Galván-Moreno VS *et al.* (2024)
Nova Geodesia 4(3):202
Review Article

Forest sampling techniques in different types of vegetation applying plot sampling, non-plot sampling, and remote sensing

Viridiana Sugey GALVÁN-MORENO[1]*, Oscar Alberto AGUIRRE-CALDERÓN[2], Eduardo ALANÍS-RODRÍGUEZ[2], Javier JIMÉNEZ-PÉREZ[2], Luis Gerardo CUÉLLAR-RODRÍGUEZ[2], Gerónimo QUIÑONEZ-BARRAZA[3], Joel RASCÓN-SOLANO[4]

*[1]Autonomous University of Nuevo León, Faculty of Forestry Sciences, Doctoral Program in Sciences with Orientation in Natural Resources Management, National Highway Km 145, ZIP 67700, Linares, Nuevo León, Mexico; viridiana2910@outlook.com (*corresponding author)*
[2]Autonomous University of Nuevo León, Faculty of Forestry Sciences, National Highway Km 145, ZIP 67700, Linares, Nuevo León, Mexico; oscar.aguirrecl@uanl.edu.mx; eduardo.alanisrd@uanl.edu.mx; javier.jimenezpr@uanl.edu.mx; luis.cuellarrd@uanl.edu.mx
[3]National Institute of Agricultural and Livestock Forestry Research, Guadiana Valley Experimental Field (INIFAP-CEVAG), Km 4.5 Durango-Mezquital Highway, 34170, Durango, Durango, Mexico; quinonez.geronimo@inifap.gob.mx
[4]Autonomous University of Chihuahua, Faculty of Agricultural and Forestry Sciences, 2.5 km on Delicias-Rosales Road 33000, Delicias, Chihuahua, Mexico; jsolano@uach.mx

Abstract

Forest inventories are undergoing rapid changes due to an increasingly complex set of economic, environmental, and social policy objectives. Therefore, the objective is to identify, analyse, and discuss the main forest inventory methods at global, regional, and local levels, with an analytical perspective on the goals they seek to achieve in various forest ecosystems. For this review, information from 79 relevant studies related to the objectives and methods used in sampling forest resources in tropical, boreal, temperate, and arid ecosystems was considered. According to the analysed studies, forest inventories in different ecosystems face challenges and apply varied methods to assess forests. In the tropics, the focus is on monitoring biomass and carbon, but they show limitations in data quality and quantity limitations. To improve accuracy, robust sampling methods are suggested. In boreal ecosystems, LiDAR and data-driven models offer detailed biomass estimates. In temperate forests, diversified sampling techniques are employed to balance accuracy and efficiency. In arid ecosystems, non-plot methods are useful for mapping density and diversity of the forests. To board the specific challenges of each region, innovative approaches are needed. Inventories have been influenced by changes in environmental policies and technology; therefore, the need to estimate key forest variables and monitor their dynamics requires robust and technologically advanced sampling methods.

Keywords: biomass; carbon; innovation; forest inventories; sampling methods

Received: 10 Jun 2024. Received in revised form: 15 Jul 2024. Accepted: 16 Jul 2024. Published online: 16 Jul 2024.

Introduction

National forest inventories have a long history, although their main current characteristics date back only to the early years of the 20th century (McRoberts *et al.*, 2010; Tomppo *et al.*, 2010). However, the requirements for forest inventory and management are changing rapidly within the context of an increasingly complex set of economic, environmental, and social policy objectives (White *et al.*, 2016). Additionally, forest inventory attributes are an important source of information for a variety of strategic and tactical forest management purposes (Brosofske *et al.*, 2013; Goodbody *et al.*, 2017), due to the need for accurate assessments of forest resources, as well as being a crucial source of information about the state and trends of these ecosystems (Tinkham *et al.*, 2018). Moreover, forest inventories employ robust statistical approaches to evaluate forest resources and support policy formulation (Alekseev *et al.*, 2019).

Generally, the objectives of forest inventories include evaluating forest health and composition, monitoring changes in tree cover, estimating wood and carbon stocks, planning sustainable management, and providing data for conservation policies and climate change mitigation. Their typical purpose has been to provide information for strategic forest and environmental decision-making (Fridman *et al.*, 2014). Historically, very different inventory systems and methods have been developed to assess the gross increment of forests and their components (Kuliešis *et al.*, 2016). They are also used to provide reliable estimates of key forest attributes directly and serve as tools to validate forest growth (Vidal *et al.*, 2016).

In managed forests, inventory efforts have focused on estimating forest performance variables such as basal area, volume, biomass, number of stems, and Lorey's height (Strunk *et al.*, 2012). They also analyze and evaluate trends in the ecologically sustainable development of forest resources (Haywood *et al.*, 2016). Sampling aims to achieve sustainability in wood supply and consider the short- and long-term ecological and economic consequences of silvicultural treatments based on actual and predicted forest conditions (Vandendaele *et al.*, 2021). Forest inventory has significantly increased the efficiency of practical forestry operations (Maltamo and Packalen, 2014). Since inventory methods are never free from errors, the decision to conduct an inventory is more about when to update it to improve data quality, rather than striving for perfect information (Eyvindson *et al.*, 2017).

In decision-making processes, the importance of the sampling method or technique employed is emphasized, as the accuracy of the relevant information, used as the basis for decisions, assumes that better data quality will lead to better decisions (Eyvindson *et al.*, 2017; Galván-Moreno *et al.*, 2023). Sampling techniques like the nearest neighbor method have emerged within the international forestry community as useful methods for predicting forest attributes in field plots with similar spatial characteristics (Tomppo *et al.*, 2008; McRoberts, 2012). This sampling method has been complemented with satellite imagery in various parts of the world (McRoberts, 2010). In this regard, Leak *et al.* (2014) mention the need for better inventory methods to support these complex interventions. Therefore, significant advances have been made in the development of laser scanning techniques over the past two decades to enhance forest inventories beyond photointerpretation methods (Woods *et al.*, 2011; Treitz *et al.*, 2012; Bouvier *et al.*, 2015; Tompalski *et al.*, 2016).

Based on the above, the objective of this investigation is to identify, analyze, and discuss the main forest inventory methods at global, regional, and local levels, with an analytical perspective on the goals they seek to achieve in various forest ecosystems. The assumption was that the diversity of forest resources, forest management methods, analysis systems, technological capacity, and precision are factors that determine the inventory method to be applied.

Materials and Methods

Despite the socioeconomic and environmental importance of forest sampling in Mexico, the available information on this activity is largely incomplete. Therefore, this review considered information from 79 relevant studies related to the objectives and methods employed in the sampling of forest resources. Preference was given to studies that present precise information on sampling techniques in various ecosystems, and how these techniques and processes can be adapted to the conditions of the forest sector in Mexico from an international perspective was discussed. A total of 79 works published between 1989 and 2024 were selected. These investigations detail the application of forest inventories with various objectives. Four forest ecosystems were considered:

- *Tropical ecosystems:* Studies included rainforests, humid deciduous forests, dry and semi-dry tropical forests, and tropical highland forest formations.
- *Boreal ecosystems:* Studies analysed coniferous forests in the frigid regions of the Northern Hemisphere.
- *Temperate ecosystems:* These included coniferous forests, pine forests, oak forests, and mixed pine-oak forests.
- *Arid ecosystems:* These consisted of grasslands and wooded savannas, hot deserts and semi-deserts, temperate zone grasslands, and cold desert biomes.

