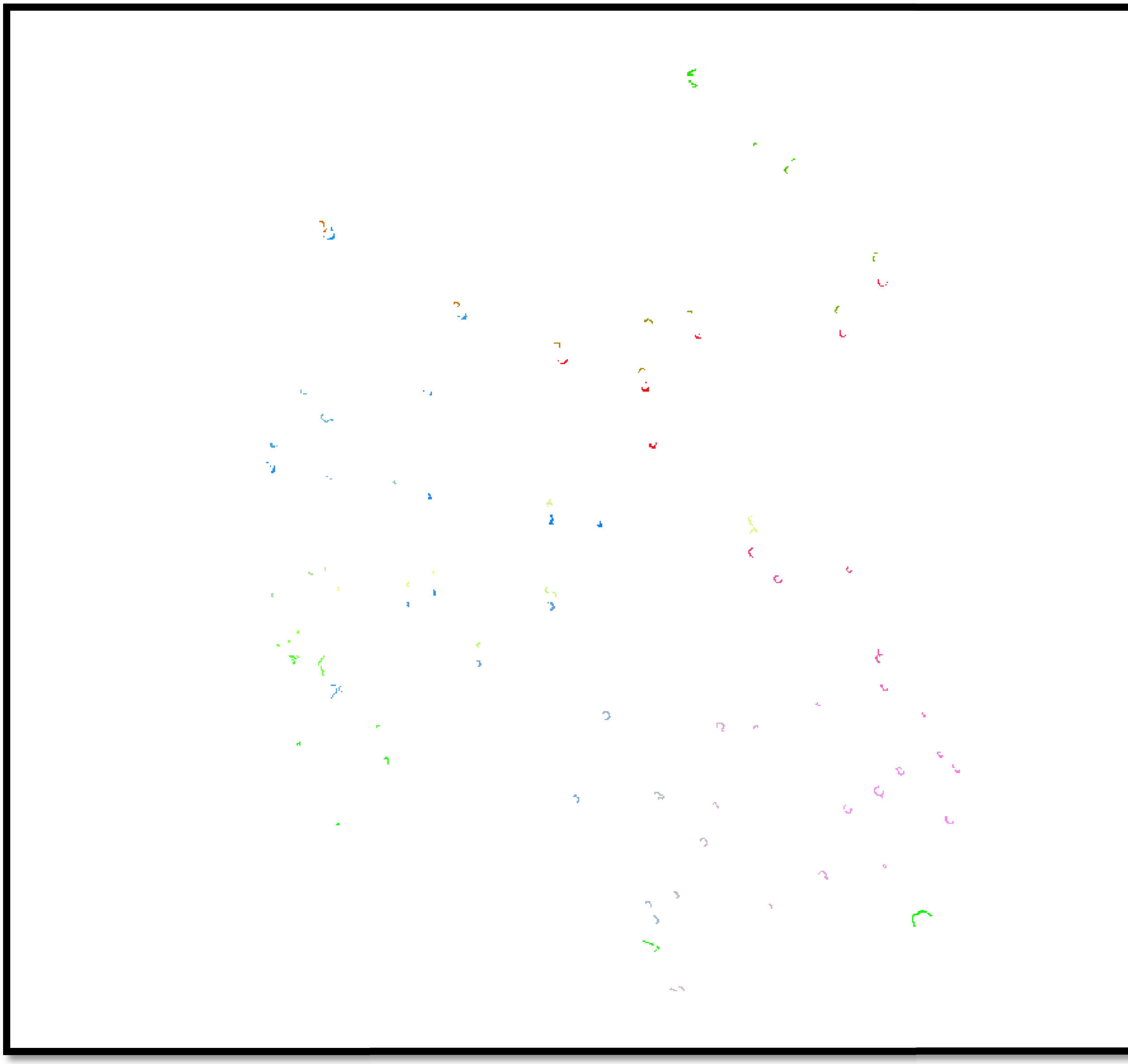

Figure 9: step5-group of section diameter at height 1.3m

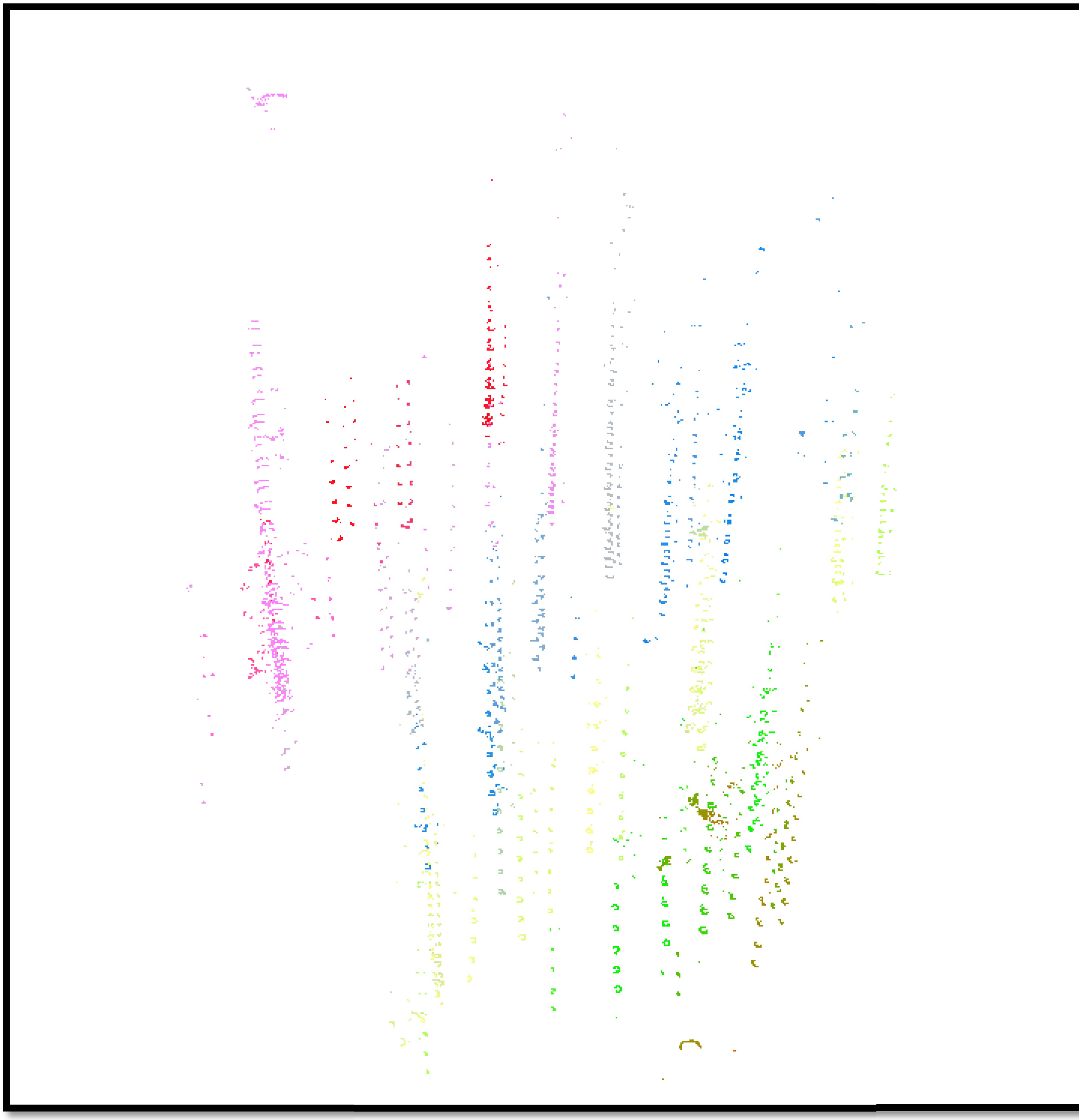

Figure 10: step6-creating multiple cross-section at 1m height interval

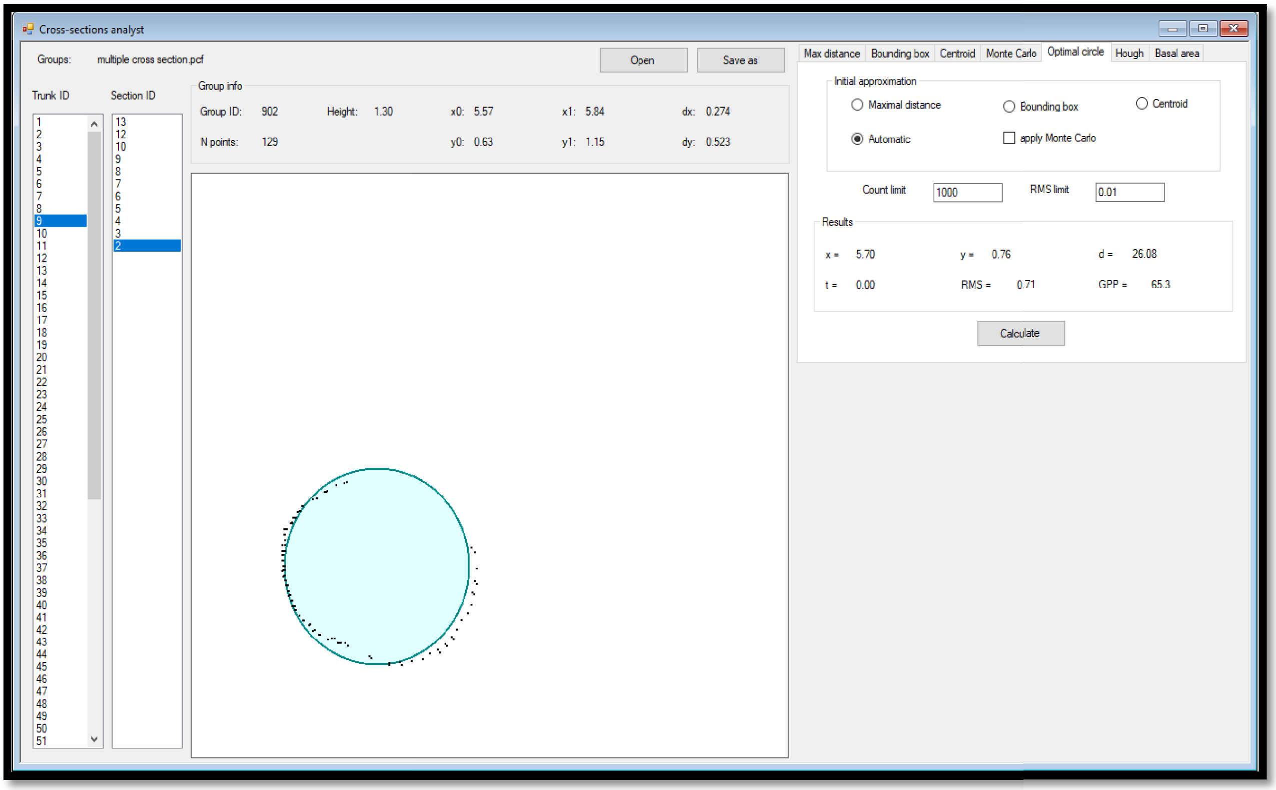

Figure 11: step7- Analyzing and correcting the section diameter at different height using cross-section analyst

3.2.11 Data Integration and Analysis

In the process of integrating TLS-UAVs and field-based forest inventory data, we embarked on data integration and analysis to combine the information obtained from both sources. First, we imported the TLS point cloud data and UAV imagery into suitable software such as Autodesk Recapand Pix4D. Then, we aligned and registered the TLS and UAV datasets to ensure spatial coherence and accurate integration. Next, we processed the field-based inventory data, including tree height and diameter measurements, and prepared them for integration with the TLS-UAV data.

