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Forest Biometrics: An Indispensable Component of Sustainable Renewable Natural Forest Resources Management

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ABSTRACT

Forest biometrics, the quantitative measurement and analysis of forest resources, is fundamental to achieving sustainable forest management. It provides precise information on forest structure, growth, and composition, enabling data-driven decisions on forest health and management. This study therefore, reviewed the essential roles of forest biometrics in ensuring the long-term health and productivity of natural forests while balancing competing demands for forest resources. Forest biometrics uses traditional tools like diameter tapes, calipers, and clinometers, along with new technology like LiDAR, satellite images, and drones, to gather more information and cover larger areas of forests. The integration of these equipment and tools enhances data precision, enabling comprehensive assessments of forest attributes, thereby advancing sustainable forest management and conservation efforts. Forest biometrics provides both quantitative and qualitative information about forest resources. However, several critical challenges facing forest biometrics include the complexity and heterogeneity of forest ecosystems, limitations in data collection and processing technologies, and the lack of standardized methodologies, integrating biometrics with other disciplines, and addressing the growing need for accurate and timely information in the face of climate change and other global challenges. Overcoming these challenges requires interdisciplinary collaboration, technological advancements, development of robust, provision of high-resolution imagery and scalable biometric tools for sustainable management practices.

Keywords: Forest biometrics, Sustainability, Natural Forest resources, Technology, and Remote sensing.

INTRODUCTION

The sustainable management of renewable natural forest resources is becoming

increasingly critical due to the growing demand for ecosystem goods and services such as clean water, food, and biodiversity.

Proper management is key to maximizing the benefits of these resources, relying heavily on accurate and comprehensive data about the forest structure and functions (Dau *et al.*, 2015). Sound management depends on the quantity and quality of information available on the forest. Basic data and information are required if renewable natural forest resources such as forest, air, water and soil are to be managed in a reasonable and sustainable manner. This information is largely obtained through forest biometrics (Zerihun and Yemir, 2013). The sustainable management of renewable natural forest resources is becoming increasingly critical due to the growing demand for ecosystem goods and services such as clean water, food, and biodiversity. Proper management is key to maximizing the benefits of these resources, relying heavily on accurate and comprehensive data about the forest structure and functions (Dau *et al.*, 2015). Sound management depends on the quantity and quality of information available on the forest. Basic data and information are required if renewable natural forest resources such as forest, air, water and soil are to be managed in a reasonable and sustainable manner. This information is largely obtained through forest biometrics (Zerihun and Yemir, 2013). According to Forest Biometrics Research Institute (2021), it is impossible to determine areas that require conservation or set reasonable harvest levels without knowledge of a forest's current standing volume, species composition, age structure and overall health. The state of renewable natural forest resources is established from the quantification of various attributes of the forest, such as volumetric stocks, growth and harvesting intensities. To estimate them, there is need to understand the relationship between these and easily measurable variables such as diameter and height (Burkhart *et al.*, 2012; López-Martínez *et al.*, 2022). These relationships are described through mathematical models that together constitute

forest biometric systems (Vargas-Larreta *et al.*, 2017). Effective forest management relies on the use of accurate, robust, and efficient biometric systems. Systems that lack these key attributes pose a significant threat to the conservation of natural resources and the ecological processes that sustain them (López-Martínez *et al.*, 2022).

Forests are dynamic ecosystems constantly facing threats from pests, diseases, wildfires, and climate change (Ezenwenyi *et al.*, 2025). Detecting changes early and understanding their impacts is vital for proactive management. Repeated biometric inventories allow for the monitoring of changes in forest structure, health indicators (defoliation, mortality rates), and biodiversity over time. This data helps identify emerging threats, evaluate the effectiveness of management interventions, and adapt strategies as conditions change (Yavitt, 2024; Ezenwenyi *et al.*, 2025).