The review aimed to provide a comprehensive understanding of the application of various inventory methods in these different ecosystems, considering the specific challenges and adaptations required for effective forest resource assessment in Mexico. Figure 1 shows the process undertaken to define the forest inventory methods used for the four main terrestrial ecosystems.

Tropical Ecosystems

Forest inventories have proven to be valuable sources of data for estimating various dasometric variables; however, inventories in tropical regions are few and of poor quality (Brown *et al.*, 1989; Brown and Gaston, 1995; Appiah, 2013). Diverse approaches have been applied to forest inventories in the tropics, prominently featuring forest monitoring and quantification of aboveground forest biomass (Picard *et al.*, 2018; Beyene *et al.*, 2020; Ploton *et al.*, 2020), to estimate forest carbon budgets and GHG emissions (Lopez-Gonzalez *et al.*, 2011; Mohren *et al.*, 2012; Malhi *et al.*, 2021), measure various types and levels of anthropogenic disturbance (Parrotta, 1992; Hannah *et al.*, 1994), estimate stock and regeneration dynamics in natural forests (Hitimana *et al.*, 2019), analyse ecological and socio-economic aspects (Corona and Marchetti, 2007), forest management and reduced-impact logging practices (Gaem *et al.*, 2022; Badouard *et al.*, 2024), among others.

Some studies aimed at increasing the precision of inventories in tropical ecosystems, such as the one conducted by McRoberts *et al.* (2013), mention that sampling options in tropical ecosystems include single plots, subdivisions, or clusters, considering size and shape based on a sampling point; similarly, subplots within plots are small and close to the sampling point according to the sampling plot configurations used (McRoberts *et al.*, 2005). On the other hand, the size of sampling sites is subject to multiple important considerations related to logistics, cost, and precision (Gregoire *et al.*, 2011; Næsset *et al.*, 2013; Knapp *et al.*, 2018). To define the size of the sampling plots, at least two variables need to be defined: first, a group of plots or a plot with its subplots should be small enough for a field team to complete all measurements in one day (Tomppo *et al.*, 2010; Tompo *et al.*, 2011); and second, the plot characteristics, such as the radius for circular plots and lengths for strip and rectangular plots, should be measured on a horizontal plane, not along uneven terrain (Kleinn *et al.*, 2015).

Mora-Espinoza *et al.* (2020) evaluated the precision and efficiency of angle count sampling in teak (*Tectona grandis* L. f.) plantations, comparing 21 circular plots with angle count sampling using different basal area factors (BAF). No significant differences were found in the estimation of variables, demonstrating the precision of the angle count method. The angle count sampling was more efficient, with relative efficiency between 4.5 and 11 times greater than fixed-area plot sampling. A BAF of 2 was determined for young teak plantations. In conclusion, angle count sampling was found to be precise and more efficient for estimating dasometric variables in this type of plantation.

In contrast, Kauffman *et al.* (2013) mention that in mangroves, both permanent and temporary plots are used. The former aim to take measurements over time in marked areas to determine changes, while the latter aim to measure composition, structure, and carbon stocks over a period. Castillo Elías *et al.* (2018) established 10 × 10 m (100 m^2) sites with the objective of understanding the structural composition of plant species and the ecological importance of the mangrove to provide conservation alternatives for the area.

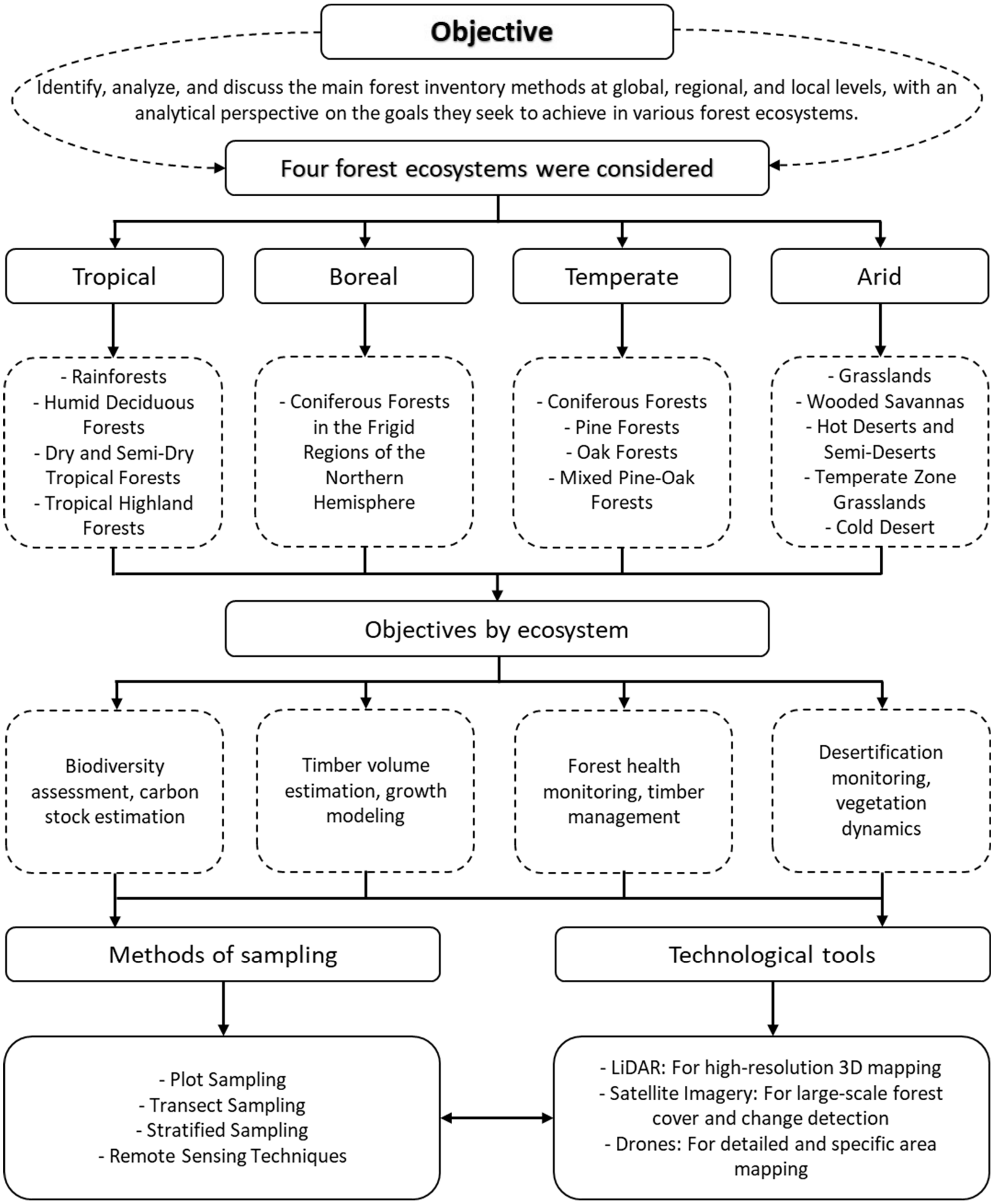

Figure 1. Sequence diagram of the analysis objective, main ecosystems studied, levels of focus, measurement techniques, and mention of technologies used in forest inventory methods from a global perspective

Due to the difficult access to mangrove forests, innovative techniques such as remote sensing, including the use of unmanned aerial vehicles for sampling, are demanded. In this regard, Jones *et al.* (2020) acquired drone images to generate a three-dimensional model and an orthomosaic, allowing them to measure tree height and canopy area, which were subsequently used to model Diameter at Breast Height (DBH and $D_{1.30}$), demonstrating potential for predicting aboveground biomass. Remote sensing is a valuable tool for monitoring these ecosystems as it enables monitoring mangrove forests at regional and local scales (Giri, 2016; Muhsoni *et al.*, 2018).