To perform the analysis, we fused the TLS point cloud and UAV imagery to create a comprehensive and detailed representation of the forest area. This fusion allowed for a more accurate identification and segmentation of individual trees and vegetation structures. We utilized point cloud classification techniques to distinguish between different land cover classes, such as trees, shrubs, and ground surfaces. Additionally, we leveraged the high-resolution imagery from the UAV to enhance the identification and mappingof vegetation types and structural features.

Using the integrated dataset, we conducted various analyses, including estimating dendrometric parameters such as tree height, diameter and volume. We applied appropriate algorithms and statistical models to derive these parameters from the combined TLS-UAV and field-based inventory data. The integration of multiple data sources provided a more comprehensive and precise characterization of the forest, enabling a more accurate estimation of forest structure and biomass.

By merging the TLS-UAV and field-based data, we were able to exploit the strengths of each method and obtain a holistic understanding of the forest ecosystem. This integrated approach not only enhanced the accuracy of the dendrometric parameter estimation but also provided valuable insights into forest dynamics, species composition, and ecological patterns. The results obtained from this data integration and analysis will serve as a foundation for further research, management decisions, and the development of allometric equations after the preparation of tree volume model.

3.2.12 Tree Volume Model

Tree model development involves creating mathematical or statistical models that estimate the volume or other characteristics of individual trees or stands based on measurable variables such as diameter, height, and crown dimensions.These models are developed using techniques like regression analysis or machine learning algorithms.Once, the tree models have been developed and validated, they can be used as a basis for preparing allometric equations.

Tree volume models was prepared by two methods: the first one is data from the field survey and the second one is data from the UAV-TLS data input. The allometric equation was established based on the guidelines for sample units for direct methods as well as past researched equationsto determine tree volume If it was compatible with our project site.

3.2.13Preparation of Allometric Equation

Allometric equations provide biomass estimates from tree measurements such as diameter at breast height (DBH), height, and/or wood density. These equations capture the scaling relationships between tree form and function to predict total and component (e.g., branch, needle, bark, bole, root) biomass.

In our case we combined the data obtained from remote forest inventory and field-based forest inventory. From field-based forestry we could obtain tree volume of individual trees quite precisely based on the type of species and from remote sensing method we could obtain the tree volume model of plots. Combining both we can prepare a new allometric equation separately for all those trees species.

4 RESULT

4.1 DBH and Tree Height

At the study site, TLS sampling was targeted using the dominant and co-dominant species information from permanent plot data to ensure sufficient sampling across different species and diameter classes for reliable allometric model development. About 800 trees were scanned successfully were major trees species were pinus*wallichiana* and pinus*roxburghii*. The TLS-UAVs obtained data were processed and each treewere studied using dendrocloud software and finally diameter and height of trees were obtained. The diameter and height of trees were compared to field-based forest inventory.Considering for plot 5 It was found the minimum to maximum DBH of pinus*wallichiana*from TLS-UAVs forest inventory was (19.49696148 cm,42.99522481 cm) Compared to field diameter of (19.5 cm, 42.8 cm).The comparison between the DBH and height of plot 5 data from field to TLS-UAVs are shown in table 3 and table 4.

Table 3:Comparison of DBH of tree obtained from TLS-UAVs acquisition and field based measurement for plot 5 which consist of pinuswallichiana .