Renewable natural forest resources management refers to the sustainable utilization of natural resources, such as wild flora and fauna, water, air and soil. These resources provide the ecosystem services that provides the quality to human life. Renewable natural forest resources management plays a critical role in sustaining life support systems by providing both goods, such as timber and food, and services, including clean air, water, and climate regulation. Unfortunately, the biological aspects of these resources' management have often been overlooked. In some cases, the rate of exploitation surpassed the natural regeneration capacity of the resources. Such overexploitation ultimately threatens the livelihoods and wellbeing of people who depend on these resources, and jeopardizes the health of ecosystems (International Institute for Sustainable Development [IISD], 2024). Hence the need to regulate natural resource use to better preserve resources and their ecosystems (FAO, 2018); IISD, 2024).

One of the paradigms for the conservation of forest resources is their sustainable use (López-Martínez *et al.*, 2022). Dau *et al.* (2015) defined sustainable management of renewable natural forest resources as comprising a host of management regimes to maintain and enhance the long-term health and integrity of renewable natural forest resources ecosystems, while providing ecological, economic, social, and cultural opportunities for the benefit of present and future generations. However, concerns from sustained yield to sustainable management was first internationally initiated by Brundtland Commission (1987) and later taken as an idea at the Earth Summit in Rio de Janeiro in 1992. In response, several initiatives and international agreements have been established to quantify large-scale sustainability (Tittler *et al.*, 2001; Dau *et al.*, 2015).

Forest biometrics provides the methodologies for designing statistically sound forest inventories (plot sampling, remote sensing integration), measuring individual trees (diameter, height, volume), and aggregating these measurements to estimate stand and forest-level parameters with known levels of precision (Yavitt, 2024). This allows managers to determine the actual timber growing stock, rates of growth, and biodiversity indicators, hence the need for this review.

Forest Biometrics as an Indispensable Component of Natural Forest Resources

The word "indispensable" is deeply rooted in human language and thought. According to Collins dictionary, it signifies something that is absolutely essential, without which something else cannot exist or function properly. Forest biometrics, the science of measuring and quantifying forest resources, is an essential tool for assessing forest resources, tracking changes over time and identifying areas needing conservation or restoration (Jirel, 2024). Therefore, this review explores

the significance of forest biometrics in the context of renewable natural resources, highlighting its applications and challenges in forestry and decision sciences.

Concepts of Renewable Natural Forest Resources

The concept of renewable natural forest resources refers to naturally occurring elements of the Earth system of which there is an endless supply because it can be replenished (Banton, 2023). The plants, animals, air, water, soil and sun are considered inexhaustible and therefore are examples of renewable natural forest resources. FAO (2018) and IISD (2024) viewed renewable natural forest resources to include the air, water, soil, flora and fauna and especially representative samples of natural ecosystems which must be safeguarded for the benefit of present and future generations through careful planning or management, as appropriate.

Important Renewable Natural Forest Resources and their Services

Forests

Forests are Renewable natural forest resources capable of providing forest products and contribute substantially to economic development. They are important to the well-being of humanity as they provide foundations for life on Earth through ecological functions, regulating climate and water resources, and serving as habitats for plants and animals (Latif and Blackburn, 2010). Forests consist of trees that buffer the earth and myriads of life forms. It is not just a collection of trees; they are much more than that. A forest is a complex system made up of biological, physical, and chemical elements that interact and are dependent on one another. Because of this intricacy, there are hundreds of distinct types of forests in the world due to the unique combinations of climate, soil, tree species, and plant life (Mohd-Zaki and Abdl-Latif, 2016). Trees are important component of the environment that function to maintain the

diversity, function and services that exist mostly in forest (Blackburn *et al.*, 2014). They are important for the carbon balance of the Earth (Hypp *et al.*, 2012). They offer a wide variety of ecosystem services, including supporting, provisioning, regulating and cultural services, while at local level, provisioning of services such as food, timber and medicine are of great significance for natives in the communities (Eguiguren *et al.*, 2019). According to Hypp *et al.* (2012), trees, in addition to solidifying the crucial structural and practical foundation of tropical forests, are important for the carbon balance of the Earth, and they provide watersheds and make available shades and homes for several life forms and most importantly serve as a main harvester of energy into the ecosystem (Akwaji *et al.*, 2022). Tree species cover gives an array of products and services that play important roles in economy and general wellbeing of human (Meer, 2018). They provide employment to people and revenue to Government. The trees are objects of beauty that provide fine scenery and attract tourists and serve as a source of recreation.