Studies such as those by Brown and Gaston (1995), Appiah (2013), Romijn *et al.* (2015) and Beyene *et al.* (2020), have investigated changes in forest cover and inventory capabilities in tropical ecosystems. By integrating traditional inventory data with remote sensing, they offer a reliable way to monitor forest dynamics. However, their application in developing countries is limited by the lack of national data and the limited use of remote sensing technologies (Hernandez-Alvarez *et al.*, 2006; Romijn *et al.*, 2015).

In Mexico, Arias-Medellín *et al.* (2014) used systematic sampling of 50 × 50 m plots in secondary and conserved jungle. They found that chronic disturbance increases diversity, richness, and evenness of cacti but reduces size and proportion of adults, affecting ecosystem biodiversity. Dupuy *et al.* (2012) observed that stem density showed a decreasing trend with increasing stand age in tropical forests. This study implemented a sampling design with two concentric circular sites, consisting of a main plot of 200 m^2 and an inner subplot of 50 m^2.

Boreal Ecosystems

Boreal forests, also known as taiga, extend across northern regions of Alaska, Canada, Northern Europe, Russia, and northeastern China, between the Arctic tundra and cold temperate forests. Their climate is characterized by long periods of snow and cool summers. These forests play a crucial role in providing ecosystem services such as carbon storage and supplying drinking water, with a significant impact on climate at the local, regional, and global levels (Frelich, 2020).

Lupi *et al.* (2017) developed allometric equations for small-diameter woody species in mixed marginal forested areas. The fixed-area plot (FAP) method was successfully used to estimate dry biomass per hectare. Biomass estimates varied according to site productivity. The use of FAP with 100 m^2 plots is recommended for estimating small-diameter biomass in densely vegetated marginal areas.

Kenning *et al.* (2005) evaluated the N-tree distance sampling as an efficient method for inventorying trees in mixed forests in Maine and New Hampshire. Compared to fixed-area sampling and modified horizontal line sampling, N-tree distance sampling proved to be fast but with some bias and high variability. A modification was introduced to limit the search distance for counted trees from the center of the plot, which helped mitigate identified issues.

In LiDAR-assisted forest sampling, plots representing the entire study area are selected. Models based on LiDAR data and canopy metrics are then built to predict soil biomass. These models are applied to the entire area, allowing detailed and accurate estimates of forest biomass on a large scale (Nelson *et al.*, 2012).

Margolis *et al.* (2015) analyzed the estimation of aboveground biomass in the North American boreal forest using LiDAR and ICESat-GLAS, achieving a relative error of 1.9%. A varied distribution of biomass was observed among Western Canada (46.6%), Eastern Canada (43.7%), and Alaska (9.7%). Discrepancies between managed and unmanaged areas are highlighted, with uncertainties related to sampling and regression between airborne and spaceborne vehicles. GLAS estimates are compared with forest inventory data and MODIS-based interpolation techniques to assess their accuracy.

In Kristensen *et al.*'s study (2015), they analyzed the potential of LiDAR aerial scanning to assess and monitor carbon reserves in boreal forests. They combined LiDAR data with detailed information on plant and soil carbon to analyze the distribution and size of carbon reserves, finding a correlation between LiDAR data and variation in carbon reserves in the field layer, but no significant models were obtained for the understory.

The research establishes a connection between forest carbon reserves and LiDAR data, providing a basis for future monitoring studies in boreal forests.

Wittke *et al.* (2019) conducted a study comparing the utility of multitemporal Sentinel-2 satellite images with airborne laser scanning (ALS) and high-resolution optical image data for forest inventories in boreal forests. They used field data from 74 forest plots in Finland as reference. The results show that higher spatial resolution data correlates with more accurate predictions, and the addition of temporal information slightly improves prediction accuracy. The importance of obtaining more evenly distributed data acquisitions during the growing season to leverage the potential of temporal features is highlighted.

Wang *et al.* (2019) evaluated, in 18 plots of fixed size 32 m × 32 m, the use of laser scanning to estimate forest biomass, differentiating between the influence of data and processing algorithms. They found that individual tree digitization varied depending on forest density and the type of laser scanning used. The lack of large trees significantly affected biomass estimates. Automated algorithms produced results similar to manual measurements in less dense forests. The combination of ground and aerial data improved the accuracy of biomass estimates.

Adnan *et al.* (2019) developed a methodology to identify forest structural types (FST) using airborne laser scanning (ALS) in the Kiihtelysvaara Forest, Finland. They used hierarchical clustering analysis and classification and regression tree analysis to determine the FST and establish discriminative thresholds. Variables such as mean quadratic diameter and GINI coefficient were crucial in identifying FST. Using ALS-derived data to predict FST, they obtained higher overall accuracy in deciduous forests than in coniferous forests. This simple two-level approach to classifying FST demonstrates the usefulness of ALS data in assessing structural heterogeneity of forests in various biogeographic regions.

Dai *et al.* (2022) compared the performance of terrestrial laser scanning (TLS) and unmanned aerial vehicle (UAV) laser scanning to estimate canopy coverage in *Pinus massoniana* Lamb. forest plots. It was carried out in 16 plots in Guangxi, China, using methods based on canopy height model (CHM) and individual tree delineation (ITD). The results showed that TLS accuracies were better than TLS, with average differences of 6.91%. Reasonable CHM pixel sizes were determined for both techniques. These findings are useful for selecting data sources and estimation methods in mapping canopy coverage in forest plots.

Temperate Ecosystems

Forest inventories in temperate forests are necessary to provide information and monitor sustainability with statistical accuracy and reasonable costs (Leiter and Hasenauer, 2023). Determinants of any sampling design are the expected variation and the precision to be achieved. Considering objectives, defining five silvicultural criteria (forest growth, economy, carbon sequestration, stand stability, and biodiversity) is essential (Hilmers *et al.*, 2020).

Methods for studying population density can be divided into two categories: 1) plot-based methods and 2) distance-based methods. The former involves enumerating individuals in a specific area, while the latter estimates and records the distances of populations of individuals from a random point or between individual specimens, typically along a transect, also called plotless methods (Zhu and Zhang, 2009).

Liang *et al.* (2016) mention that field samples can be used to calculate means and totals over the area of interest or to assist in remote sensing-based forest mapping. Therefore, the accuracy in forest inventories depends on the quality and quantity of the sample. Many forest sampling processes have been developed (Iles, 2003). Each country has its own forest inventory system with its methodology ranging from grid sampling designs to forest studies and/or a combination of remote sensing data with ground forest information (Tomppo *et al.*, 2010).