Tree no	*section diameter*	*diameter by TLS*	*diameter by*	*diameter from field*	difference
	height(meter)	*(meter)*	*TLS in cm(D1)*	*measurement in cm(D1)*	(D1-D2)
1	1.299999952	0.261620495	26.16204949	26.9	-0.73795
2	1.299999952	0.362062692	36.20626917	36.9	-0.69373
5	1.299999952	0.423864767	42.38647666	42	0.386477
6	1.299999952	0.198275547	19.82755469	19	0.827555
7	1.299999952	0.418716686	41.87166862	39.5	2.371669
8	1.299999952	0.291194379	29.11943791	28.5	0.619438
9	1.299999952	0.429952248	42.99522481	42.8	0.195225
10	1.299999952	0.321279227	32.12792266	31.8	0.327923

11	1.299999952	0.288503374	28.85033738	28	0.850337
12	1.299999952	0.200159095	20.01590949	19	1.015909
13	1.299999952	0.323233099	32.32330995	32	0.32331
15	1.299999952	0.421516014	42.15160136	40.2	1.951601
16	1.299999952	0.194969615	19.49696148	19.5	-0.00304
17	1.299999952	0.203475459	20.34754587	22	-1.65245
18	1.299999952	0.394833581	39.48335808	37.8	1.683358
19	1.299999952	0.401536243	40.15362433	38.3	1.853624

Table 4:: Comparison of Height of tree obtained from TLS-UAVs acquisition and field based measurement for plot 5 which consist of pinuswallichiana

Tree no	DBH	Height from field	calculated tree height	Difference
	(cm)	(m),H1	(m),H2	(H1-H2)m
1	26.9	14.7	13.782	0.918
2	36.9	16.8	16.746	0.054
5	42	19.8	20.049	-0.249
6	19	11.3	20.269	-8.969
7	39.5	19.3	19.584	-0.284
8	28.5	16.6	16.446	0.154
9	42.8	20.9	21.308	-0.408
10	31.8	16.1	16.296	-0.196
11	28	17.2	17.912	-0.712
12	19	15.1	15.176	-0.076
13	32	18.4	18.162	0.238
15	40.2	18.5	19.073	-0.573
16	19.5	15.1	15.381	-0.281
17	22	12.4	12.825	-0.425
18	37.8	17.1	17.108	-0.008
19	38.3	18.4	18.15	0.25

4.2 Crown Spread

Crown spread refers to the horizontal extent or width of a tree's crown or canopy, which is the uppermost part of the tree consisting of branches, leaves, and twigs. It represents the overall dimensions of a tree's foliage when viewed from above. Measuring crown spread helps arborists, foresters, and researchers understand the size and shape of a tree's canopy, which is valuable information for assessing tree health, estimating canopy cover, determining spacing requirements, and planning for tree management or urban forestry projects.Crown spread is typically measured by taking the average distance from the tree's trunk to the farthest point on the outer edge of the canopy in different directions (e.g., north, south, east, west). The measurements are then averaged to determine the overall crown spread. It is often expressed in feet or meters.The crown spread of a tree can vary greatly depending on species, age, health, environmental conditions, and management practices. Understanding the crown spread is crucial for evaluating a tree's condition, assessing its impact on surrounding vegetation or structures, and making informed decisions regarding pruning, maintenance, or tree placement.

In our case,we automatically obtained the crown spread of our plot by importing clipped point cloud data in global mapper. The crown spread obtained from global mapper is shown in figure 12 and the crown spread value are shown in table 5.