Forests today face multiple of threats from fire, disease, pollution and insect outbreak. Most of these factors can negatively affect large forest areas in a short time period. Besides that, it can create chronic stresses for long-term consequences on the species and nature of a forest ecosystem within where much of their original extent depleted (Latif and Blackburn, 2010), hence the need for its biometrics analysis.

Sustainable wildlife management

Sustainable wildlife management (SWM) is the sound management of wildlife species to sustain their populations and habitat over time, taking into account the socioeconomic needs of human populations (FAO, 2015). This requires that all land-users within the wildlife habitat are aware of and consider the effects of their activities on the wildlife resources and habitat, and on other user groups. In this

review, the term “wildlife” refers to “terrestrial or semi-terrestrial vertebrates”. In view of its ecological, social and economic value, wildlife is an important renewable natural resource, with significance for areas such as rural development, land-use planning, food supply, tourism, scientific research and cultural heritage. If sustainably managed, wildlife can provide continuous nutrition and income and contribute considerably to the alleviation of poverty as well as to safeguarding human and environmental health (FAO, 2015).

Forest Biometrics

Forest biometric systems are the most widely used analytical tools for analysis of forest growth and yield (Vargas-Larreta *et al.*, 2017). According to Forest Biometrics Research Institute (2021), Forest biometrics may be defined by understanding the specific combination of the words, forest and biometrics. Biometrics can be best defined by breaking down the word: bio (biological) and metric (measurement). Therefore, biometrics simply means biological measurements. Forest Biometrics Research Institute (2021) noted that forestry is a profession, embracing the science, art and practice of treating, managing, using and conserving forests and associated resources such as air, soil and water for human benefit and in a sustainable manner to meet desired goals, needs and values. The broad field of forestry consists of those biological, physical, and managerial sciences that are applied to forest management and conservation (Forest Biometrics Research Institute, 2021). Data such as tree diameter and height give forestry companies information that can be built and projected into the future. This is valuable, as it offers informed decision-making opportunities rather than working off of assumptions (Rayonier, 2024).

Forest biometrics encompasses the quantification of biological and physical characteristics of trees and associated vegetation, insects, disease, wildlife,

topography, soils, and climate, individually and collectively. These characteristics include all quantifiable attributes within forestry, both temporal and spatial (Forest Biometrics Research Institute, 2021). Forest biometrics embraces the evaluation of the main fundamentals of the natural laws and the methods of mathematical statistics which are important to forestry. It informs policy decisions such as ranking habitat for species at risk, modeling future climate change scenarios and studying the economics of forests impacted by disturbance (British Columbia, 2018).

Historically, biometric systems can be traced to the late 18th century in Germany, where the practice of building region and species-specific models by generating production tables began (Assmann, 2013). In Mexico, the first documented records of biometric systems date back to the 1970s. From this date onwards and because of environmental heterogeneity (e.g., tree age, nutrient availability, competition and density of individuals) and the high diversity of forest species, a plethora of models to account for this variability have been developed (López-Martínez *et al.*, 2022). Additionally, Mexican environmental legislation demands the use of equations at the species level (López-Martínez *et al.*, 2022).

Equipment and Tools for Forest Biometrics

Equipment and tools used in contemporary forest biometrics, which also highlights new developments are categorized into traditional and emerging technology tools:

Traditional Tools

Diameter tapes and calipers: These remain fundamental for measuring tree diameter at breast height (DBH), a key metric for tree volume estimation. McRoberts *et al.* (2015), mentioned the use of diameter tapes for measuring trees in a forest ecosystem services analysis. According to Fraisse *et al.* (2014), the use of both diameter tapes and calipers for tree diameter measurements is very effective.

Height meters: Tools like clinometers and laser rangefinders measure tree heights, allowing calculation of individual tree volume and stand density. Sharma *et al.* (2010) focused their study on the use of clinometers for tree height measurement and proposed a new mathematical model for improved accuracy. Mutanga *et al.* (2015) discovered the use of laser rangefinders for tree height measurement alongside other techniques like Light Detection and Ranging (LiDAR).