Sampling in temperate forests is crucial for understanding the structure, composition, and dynamics of these ecosystems. In a study in giant plantation forests in Santiago del Estero, Argentina, Pece *et al.* (2000) compared sampling methods in fixed plots. They used Probability Proportional to Size Sampling (PPS), Horizontal Point, and Horizontal Line with variable-area plots. They found no significant differences between treatments. Estimates obtained by Point and Horizontal Line were as precise as those of fixed plots, showing higher relative efficiency in the former. On the other hand, Vidal *et al.* (2016) and Pucher *et al.* (2022) mention that predominant sampling methods in European terrestrial forests, according to studies, are horizontal point sampling, variable-radius plot sampling, or Bitterlich sampling. Leiter and Hasenauer (2023) evaluated the accuracy of two sampling methods in Central European forests to improve biodiversity: angle count sampling and fixed-area plot sampling. Using simulations in Plenter forests in Switzerland, they analyzed the variability and error of these methods for three key parameters. They suggest that a fixed-area plot with circles of 300 m^2 is optimal for balancing profitability and precision, although other options such as 500 m^2 plots or a combined method are also considered.

The combined use of field data and remote sensors for forest inventories is a current topic of interest. One of the significant challenges for its practical application is optimizing/minimizing the volume of data to achieve acceptable estimations (Galeote-Leyva *et al.*, 2022). This is particularly feasible in temperate forests with relatively simplistic structures and open canopy covers, where LiDAR has been shown to extract information from individual canopies more accurately.

In Mexico, Galván-Moreno *et al.* (2023) compared fixed-size sites and Bitterlich sites with a census in *Pinus arizonica* Engelm. forests, evaluating accuracy, sampling times, and costs. They did not obtain significant differences in the number of trees per hectare between methods and census. Basal area was similar between methods, but fixed dimensions showed greater error. Estimated volume per hectare was similar to the census, with greater precision in the variable area method. There were significant differences in time and costs between methods, but both were statistically acceptable.

On the other hand, Aguirre *et al.* (1995) determined the optimal size of circular plots in a stand of *Pinus cooperi* Blanco in Durango, Mexico, to be 0.05 hectares; however, they did not obtain definitive results on estimates with basal area factor. Likewise, Aguirre Calderón *et al.* (1997) evaluated different sizes of circular sampling sites in a stand of *Pinus cooperi* Blanco in Durango, Mexico, determining an optimal size of 0.06 hectares based on statistical parameters of basal area.

Arid Ecosystems

Suganuma *et al.* (2006) examined the feasibility of using canopy cover and other stand attributes to accurately estimate forest biomass. They evaluated 35 plots (50 × 50 m), calculating tree biomass using allometric equations. Stand basal area (SBA) was found to have the highest accuracy, but canopy cover (CC) and leaf area index (LAI) are valuable indicators, especially in open forests.

Nunes *et al.* (2015) randomly selected an area of approximately 1,000 m^2 at each sampling location, employing three sampling designs (MW): modified Whittaker plots (20 × 50 m with a subplot of 100 m^2, 2 of 10 m^2, and 10 of 1 m^2); (DE): Dengler plots (31.6 × 31.6 m with 3 subplots of 100 m^2, 3 of 10 m^2, and 6 of 1 m^2); and (PT): point method (6 transects of 20 m with 41 points each spaced every 0.5 m), overlaying them as much as possible over the selected area. The PT method stood out for its accuracy in detecting species and traits, outperforming MW and DE. This ensures the inclusion of less common species, essential for the resilience and function of semi-arid ecosystems. Its advantages were evident in various environments, and it is expected to be less biased and more reproducible than visually estimated methods.

Basiri *et al.* (2018) evaluated distance methods to estimate tree density of *Populus euphratica* in riparian forests of Maroon, Iran. They tested 40 estimators in pure and mixed stands, using 50 quadrants of 30 × 30 m. In pure stands, the variable area transect method and the quadrant method proved to be the most effective for density estimation, while in mixed stands, the point-centered quarter method was superior. The use of composite three basic distances (BDAV3) and basic distance-nearest neighbor (BDNN2) is recommended for density estimation.

Gerhold *et al.* (2013) examined grassland manipulation between 2002 and 2011 by adding fertilizers or sucrose in small plots (50 × 50 cm). They were able to link annual changes in species diversity with alterations in functional and phylogenetic diversity, using abundance-weighted distance measures.

Table 1. Comparative table of sampling methods and objectives by ecosystem type

Sampling Method	Ecosystem	Main Objectives
Transects	Tropical Temperate	**Tropical:** Evaluate the quantity and quality of forest resources (timber, biodiversity). **Temperate:** Assess seasonal changes and impact.
Random Sampling	Tropical Boreal	**Tropical:** Represent the variability of the ecosystem. **Boreal:** Obtain a representative sample for biomass and carbon studies.
Point Sampling	Arid	**Arid:** Adaptation to low vegetation and water density, ecosystem resilience.
Adapted Plots	Arid	**Arid:** Evaluation of arid conditions and ecosystem resilience.
Remote Sensing	Tropical Boreal Arid Temperate	**Tropical:** Monitoring deforestation, changes in forest cover, and biodiversity on a regional to global scale. **Boreal:** Assessing changes in forest biomass and carbon, detecting disturbances (such as wildfires). **Arid:** Monitoring desertification, changes in vegetation, and water resource management. **Temperate:** Detecting seasonal and phenological changes, monitoring disturbances, and land use.
Variable Dimension	Tropical Boreal Temperate	**Tropical:** Measuring diversity and density of tree species. **Boreal:** Assessing forest structure and regeneration dynamics. **Temperate:** Monitoring species distribution and forest structure.
Concentric Sites	Tropical Boreal Temperate Arid	**Tropical:** Assessing species diversity at different spatial scales. **Boreal:** Measuring forest density and structure at various radii. **Temperate:** Detailed analysis of forest structure and biodiversity. **Arid:** Evaluating spatial variability in low-density ecosystems.
Bitterlich Method	Tropical Boreal Temperate Arid	**Tropical:** Rapid estimation of tree density and biomass. **Boreal:** Efficient assessment of forest density and volume estimation. **Temperate:** Quick and effective measurement of forest structure. **Arid:** Evaluation of tree density and forest resources in areas with low vegetation.
Structural Groups	Tropical Boreal Temperate	**Tropical:** Analysis of the composition and structure of vegetative groups. **Boreal:** Study of the dynamics and succession of vegetative groups. **Temperate:** Evaluation of species interactions and structure of plant communities.
Neighborhood	Tropical Boreal Temperate	**Tropical:** Analysis of the interaction between individuals and their immediate environment. **Boreal:** Study of proximity and competition among trees. **Temperate:** Evaluation of spatial distribution and competition among species.
Rectangular Strips	Tropical Boreal Arid	**Tropical:** Assessment of species distribution and density. **Boreal:** Measurement of forest structure and density. **Arid:** Evaluation of spatial distribution and density in low vegetation ecosystems.
Clusters	Tropical Boreal Temperate Arid	**Tropical:** Assessment of ecosystem diversity and structure across a wide area. **Boreal:** Monitoring of forest structure and biomass. **Temperate:** Evaluation of vegetation structure and density. **Arid:** Monitoring of vegetation and spatial variability in low-density areas.
Subplots	Tropical Boreal Temperate	**Tropical:** Detailed analysis of species diversity and structure. **Boreal:** Assessment of forest regeneration and dynamics. **Temperate:** Study of forest structure and biodiversity.
Quadrants	Tropical Boreal Temperate	**Tropical:** Analysis of species distribution and abundance in delimited areas. **Boreal:** Assessment of forest density and structure in small units. **Temperate:** Study of vegetation composition and structure.