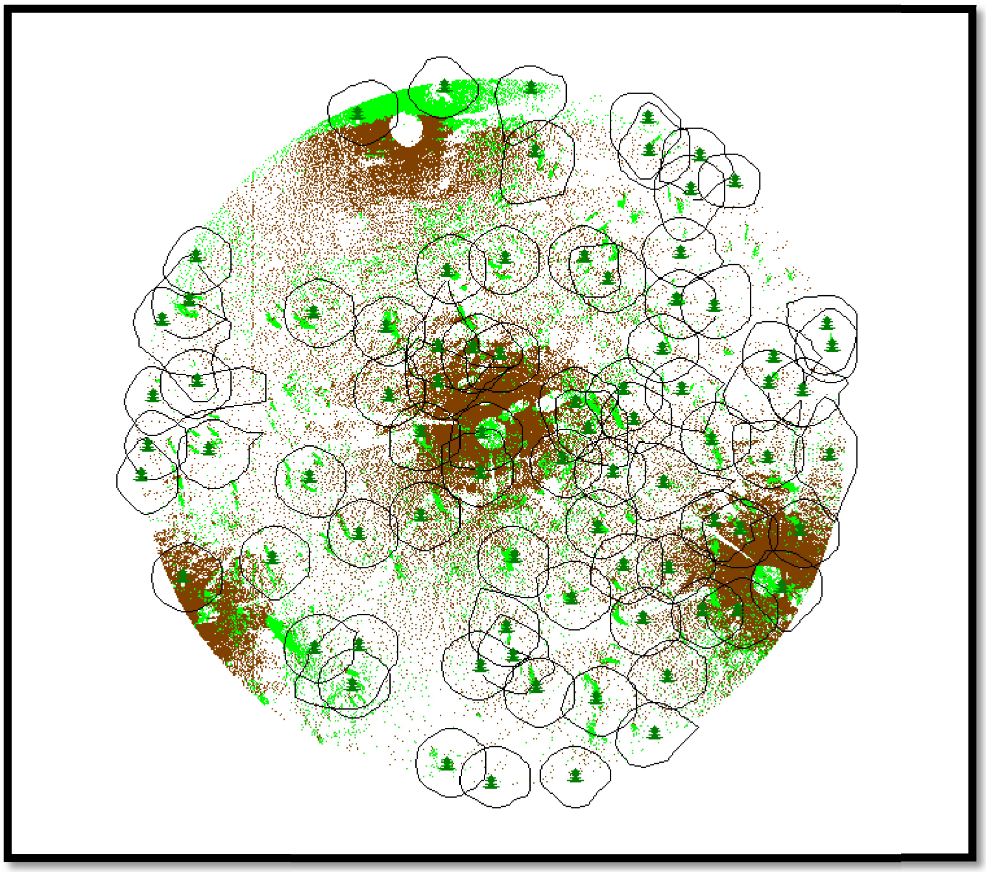

Figure 12: Number of trees and its spread detected by global mapper software

Table 5: Crown Spread of tree obtained from TLS-UAVs acquisition for plot 5 which consist of pinuswallichiana .

Tree no	DBH from TLS (m)	Height from TLS (m),H1	Crown Spread from TLS
1	0.261620495	13.782	5.5 m
2	0.362062692	16.746	6.1 m
5	0.423864767	20.049	5.3 m
6	0.198275547	20.269	5.4 m
7	0.418716686	19.584	4.9 m
8	0.291194379	16.446	5.3 m
9	0.429952248	21.308	6.0 m
10	0.321279227	16.296	4.9 m
11	0.288503374	17.912	5.2 m
12	0.200159095	15.176	4.7 m
13	0.323233099	18.162	4.8m
15	0.421516014	19.073	5.8 m
16	0.194969615	15.381	4.7 m
17	0.203475459	12.825	5.0 m
18	0.394833581	17.108	4.9 m
19	0.401536243	18.15	5.6 m

5 CONCLUSION

The proposed project on the preparation of allometric equations using TLS and UAVs has the potential to significantly improve tree volume model preparation in forest ecosystems. The integration of these advanced technologies offers enhanced accuracy, cost-effectiveness, and efficiency in data collection. To ensure successful implementation, it is important to address data processing challenges, validate the equations, adhere to standard protocols, and foster collaboration among stakeholders. The outcomes of this project can contribute to improved forest management, carbon accounting, and climate change mitigation efforts.

6 RECOMMENDATION

The integration of Terrestrial Laser Scanners (TLS) and Unmanned Aerial Vehicles (UAVs) offers great potential for data collection in forest ecosystems. However, the registration of TLS and UAV data can be challenging due to factors such as limited targets, adverse climate conditions, and other variables. This section provides recommendations based on identified findings to overcome these problems encountered during the registration process.