Plot-based measurements: Establishing fixed-area plots within forests enables ground-truthing data for remote sensing techniques. Næsset *et al.* (2004) highlighted the importance of plot-based measurements for validating remote sensing techniques, including airborne laser scanning for forest biomass estimation. McRoberts *et al.* (2014) reported the role of plot-based measurements in conjunction with remote sensing for forest inventory.

Emerging Technologies

Remote sensing: LiDAR (Light Detection and Ranging) technology provides high-resolution 3D point clouds of forests, enabling accurate estimates of canopy cover, biomass, and aboveground carbon stocks (McRoberts *et al.*, 2022). LiDAR technology is revolutionizing forest biometrics. Its systems mounted on drones or airplanes generate high-resolution 3D point clouds of forests, enabling precise estimations of canopy cover, biomass, and tree heights over large areas (Næsset and Gobakken, 2012; Popescu *et al.*, 2008)

Unmanned aerial vehicles (UAVs): Drones equipped with LiDAR, hyperspectral, and multispectral sensors offer rapid and cost-effective data collection over large areas (Jaiswal *et al.*, 2022). UAVs or drones equipped with LiDAR, hyperspectral sensors, and high-resolution cameras offer efficient data collection over extensive forest areas (Lisein *et al.*, 2013).

Terrestrial laser scanning (TLS): TLS provides detailed 3D data of forest stands,

enabling accurate tree segmentation, volume estimation, and assessments of forest health (Liang *et al.*, 2016). Ground-based LiDAR scanners provide detailed structural information of individual trees and understory vegetation (Liang *et al.*, 2018). Image analysis software coupled with terrestrial or drone-based imagery facilitates tree crown delineation and measurement of various crown parameters (Mutanga *et al.*, 2015).

Proximal sensing: Instruments like dendrometers using acoustic waves or electrical impedance can measure tree diameter growth continuously (Ren *et al.*, 2018).

Many other studies discuss these traditional and modern forest measurement techniques.

Relevance of Forest Biometrics

According to Killmann and Palmer (2024); Shan *et al.*, 2024) and Yavitt (2024), forest biometric is important because it provides reliable, good quality information. Such information is important in ensuring appropriate planning and management. They outlined that forest biometric is critically important for:

Livelihoods: Giving the right advice: Decisions based on resource assessments can influence the long-term survival of species and thus livelihoods. Oversimplification of complex situations, risking giving poor recommendations, should be avoided. It is critical that community-based assessments provide useful and reliable information. Advisers should therefore, see this as an ethical obligation.

Exploitation: Avoiding overharvesting: Good quality information is important to ensure that decisions do not lead to decline of the target species, which may in turn put commercial ventures based on those species at risk. As yet, few renewable natural forest resources enterprises base harvesting decisions on reliable data and overexploitation is not uncommon. In such cases, it is critical that robust monitoring systems are implemented to

deal with any negative consequences and make corrective actions.

Valuation of tropical forest resources:

Allowing comparisons: The use of renewable natural forest resources data by people not involved in the inventory requires some level of standardization of what is measured and data quality. It is difficult to compare results from assessments that are carried out differently.

Strategic overviews: Planning and prioritization: Often the data used for national, regional or international statistics come from local assessments of renewable natural forest resources particularly, non-timber forest products. This synthesis of various studies, sometimes referred to as "meta-analysis," entails more than just compiling data; rather, it entails additional analysis for a broader interpretation. Whilst it is a cost-effective way of generating large-scale data, it is only as reliable as the data it uses. It will only provide biometrically adequate results if the local assessments do.

Credibility: Avoiding political bias: Ensuring that data are biometrically sound can add weight to recommendations based on that information. Where governments have to defend their reasons for setting quotas to those who lobby for higher (industry/trade) or lower (conservationists) levels, reliable data are important. A case study in Cameroon provides a useful example of the role of reliable data in political debate concerning the national quota for *Prunus africana* bark.