Silva *et al.* (2017) compared square sampling, point-centered quarter method (PCQM), and tree sampling with reference quadrant sampling (QD) in stands of *Pittosporum undulatum* in the Azores. Square sampling was found to be the most accurate and precise method, followed by PCQM. Despite slightly underestimating tree density, square sampling showed low bias and high precision, making it recommended for biomass assessment programs.

Kiani *et al.* (2013) evaluated plotless sampling methods for efficient mapping of plant communities in two 30-ha Saksaul population sites located in Siahkooh, Iran, with different patterns. Using spatial data and stem mapping in ArcGIS, they assessed the point-centered quarter method (PCQ), joint-point method (JP), random-pair method (RP), T-square method (T-Sq), and n-tree methods in addition to fixed-area plot (FAP), n-tree method, and variable-area transect (VAT). Results favored VAT for random patterns at site I and VAT for clustered patterns at site II. N-tree methods were effective for coverage estimation. Overall, VAT was recommended for its simplicity and effectiveness, especially in uncertain spatial patterns.

Mirzaei and Bonyad (2016) evaluated fixed-area and distance methods in the open forest area of Zagros, Iran. They were compared based on data obtained from a complete survey. They systematically installed 37 sampling plots with a grid of 100 × 100 m in the study area. Results showed significant differences between methods. Transect sampling proved to be more economical and practical for quantifying forest characteristics.

According to Briones *et al.* (2018), forest sampling efforts in arid zones in Mexico have been highly variable, as estimates have been made based on plots ranging from 25 m^2, square plots of 600 m^2, to circular sites of 1,000 m^2.

In summary, Table 1 indicates the forest sampling methods used in the four types of ecosystems considered in this review. It also shows the objectives of the samplings and how these inventory objectives are executed in relation to the type of sampling to be employed. Sampling sites encompass the implementation of fixed-size plots, variable-size plots, or those based on structural tree groups, along with the use of remote sensing techniques.

The table outlines various sampling methods employed across different ecosystems and their primary objectives. These methods range from transects to remote sensing, each tailored to specific environmental conditions and research goals. In tropical ecosystems, there's a focus on assessing forest resources and biodiversity, while in temperate regions, the emphasis is on monitoring seasonal changes and species distribution. In boreal areas, methods aim at obtaining representative samples for biomass studies and evaluating forest structure, whereas in arid environments, the focus is on assessing adaptation to low vegetation density and managing ecosystem resilience. Each method serves a unique purpose in understanding and managing diverse ecosystems worldwide.

Conclusions

Forest inventories face challenges regarding the costs involved, accuracy, and efficiency due to the complexity of management objectives and ecosystem variability. The history and evolution of these inventories, influenced by changes in policies and technology, reflect their importance in environmental decision-making. The need to estimate key forest variables and monitor their dynamics requires robust and technologically advanced sampling methods. The integration of techniques such as plot sampling, non-plot sampling, and remote sensing provides valuable tools for improving data quality. However, challenges persist in the selection and application of sampling methods, underscoring the importance of continuing to advance the development of forest inventory techniques to address current and future environmental and management challenges.

Authors' Contributions

All authors contributed to the manuscript. The authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

Acknowledgements

The authors thank the National Council of Humanities, Sciences and Technologies (CONAHCYT) of Mexico for the scholarship awarded to the first author to carry out his Doctorate studies in Sciences with an emphasis on Natural Resource Management.

Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

References

Adnan S, Maltamo M, Coomes DA, García-Abril A, Malhi Y, Manzanera JA, Butt N, Morecroft M, Valbuena R (2019). A simple approach to forest structure classification using airborne laser scanning that can be adopted across bioregions. Forest Ecology and Management 433:111-121. *https://doi.org/https://doi.org/10.1016/j.foreco.2018.10.057*

Aguirre Calderón OA, Jiménez Pérez J, Treviño Garza EJ, Meraz Alemán B (1997). Evaluación de diversos tamaños de sitio de muestreo en inventarios forestales [Assessment of Various Plot Sizes in Forest Inventories]. Madera y Bosques 3(1):71-79. *https://doi.org/10.21829/myb.1997.311380*

Aguirre OA, Jiménez Pérez J, Meraz B (1995). Optimizing inventories for forest management: A study case in Durango, México. Forest Systems 4(1):107-118. *https://doi.org/https://doi.org/10.5424/540*

Alekseev A, Tomppo E, McRoberts RE, von Gadow K (2019). A constructive review of the State Forest Inventory in the Russian Federation. Forest Ecosystems 6(1):9. *https://doi.org/10.1186/s40663-019-0165-3*

Appiah M (2013). Tree population inventory, diversity and degradation analysis of a tropical dry deciduous forest in Afram Plains, Ghana. Forest Ecology and Management 295:145-154. *https://doi.org/https://doi.org/10.1016/j.foreco.2013.01.023*

Arias-Medellín LA, Flores-Palacios A, Martínez-Garza C (2014). Cacti community structure in a tropical Mexican dry forest under chronic disturbance. Botanical Sciences 92(3):405-415. *https://doi.org/https://doi.org/10.17129/botsci.92*

Badouard V, Schmitt S, Salzet G, Gaquiere T, Rojat M, Bedeau C, Brunaux O, Derroire G (2024). LoggingLab: An R package to simulate reduced-impact selective logging in tropical forests using forest inventory data. Ecological Modelling 487:110539. *https://doi.org/10.1016/j.ecolmodel.2023.110539*

Basiri R, Moradi M, Kiani B, Maasumi Babaarabi M (2018). Evaluation of distance methods for estimating population density in *Populus euphratica* Olivier natural stands (case study: Maroon riparian forests, Iran). Journal of Forest Science 64(5):230-244. *http://dx.doi.org/10.17221/146/2017-JFS*

Beyene SM, Hussin YA, Kloosterman HE, Ismail MH (2020). Forest Inventory and Aboveground Biomass Estimation with Terrestrial LiDAR in the Tropical Forest of Malaysia. Canadian Journal of Remote Sensing 46(2):130-145. *https://doi.org/10.1080/07038992.2020.1759036*

Bouvier M, Durrieu S, Fournier RA, Renaud J-P (2015). Generalizing predictive models of forest inventory attributes using an area-based approach with airborne LiDAR data. Remote Sensing of Environment 156:322-334. *https://doi.org/https://doi.org/10.1016/j.rse.2014.10.004*

Briones O, Búrquez A, Martínez-Yrízar A, Pavón N, Perroni Y (2018). Biomasa y productividad en las zonas áridas mexicanas. Madera y Bosques 24: e2401898. *https://doi.org/10.21829/myb.2018.2401898*

Brosofske KD, Froese RE, Falkowski MJ, Banskota A (2013). A Review of methods for mapping and prediction of inventory attributes for operational forest management. Forest Science 60(4):733-756. *https://doi.org/10.5849/forsci.12-134*

Brown S, Gaston G (1995). Use of forest inventories and geographic information systems to estimate biomass density of tropical forests: Application to tropical Africa. Environmental Monitoring and Assessment 38(2):157-168. *https://doi.org/10.1007/BF00546760*

Brown S, Gillespie AJ, Lugo AE (1989). Biomass estimation methods for tropical forests with applications to forest inventory data. Forest Science 35(4):881-902. *https://doi.org/10.1093/forestscience/35.4.881*