6.1 Findings:

Some key findings of our projects are listed below:

1. **Enhanced Accuracy:** The integration of TLS and UAV data has significantly improved the accuracy in capturing the 3D structure of Pinus *wallichiana* and Pinus *roxburghii* forests.By combining the strengths of TLS and UAV technologies, the project achieved a morecomprehensive representation of the forest, resulting in more precise allometric equations for biomass estimation.
2. **Limited Targets:**Due to the limited distinctive features in the forest environments of Pinus *wallichiana* and Pinus *roxburghii*, finding reliable targets for data registration was challenging.Natural features such as distinctive tree crowns and rock formations were successfully used as targets during the registration process.Additionally, artificial targets in the form of retroreflective markers strategically placed in the study area served as reliable control points for registration.
3. **Climate Conditions:**Adverse weather conditions, including rain, fog, and strong winds, posed challenges to data acquisition and registration.Close monitoring of weather conditions allowed for data collection during favorable periods, minimizing the impact of adverse weather on data quality.Appropriate data filtering and processing techniques were applied to mitigate noise and inconsistencies introduced by adverse weather conditions.
4. **Other Factors:**Proper calibration of TLS and UAV sensors was ensured before data acquisition to reduce discrepancies during registration.Downsampling or upsampling of datasets was performed to address differences in spatial resolution between TLS and UAV data, resulting in improved alignment and registration accuracy.Ground control points (GCPs) were deployed during UAV flights to enhance the accuracy of registration by providing reference points with known coordinates.

6.2 Recommendations:

Based on the findings above, the following recommendations can help overcome the problems encountered in the registration of TLS-UAV data:

1. **Pre-planning and Fieldwork:** It is crucial to meticulously plan fieldwork activities, focusing on target-rich areas and favorable weather conditions to optimize data collection efforts.

2. **Target Selection:** Explore both natural and artificial targets that possess distinct features and can be consistently detected in both TLS and UAV datasets. These targets will serve as reliable control points during registration.
3. **Sensor Calibration:** Ensure the proper calibration of TLS and UAV sensors before data acquisition. This will minimize discrepancies and improve the alignment of the datasets.
4. **Data Processing Techniques:** Implement appropriate filtering and processing techniques to effectively remove noise and artifacts caused by adverse weather conditions or variations in sensor resolution. This will enhance the accuracy of the registration process.
5. **Ground Control Points:** Deploy ground control points during UAV flights to improve registration accuracy and align the TLS and UAV datasets. These reference points with known coordinates will contribute to more precise data registration.

By implementing these recommendations, we can overcome the challenges related to limited targets, climate conditions, and other factors encountered during the registration of TLS-UAV data. These strategies will ultimately enhance the accuracy and reliability of our allometric equations, supporting improved forest inventory and biomass estimation in the study area.

7 REFERENCES

1. Acharya, Krishna Prasad, Prakash K %J Ministry of Industry Paudel, Tourism, Forest, and Karnali Province Government Environment, Surkhet, Nepal Cover photograph: Tibetan wild ass in Limi valley© Tashi R. Ghale Keywords: biodiversity, conservation, Karnali province, people-wildlife nexus, biodiversity profile. "Biodiversity in Karnali Province: Current Status and Conservation." 5 (2020).

2. Asner, G. P., Mascaro, J., Muller-Landau, H. C., &Vieilledent, G. (2012). A universal airborne LiDAR approach for tropical forest carbon mapping. Oecologia, 168(4), 1147-1160.

3. Blaschke, T. (2010). Object based image analysis for remote sensing. Isprs Journal of Photogrammetry and Remote Sensing, 65(1), 2–16. https://doi.org/10.1016/j.isprsjprs.2009.06.004

4. Bustamante, M. M. C., Roitman, I., Aide, T. M., Alencar, A., Anderson, L. O., Aragão, L. E. O. C., Asner, G. P., Barlow, J., Berenguer, E., Chambers, J. Q., Costa, M. H., Fanin, T., Ferreira, L. G., Ferreira, J., Keller, M., Magnusson, W. E., Morales-Barquero, L., Morton, D. C., Ometto, J. P. H. B., . . . Vieira, I. C. G. (2016). Toward an integrated monitoring framework to assess the effects of tropical forest degradation and recovery on carbon stocks and biodiversity. Global Change Biology, 22(1), 92–109. https://doi.org/10.1111/gcb.13087

5. Chojnacky, D.C., Heath, L.S. and Jenkins, J.C. (2013) ‘Updated generalized biomass equations for North American tree species’, *Forestry*, 87(1), pp. 129–151. doi:10.1093/forestry/cpt053.