Forest Biometrics and Renewable Natural Forest Resources Nexus

Forest biometrics, the science of quantifying renewable natural forest resource attributes, is essential for sustainable forest management (Forest Biometrics Research Institute, 2021). In view of this, forest biometrics programs have been at the heart of forestry over time. Over the intervening period, the field of renewable natural forest resources has changed in critical ways. It has evolved to embrace a

much broader view of the goals for renewable natural forest resource management (Temesgen *et al.*, 2007). Forest biometrics has become increasingly quantitative in its approaches to forestry research and management. Forest biometrics inform decision-makers, stakeholders and the general public about issues and opportunities relating to the sustainable use and conservation of terrestrial and semi-terrestrial renewable natural forest resources (FAO, 2015). Sustainable use and conservation have magnified the importance of forest biometrics as a tool of forestry science. Forest biometrics offers valuable information for decision making because it provides quantitative measures of current resources, means to compare differences between alternative experimental resource treatments and methods to project future outcomes of management practices (Temesgen *et al.*, 2007). Rising forest values increase the demand for accuracy and precision in quantitative approaches for management prescriptions and projected outcomes, necessitating quantitative approaches. The rapid emergence of quantitative tools for forest resource management and planning (e.g., geographic information systems [GIS]) has bridged a knowledge gap between the technologies and large-scale forest inventory and monitoring. Corporations are in a unique position to provide insights on information needs to use these technologies successfully. Co-sponsoring research to provide this information not only advances the field and trains new scientists, but also yields results that directly affect a company's profitability (Temesgen *et al.*, 2007).

Solution providers (companies that develop and market hardware and software technologies) often take the lead in integrating new tools and techniques to meet challenges faced in large-scale inventory and monitoring. Collaboration with these providers can give forest biometrics scientists access to their

findings and resources. Such access is critical to sustain relevant research into today's inventory and monitoring problems. As an example, Stand Management, Hardwood, Genetics Cooperatives, as well as consulting firms, users' group, and private growth modelers have integrated forest growth models, developed by both university and federal researchers, into their planning tools, thereby, obtaining data to address integration process obstacles, model performance under extensive use, and identification of missing model features that are crucial for developing new research approaches that address specific demands (Temesgen *et al.*, 2007).

Linking forest biometrics and decision sciences

Although forest biometrics traditionally has been a less visible component of forest management and planning, it is directly linked to the decision sciences such as policy, economics and planning. In economic decisions, forest biometrics plays an integral part in providing the most accurate information possible for forest attributes in current inventory and in future projections. Forest biometrics is also playing an increasingly important role in providing new ways to quantify qualitative information so that it can be more effectively drawn into the decision process. Forest biometrics can be even more closely linked to business decision making. The vitality of forestry businesses is dependent on the accuracy of quantitative information pertaining to direct action taken by the company. Many forestry businesses have in-house biometricians who analyze data that are vital to the success or failure of proposed ventures. This is a case in which the consequences of the performance of a forest biometrics specialist can be directly felt by both the specialist and the employer (Temesgen *et al.*, 2007).

Applications of Forest Biometrics in Forestry

To illustrate the sophistication and complexity of current forest biometrics applications in modern forestry practice, the following example may be considered:

Forest ecosystem and landscape analysis

Historically, foresters have focused on managing individual stands. This orientation arose partly because the stand was the traditional operational unit of forest management but also because of the difficulty of projecting multiple resource values at the landscape level. Modern forest biometrics methods, models, and statistical tools have greatly reduced these limitations, allowing for simultaneous analysis of many resource values at the landscape level. This has enabled application of high-capacity optimization methods (e.g., heuristic schemes such as tabu search, simulated annealing, and genetic algorithms) to solve multivariate landscape optimization problems that were intractable 20 years ago (e.g., Bettinger *et al.*, 1997; 1999). Ongoing cooperative work between Oregon Department of Forestry (2010) was able to utilize multiple aspects of forest biometrics in problem formulation and analysis which include forest inventory of stands, spatial overlays of the road and stream network on the stand location map in three dimensions (GIS), projection of forest growth by treatment alternative for each stand over time, spatial quantification of wildlife habitat structure, and quantification of constraints imposed by the Oregon Forest Practices Act in United States of America. Using these inputs, an optimization process efficiently searches for the best mix of management alternatives over the landscape that maximizes present net worth, while meeting necessary habitat and riparian protection constraints over time. The Blue River watershed study conducted by Cissel *et al.* (1999) in the Oregon Cascade Range provides a second illustration of the use

of forest biometrics in landscape management planning.