Castillo Elías B, Gervacio Jiménez H, Bedolla Solano R (2018). Estructura forestal de una zona de manglar en la laguna de Coyuca de Benítez, Guerrero [The Forest Structure of a Mangrove Area in the Coyuca de Benítez Lagoon, Guerrero]. Revista Mexicana de Ciencias Forestales 9(45). *https://doi.org/10.29298/rmcf.v9i45.140*

Corona P, Marchetti M (2007). Outlining multi-purpose forest inventories to assess the ecosystem approach in forestry. Plant Biosystems - An International Journal Dealing with all Aspects of Plant Biology 141(2):243-251. *https://doi.org/10.1080/11263500701401836*

Dai W, Guan Q, Cai S, Liu R, Chen R, Liu Q, Chen C, Dong Z (2022). A comparison of the performances of Unmanned-Aerial-Vehicle (UAV) and terrestrial laser scanning for forest plot canopy cover estimation in *Pinus massoniana* forests. Remote Sensing 14(5):1188. *https://www.mdpi.com/2072-4292/14/5/1188*

Dupuy JM, Hernández-Stefanoni JL, Hernández-Juárez RA, Tetetla-Rangel E, López-Martínez JO, Leyequién-Abarca E, Tun-Dzul FJ, May-Pat F (2012). Patterns and correlates of tropical dry forest structure and composition in a highly replicated chronosequence in Yucatan, Mexico. Biotropica 44(2):151-162. *https://doi.org/10.1111/j.1744-7429.2011.00783.x*

Eyvindson KJ, Petty AD, Kangas AS (2017). Determining the appropriate timing of the next forest inventory: incorporating forest owner risk preferences and the uncertainty of forest data quality. Annals of Forest Science 74(1):2. *https://doi.org/10.1007/s13595-016-0607-9*

Frelich LE (2020). Boreal and Taiga Biome. In: Goldstein MI, DellaSala DA (Eds). Encyclopedia of the World's Biomes. Elsevier pp 103-115. *https://doi.org/10.1016/B978-0-12-409548-9.11926-8*

Fridman J, Holm S, Nilsson M, Nilsson P, Ringvall AH, Ståhl G (2014). Adapting National Forest Inventories to changing requirements – the case of the Swedish National Forest Inventory at the turn of the 20th century, Vol 48. *https://doi.org/doi:10.14214/sf.1095*

Gaem PH, Andrade A, Mazine FF, Vicentini A (2022). Tree species delimitation in tropical forest inventories: Perspectives from a taxonomically challenging case study. Forest Ecology and Management 505:119900. *https://doi.org/10.1016/j.foreco.2021.119900*

Galeote-Leyva B, Valdez-Lazalde JR, Ángeles-Pérez G, De los Santos-Posadas HM, Romero Padilla JM (2022). Inventario forestal asistido por LIDAR: efecto de la densidad de retornos y el diseño de muestreo sobre la precision [LIDAR-Assisted forest inventory: Effect of return density and sampling design on accuracy]. Madera y Bosques 28(2):e2822330. *https://doi.org/10.21829/myb.2022.2822330*

Galván-Moreno VS, Olivas-García JM, Rascón-Solano J, Hernández-Salas J (2023). Evaluation of two sampling methods for even-age *Pinus* forest in northern Mexico. Notulae Scientia Biologicae 15(2):11564. *https://doi.org/10.55779/nsb15211564*

Gerhold P, Price JN, Püssa K, Kalamees R, Aher K, Kaasik A, Pärtel M (2013). Functional and phylogenetic community assembly linked to changes in species diversity in a long-term resource manipulation experiment. Journal of Vegetation Science 24(5):843-852. *https://doi.org/10.1111/jvs.12052*

Giri C (2016). Observation and monitoring of mangrove forests using remote sensing: Opportunities and challenges. Remote Sensing 8(9):783. *https://doi.org/10.3390/rs8090783*

Goodbody TRH, Coops NC, Marshall PL, Tompalski P, Crawford P (2017). Unmanned aerial systems for precision forest inventory purposes: A review and case study. The Forestry Chronicle 93(01):71-81. *https://doi.org/10.5558/tfc2017-012*

Gregoire TG, Ståhl G, Næsset E, Gobakken T, Nelson R, Holm S (2011). Model-assisted estimation of biomass in a LiDAR sample survey in Hedmark County, Norway. Canadian Journal of Forest Research 41(1):83-95. *https://doi.org/10.1139/x10-195*

Hannah L, David L, Charles H, Carr JL, Ali L (1994). A preliminary inventory of human disturbance of world ecosystems. Ambio 23(4/5):246-250. *http://www.jstor.org/stable/4314213*

Haywood A, Mellor A, Stone C (2016). A strategic forest inventory for public land in Victoria, Australia. Forest Ecology and Management 367:86-96. *https://doi.org/10.1016/j.foreco.2016.02.026*

Hernandez-Alvarez E, Pelz DR, Carlos R-F (2006). Inventorying and monitoring of tropical dry forests tree diversity in Jalisco, Mexico using a Geographical Information System. Research and Development pp 638-648. *https://www.fs.usda.gov/research/treesearch/26551*

Hilmers T, Biber P, Knoke T, Pretzsch H (2020). Assessing transformation scenarios from pure Norway spruce to mixed uneven-aged forests in mountain areas. European Journal of Forest Research 139(4):567-584. *https://doi.org/10.1007/s10342-020-01270-y*

Hitimana J, Ole Kiyiapi JL, Bekuta BK (2019). Efficient protocol of complete inventory for tree regeneration and recruitment studies over one hectare in selected tropical natural forests, Kenya. Repositorio Dspace 6(3):376-392. *https://doi.org/10.22271/tpr.2019.v6.i3.047*

Iles K (2003). A sampler of inventory topics. Kim Iles and Associates, Nanaimo, BC.

Jones AR, Raja Segaran R, Clarke KD, Waycott M, Goh WSH, Gillanders BM (2020). Estimating mangrove tree biomass and carbon content: A comparison of forest inventory techniques and drone imagery [Original Research]. Frontiers in Marine Science 6. *https://doi.org/10.3389/fmars.2019.00784*

Kauffman JB, Donato DC, Adame MF (2013). Protocolo para la medición, monitoreo y reporte de la estructura, biomasa y reservas de carbono de los manglares [Protocol for the Measurement, Monitoring, and Reporting of Mangrove Structure, Biomass, and Carbon Reserves] Vol 117, Cifor.

Kenning RS, Ducey MJ, Brissette JC, Gove JH (2005). Field efficiency and bias of snag inventory methods. Canadian Journal of Forest Research 35(12):2900-2910. *https://doi.org/10.1139/x05-207*

Kiani B, Fallah A, Tabari M, Hosseini SM, Parizi M (2013). A comparison of distance sampling methods in Saxaul (*Halloxylon ammodendron* CA Mey Bunge) Shrub-Lands. Polish Journal of Ecology 61(2):207-219.