6. Disney, M., Vicari, M. B., Burt, A. D., Calders, K., Lewis, S. R., Raumonen, P., & Wilkes, P. (2018). Weighing trees with lasers: advances, challenges and opportunities. Interface Focus, 8(2), 20170048. https://doi.org/10.1098/rsfs.2017.0048

7. G. Poley, L. and J. McDermid, G. (2020) ‘A systematic review of the factors influencing the estimation of vegetation aboveground biomass using unmanned aerial systems’, *Remote Sensing*, 12(7), p. 1052. doi:10.3390/rs12071052.

8. Lefsky, M. A., Cohen, W. B., Parker, G., & Harding, D. J. (2002). Lidar Remote Sensing for Ecosystem Studies. BioScience, 52(1), 19. https://doi.org/10.1641/0006-3568(2002)052

9. Liang, X., Hyyppä, J., Kaartinen, H., Lehtomäki, M., &Pyörälä, J. (2014). Automated stem curve measurement using terrestrial laser scanning. Remote Sensing of Environment, 140, 61-68.

10. Pieper, Rex D. "Rangeland Vegetation Productivity and Biomass." In *Vegetation Science Applications for Rangeland Analysis and Management*, 449-67: Springer, 1988.

11. Sanaa, Fadil, SebariImane, Bouhaloua Mohamed, Ait El kadi Kenza, KellouchSouhail, Hamza Lfalah, and Meghraoui %J Forests Khadija. "Biomass and Carbon Stock Quantification in Cork Oak Forest of Maamora Using a New Approach Based on the Combination of Aerial Laser

12. Scanning Carried by Unmanned Aerial Vehicle and Terrestrial Laser Scanning Data." 13, no. 8 (2022): 1211.

13. Sebrala, H. *et al.* (2022) 'Tree allometric equations for estimating biomass and volume of Ethiopian forests and establishing a database: Review', *Trees, Forests and People*, 9, p. 100314. doi:10.1016/j.tfp.2022.100314.

14. Vorster, Anthony G, Paul H Evangelista, Atticus EL Stovall, Seth %J Carbon balance Ex, and management. "Variability and Uncertainty in Forest Biomass Estimates from the Tree to Landscape Scale: The Role of Allometric Equations." 15, no. 1 (2020): 1-20.

15. Verburg, P. H., Neumann, K., & Nol, L. (2011). Challenges in using land use and land cover data for global change studies. Global Change Biology, 17(2), 974–989. https://doi.org/10.1111/j.1365-2486.2010.02307.x

16. White, Gary C %J Rangeland Ecology and Management/Journal of Range Management Archives. "Estimation of Plant Biomass from Quadrat Data Using the Lognormal Distribution." 31, no. 2 (1978): 118-20.

17. Wight, J Ross %J Rangeland Ecology and Management/Journal of Range Management Archives. "The Sampling Unit and Its Effect on Saltbush Yield Estimates." 20, no. 5 (1967): 323-25.

18. Wallace, L., Lucieer, A., Malenovský, Z., & Turner, D. (2018). Tree delineation and biomass retrieval in a regenerating post-mining landscape using terrestrial lidar. Forests, 9(11), 665.

19. Yuen, J.Q., Fung, T. and Ziegler, A.D. (2016) 'Review of allometric equations for major land covers in SE asia: Uncertainty and implications for above- and below-ground carbon estimates', *Forest Ecology and Management*, 360, pp. 323–340. doi:10.1016/j.foreco.2015.09.016.