The Roles of Forest Biometrics in Renewable Natural Forest Resources Management

Forest biometrics plays critical roles in the management and sustainable use of renewable natural forest resources. These roles can be categorized into three as follows:

1. Forest biometrics as a tool in data collection

Biometrics aids in data collection in forest research through appropriate experimental designs and reliable procedures, ensuring quality data based on appropriateness and compliance with experimentation principles (Akindele, 2008). Experimental principles include randomization, replication, and local control, ensuring objectivity and eliminating bias. Randomization allocates units to treatments, replication increases reliability, and local control ensures accuracy (Akindele, 2008). It should be noted that repeated measurements on the same experimental unit or multiple readings for a treatment appearing once are not true replications (Akindele, 2004). A third principle of experimentation is local control, which refers to the amount of grouping or blocking of the experimental units used in the experimental design. It is aimed at ensuring that the units within each block are relatively homogenous while the units between the blocks are heterogeneous. Local control enhances the efficiency of experimental designs by reducing the effect of extraneous factors on the treatment comparison, thereby decreasing the error variance. It should be emphasized that sound experimental design and adherence to the principles of experimentation are essential in forestry research. Failure to consider these issues will result in unnecessary waste and, in the worst case, bad decisions resulting in serious damage to sensitive forest ecosystems (Akindele, 2008). Akindele (2008) identified

the following practical details to be considered:

- All pertinent measurements of the experimental (sampling) units must be identified.
- Appropriate field procedures and data collection forms must be developed.
- Provision must be made for adequate supervision of the data collection.
- In large-scale studies, strategies for coordination and optimization of procedures should be put in place.

Types of experimental designs used in forestry research

Akindele (2008) outlined a general list of experimental designs to include completely randomized design, randomized complete block design, Latin square design, nested or hierarchical design, split plot design, split-split plot design, split block design, lattice design and response surface designs.

He also listed the conditions under which each of them is applicable. According him, when properly applied, these designs lead to collection of reliable data. The data could be terminal data collected at the end of the experiment or periodic data collected at intervals during the experiment. One aspect of experimentation that has gained prominence in forestry research is the use of factorial experiments. The term “factorial” describes a specific way in which the treatments are formed and does not, in any way, refer to the design used for laying out the experiment (Akindele, 2008). Factorial experiments enable simultaneous evaluation of main effects and interactions of factors, but may become too large for single experiments. Alternatives include fractional testing (Akindele, 2008). A design uniquely suited for such situations is the fractional factorial design, which provides a systematic way of selecting and testing only a fraction of the complete set of factorial treatment combinations. In exchange, however, there is loss of information on some pre-selected effects. Further discussion of this

design and its application in forestry research has been provided by Jayaraman (1999).

2. Forest biometrics as a tool in data analysis

Biometrics is widely used in forestry research, with design and analysis closely linked. Poor design often results from inadequate data analysis methods (Akindele, 2008). Data analysis normally proceeds with application of relevant tools to condense the data and extract useful information from them. For experimental data, analysis of variance (ANOVA) methods is commonly applied. ANOVA has gained so much popularity that discussions of experimental designs are often more about ANOVA than fundamental issues of design. ANOVA is basically an arithmetic method of partitioning the total variation of the collected data into components representing the sources of variation recognized in the experiment (Akindele, 2004). The basic premise of ANOVA is that the observed variability in experimental data can be attributed to a finite number of identifiable sources, including factors under the control of the investigator, uncontrolled experimental errors, and various interactions (Akindele, 2008).

With the advent of computers, other methods of data analysis have been used in forestry research. For instance, simulation is a method of considerable importance to forestry which has gained wider acceptance in recent times. It is particularly useful in forestry because simulation techniques can replace large scale field experiments which are extremely costly and time consuming. In addition, other approaches such as Bayesian statistics, multivariate analysis, generalized linear models, non-linear regression, stochastic approximations, and spatial analysis are now being used, but most forest scientists in the tropics are not familiar with these approaches (Akindele, 2008).