Kleinn C, Bhandari N, Fehrmann L (2015). Observations and measurements. In: Knowledge reference for national forest assessments. Food and Agriculture Organization of the United Nations, Rome pp 41-52. *https://www.fao.org/3/i4822e/i4822e.pdf*

Knapp N, Huth A, Kugler F, Papathanassiou K, Condit R, Hubbell SP, Fischer R (2018). Model-Assisted Estimation of Tropical Forest Biomass Change: A Comparison of Approaches. Remote Sensing 10(5):731. *https://www.mdpi.com/2072-4292/10/5/731*

Kristensen T, Næsset E, Ohlson M, Bolstad PV, Kolka R (2015). Mapping above-and below-ground carbon pools in boreal forests: The case for airborne lidar. PLoS ONE 10(10):e0138450. *https://doi.org/10.1371/journal.pone.0138450*

Kuliešis A, Tomter SM, Vidal C, Lanz A (2016). Estimates of stem wood increments in forest resources: comparison of different approaches in forest inventory: consequences for international reporting: case study of European forests. Annals of Forest Science 73(4):857-869. *https://doi.org/10.1007/s13595-016-0559-0*

Leak WB, Yamasaki M, Holleran R (2014). Silvicultural guide for northern hardwoods in the northeast. General Technical Report. Northern Research Station NRS-132. Newtown Square, PA: US Department of Agriculture, Forest Service. *https://doi.org/10.2737/NRS-GTR-132*

Leiter M, Hasenauer H (2023). Continuous cover forestry: Which sampling method should be used to ensure sustainable management? Trees, Forests and People 13:100419. *https://doi.org/10.1016/j.tfp.2023.100419*

Liang X, Kankare V, Hyyppä J, Wang Y, Kukko A, Haggrén H, Yu X, Kaartinen H, Jaakkola A, Guan F, Holopainen M, Vastaranta M (2016). Terrestrial laser scanning in forest inventories. ISPRS Journal of Photogrammetry and Remote Sensing 115:63-77. *https://doi.org/10.1016/j.isprsjprs.2016.01.006*

Lopez-Gonzalez G, Lewis SL, Burkitt M, Phillips OL (2011). ForestPlots.net: a web application and research tool to manage and analyse tropical forest plot data. Journal of Vegetation Science 22(4):610-613. *https://doi.org/10.1111/j.1654-1103.2011.01312.x*

Lupi C, Larocque GR, DesRochers A, Labrecque M, Mosseler A, Major J, Beaulieu J, Tremblay F, Gordon AM, Thomas BR, Vézina A, Bouafif H, Cormier D, Sidders D, Krygier R (2017). Biomass from young hardwood stands on marginal lands: Allometric equations and sampling methods. Biomass and Bioenergy 98:172-181. *https://doi.org/10.1016/j.biombioe.2017.01.023*

Malhi Y, Girardin C, Metcalfe DB, Doughty CE, Aragão LEOC, Rifai SW, Oliveras I, Shenkin A, Aguirre-Gutiérrez J, Dahlsjö CAL, Riutta T, Berenguer E, Moore S, Huasco WH, Salinas N, da Costa ACL, Bentley LP, Adu-Bredu S, Marthews TR, Meir P, Phillips OL (2021). The Global Ecosystems Monitoring network: Monitoring ecosystem productivity and carbon cycling across the tropics. Biological Conservation 253:108889. *https://doi.org/10.1016/j.biocon.2020.108889*

Maltamo M, Packalen P (2014). Species-specific management inventory in Finland. In: Maltamo M, Næsset E, Vauhkonen J (Eds). Forestry Applications of Airborne Laser Scanning. Managing Forest Ecosystems, Vol 27. Springer, Dordrecht. *https://doi.org/10.1007/978-94-017-8663-8_12*

Margolis HA, Nelson RF, Montesano PM, Beaudoin A, Sun G, Andersen H-E, Wulder MA (2015). Combining satellite lidar, airborne lidar, and ground plots to estimate the amount and distribution of aboveground biomass in the boreal forest of North America. Canadian Journal of Forest Research 45(7):838-855. *https://doi.org/10.1139/cjfr-2015-0006*

McRoberts RE (2010). The effects of rectification and Global Positioning System errors on satellite image-based estimates of forest area. Remote Sensing of Environment 114(8):1710-1717. *https://doi.org/10.1016/j.rse.2010.03.001*

McRoberts RE (2012). Estimating forest attribute parameters for small areas using nearest neighbors techniques. Forest Ecology and Management 272:3-12. *https://doi.org/10.1016/j.foreco.2011.06.039*

McRoberts RE, Bechtold WA, Patterson PL, Scott CT, Reams GA (2005). The enhanced forest inventory and analysis program of the USDA forest service: Historical perspective and announcement of statistical documentation. Journal of Forestry 103(6):304-308. *https://doi.org/10.1093/jof/103.6.304*

McRoberts RE, Tompo EO, Vibrans AC, de Freitas JV (2013). Design considerations for tropical forest inventories. Pesquisa Florestal Brasileira 33(74):189-202. *https://doi.org/10.4336/2013.pfb.33.74.430*

McRoberts RE, Tomppo EO, Næsset E (2010). Advances and emerging issues in national forest inventories. Scandinavian Journal of Forest Research 25(4):368-381. *https://doi.org/10.1080/02827581.2010.496739*

Mirzaei M, Bonyad AE (2016). Comparison of fixed area and distance sampling methods in open forests: case study of Zagros Forest, Iran. Journal of Forestry Research 27(5):1121-1126. *https://doi.org/10.1007/s11676-016-0239-9*

Mohren GMJ, Hasenauer H, Köhl M, Nabuurs GJ (2012). Forest inventories for carbon change assessments. Current Opinion in Environmental Sustainability 4(6):686-695. *https://doi.org/10.1016/j.cosust.2012.10.002*

Mora-Espinoza JA, Peñalver-Romeo A, Aguilar-Torres FJ, Rivas-Barzola JR, Triana-Tomalá Á (2020). Método de muestreo angular para el inventario de plantaciones forestales de teca (*Tectona grandis* L. f.) [Angular Sampling Method for Inventory of Teak (*Tectona grandis* L. f.) Plantations]. Revista Chapingo Serie Ciencias Forestales y del Ambiente 26(3):419-432. *https://doi.org/10.5154/r.rchscfa.2019.11.081*

Muhsoni FF, Sambah AB, Mahmudi M, Wiadnya DGR (2018). Comparison of different vegetation indices for assessing mangrove density using sentinel-2 imagery. GEOMATE Journal 14(45):42-51. *https://geomatejournal.com/geomate/article/view/2037*

Næsset E, Bollandsås OM, Gobakken T, Gregoire TG, Ståhl G (2013). Model-assisted estimation of change in forest biomass over an 11 year period in a sample survey supported by airborne LiDAR: A case study with post-stratification to provide "activity data". Remote Sensing of Environment 128:299-314. *https://doi.org/10.1016/j.rse.2012.10.008*

Nelson R, Gobakken T, Næsset E, Gregoire TG, Ståhl G, Holm S, Flewelling J (2012). Lidar sampling – Using an airborne profiler to estimate forest biomass in Hedmark County, Norway. Remote Sensing of Environment 123:563-578. *https://doi.org/10.1016/j.rse.2011.10.036*

Nunes A, Tapia S, Pinho P, Correia O, Branquinho C (2015). Advantages of the point-intercept method for assessing functional diversity in semi-arid areas [Advantages of the point-intercept method for assessing functional diversity in semi-arid areas] [Research Articles]. iForest - Biogeosciences and Forestry 8(4):471-479. *https://doi.org/10.3832/ifor1261-007*

Parrotta JA (1992). The role of plantation forests in rehabilitating degraded tropical ecosystems. Agriculture, Ecosystems and Environment 41(2):115-133. *https://doi.org/10.1016/0167-8809(92)90105-K*

Pece M, Ríos N, Gaillard de Benítez C, Acosta V (2000). Comparación entre métodos de muestreo [Comparison Between Sampling Methods]. Investigación Agraria. Sistemas y Recursos Forestales 9(1):45-58.

Picard N, Gamarra JGP, Birigazzi L, Branthomme A (2018). Plot-level variability in biomass for tropical forest inventory designs. Forest Ecology and Management 430:10-20. *https://doi.org/10.1016/j.foreco.2018.07.052*

Ploton P, Mortier F, Barbier N, Cornu G, Réjou-Méchain M, Rossi V, Alonso A, Bastin J-F, Bayol N, Bénédet F, Bissiengou P, Chuyong G, Demarquez B, Doucet J-L, Droissart V, Kamdem NG, Kenfack D, Memiaghe H, Moses L, Sonké B, Texier N, Thomas D, Zebaze D, Pélissier R, Gourlet-Fleury S (2020). A map of African humid tropical forest aboveground biomass derived from management inventories. Scientific Data 7(1):221. *https://doi.org/10.1038/s41597-020-0561-0*

Pucher C, Neumann M, Hasenauer H. An improved forest structure data set for Europe. Remote Sensing 14(2):395. *https://doi.org/10.3390/rs14020395*

Romijn E, Lantican CB, Herold M, Lindquist E, Ochieng R, Wijaya A, Murdiyarso D, Verchot L (2015). Assessing change in national forest monitoring capacities of 99 tropical countries. Forest Ecology and Management 352:109-123. *https://doi.org/10.1016/j.foreco.2015.06.003*

Silva LB, Alves M, Elias RB, Silva L (2017). Comparison of tree sampling methods in *Pittosporum undulatum* invaded woodlands. International Journal of Forestry Research 2818132. *https://doi.org/10.1155/2017/2818132*

Strunk J, Temesgen H, Andersen H-E, Flewelling JP, Madsen L (2012). Effects of lidar pulse density and sample size on a model-assisted approach to estimate forest inventory variables. Canadian Journal of Remote Sensing 38(5):644-654. *https://doi.org/10.5589/m12-052*

Suganuma H, Abe Y, Taniguchi M, Tanouchi H, Utsugi H, Kojima T, Yamada K (2006). Stand biomass estimation method by canopy coverage for application to remote sensing in an arid area of Western Australia. Forest Ecology and Management 222(1):75-87. *https://doi.org/10.1016/j.foreco.2005.10.014*

Tinkham WT, Mahoney PR, Hudak AT, Domke GM, Falkowski MJ, Woodall CW, Smith AMS (2018). Applications of the United States Forest Inventory and analysis dataset: a review and future directions. Canadian Journal of Forest Research 48(11):1251-1268. *https://doi.org/10.1139/cjfr-2018-0196*

Tompalski P, Coops NC, White, JC, Wulder MA (2016). Enhancing forest growth and yield predictions with airborne laser scanning data: Increasing spatial detail and optimizing yield curve selection through template matching. Forests 7(11):255. *https://doi.org/10.3390/f7110255*

Tompo E, Heikkinen J, Henttonen HM, Ihalainen A, Katila M, Mäkelä H, Tuomainen T, Vainikainen N (2011). Designing and conducting a forest inventory - case: 9th National Forest Inventory of Finland (Vol XII). *https://doi.org/10.1007/978-94-007-1652-0*

Tomppo E, Gschwantner T, Lawrence M, McRoberts RE, Gabler K, Schadauer K, Vidal C, Lanz A, Ståhl G, Cienciala E (2010). National forest inventories. Pathways for Common Reporting. European Science Foundation 1:541-553.

Tomppo E, Olsson H, Ståhl G, Nilsson M, Hagner O, Katila M (2008). Combining national forest inventory field plots and remote sensing data for forest databases. Remote Sensing of Environment 112(5):1982-1999. *https://doi.org/https://doi.org/10.1016/j.rse.2007.03.032*

Treitz P, Lim K, Woods M, Pitt D, Nesbitt D, Etheridge D (2012). LiDAR Sampling density for forest resource inventories in Ontario, Canada. Remote Sensing 4(4):830-848. *https://doi.org/10.3390/rs4040830*

Vandendaele B, Fournier RA, Vepakomma U, Pelletier G, Lejeune P, Martin-Ducup O (2021). Estimation of northern hardwood forest inventory attributes using UAV Laser Scanning (ULS): Transferability of laser scanning methods and comparison of automated approaches at the tree- and stand-level. Remote Sensing 13(14):2796. *https://www.mdpi.com/2072-4292/13/14/2796*

Vidal C, Alberdi IA, Hernández-Mateo L, Redmond JJ (2016). National Forest Inventories (Vol XXXII). Springer Cham. *https://doi.org/https://doi.org/10.1007/978-3-319-44015-6*

Wang Y, Pyörälä J, Liang X, Lehtomäki M, Kukko A, Yu X, Kaartinen H, Hyyppä J (2019). *In situ* biomass estimation at tree and plot levels: What did data record and what did algorithms derive from terrestrial and aerial point clouds in boreal forest. Remote Sensing of Environment 232:111309. *https://doi.org/https://doi.org/10.1016/j.rse.2019.111309*

White JC, Coops NC, Wulder MA, Vastaranta M, Hilker T, Tompalski P (2016). Remote sensing technologies for enhancing forest inventories: A review. Canadian Journal of Remote Sensing 42(5):619-641. *https://doi.org/10.1080/07038992.2016.1207484*

Wittke S, Yu X, Karjalainen M, Hyyppä J, Puttonen E (2019). Comparison of two-dimensional multitemporal Sentinel-2 data with three-dimensional remote sensing data sources for forest inventory parameter estimation over a boreal forest. International Journal of Applied Earth Observation and Geoinformation 76:167-178. *https://doi.org/https://doi.org/10.1016/j.jag.2018.11.009*

Woods M, Pitt D, Penner M, Lim K, Nesbitt D, Etheridge D, Treitz P (2011). Operational implementation of a LiDAR inventory in Boreal Ontario. The Forestry Chronicle 87(4):512-528. *https://doi.org/10.5558/tfc2011-050*

Zhu X, Zhang J (2009). Quartered neighbor method: A new distance method for density estimation. Frontiers of Biology in China 4(4):574-578. *https://doi.org/10.1007/s11515-009-0039-0*

The journal offers free, immediate, and unrestricted access to peer-reviewed research and scholarly work. Users are allowed to read, download, copy, distribute, print, search, or link to the full texts of the articles, or use them for any other lawful purpose, without asking prior permission from the publisher or the author.

License - Articles published in Nova Geodesia are Open-Access, distributed under the terms and conditions of the Creative Commons Attribution (CC BY 4.0) License.

© Articles by the authors; Licensee SMTCT, Cluj-Napoca, Romania. The journal allows the author(s) to hold the copyright/to retain publishing rights without restriction.

Notes:

- Material disclaimer: The authors are fully responsible for their work and they hold sole responsibility for the articles published in the journal.
- Maps and affiliations: The publisher stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.
- Responsibilities: The editors, editorial board and publisher do not assume any responsibility for the article's contents and for the authors' views expressed in their contributions. The statements and opinions published represent the views of the authors or persons to whom they are credited. Publication of research information does not constitute a recommendation or endorsement of products involved.