In recent decades, due to the increase in computing power, more complex models, both in their structure and number of parameters,

have been generated to increase their descriptive and predictive power (López-Martínez *et al.*, 2022). However, model complexity does not guarantee an increase in model fit to the data or a higher accuracy in prediction (López-Martínez *et al.*, 2022). On the one hand, fit has been assessed through a variety of statistical metrics, such as the coefficient of determination (R^2), root mean square error (RMSE) and average bias (e), among others, being the most commonly used due to its ease of interpretation and its model interoperability. On the other hand, prediction accuracy has been assessed through model validation in which the model is used to predict the forest attribute of interest on a new set of data and fit is evaluated on these predictions (López-Martínez *et al.*, 2022).

3. Biometrics as a tool in data interpretation

Forest data analysis requires interpretation for forest managers and policy makers. In view of several statistics displayed in computer print-outs, there is the need to know what is relevant and how to draw inferences from them. In drawing inferences, there is the need to avoid the temptation of over-generalization or over-interpretation. Although everyone wants to do a piece of research that has sweeping value in all reaches of a field. Unfortunately, this is very rarely the case, due to the inherent limitations of the research design and execution. All researchers need to appreciate that fact and not embarrass themselves by over-interpreting their findings (Akindele, 2008).

When interpreting study results from research where it is not practically possible to adhere strictly to any of the principles of experimentation, researchers should account for the site-specific characteristics leading to the initial noncompliance. It should then be understood that such altered experiments can no longer provide reliable knowledge of cause, but only generates hypotheses for validation when future management actions are implemented. Similarly, when a study

considers only a portion of the system of interest (due to lack of randomization, replication, or funding), generalization of the results to the entire system could be inappropriate and misleading (Akindele, 2008). In this case, the study objectives and scope must be re-evaluated.

Critical Challenges of Forest Biometrics

Forest resource management faces complex decision problems, requiring various scientific methods and data. Qualitative and quantitative estimates are desirable for long-term replicability (Temesgen *et al.*, 2007). The application of forest biometrics is hindered by significant challenges. According to Franklin *et al.* (1981), inherent complexity and heterogeneity of forest ecosystems pose difficulties for accurate data collection and modelling. Moreover, traditional ground-based measurements are time-consuming and labour-intensive, limiting data availability and spatial coverage (Magnussen *et al.*, 2015), this recognition offers forest biometrics professionals both a challenge to continue developing tools useful in the analysis of large and highly integrated systems and an opportunity to grow as a partner with other disciplines in the land-management decision areas. Advances in remote sensing have mitigated some of these issues, but challenges related to data processing, calibration, and validation persist (Lucas *et al.*, 2013). Integrating biometrics with other disciplines, such as ecology, economics, and climate science, is crucial for comprehensive forest management. However, disparities in data formats, scales, and modeling approaches create obstacles (Pretzsch, 2009). Furthermore, the dynamic nature of forests, influenced by climate change, disturbances, and management practices, demands continuous updates of biometric models and information systems (Peng *et al.*, 2014).

CONCLUSION

This review outlined several forest biometrics techniques and procedures that are employed as instruments or tools in research on renewable natural forest resources, along with the circumstances in which each is best suitable. The use of forest biometrics as a highly practical instrument in all facets of renewable natural forest resources study has grown in popularity. Tools for improving and expanding quantitative thinking in forestry and other related fields that study renewable natural forest resources have been made available by forest biometrics. Biometric systems are the basis of forest management and consist of a set of equations that describe the relationships between forest attributes and biometric variables. Forest biometrics is a dynamic field with continuous advancements in tools and instruments. It is employed in the planning of studies, data analysis and inference. Appropriate renewable natural forest resource management techniques, such as creating databases of current data, census indicators to populations, tracking outcomes, modeling populations and planning forest resource management, may provide assistance when funding is available to support the management of important forest ecosystems.

RECOMMENDATIONS

To enhance forest biometrics assessments, it is crucial to identify, subsidize, and promote the use of advanced equipment, high-resolution imagery, and field measurements. By employing a combination of traditional and modern approaches, forest managers can obtain crucial data for sustainable forest management practices. Concerned stakeholders and research organizations should establish research partnerships to improve the method of data collection and analyses as well as quality of data and research.

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