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Research Article

Forest inventory as a tool for sustainable management and conservation of global forest ecosystems

***[1]Ruqayia and [2]Muhammad Haseeb Parvez, [3]Muhammad Arslan Safdar**

[1]Institute of Plant Science, University of Sindh Jamshoro, Sindh Pakistan
[2]Faculty of Agricultural Science, Bahauddin Zakariya University, Multan, Pakistan
[3]Department of Economics, University of Education LahoreUniversity of Education Lahore, Pakistan

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Abstract

Forest inventory plays a crucial role in the sustainable management and conservation of global forest ecosystems. This article provided insights into the development of forest inventory methodologies, progressing from conventional ground-based surveys to cutting-edge technologies such as remote sensing, GIS, and LiDAR. The article explores the key factors in forest inventories, including biodiversity indices, ecosystem health indicators, and habitat quality assessments, highlighting their significance in successful conservation strategies. The article showcases various case studies that demonstrate the successful implementation of forest inventory in conservation efforts. These examples highlight the integration of these methodologies with policy and management strategies, community engagement, and ongoing monitoring. It also discusses the difficulties of coordinating inventory efforts with conservation objectives, with a particular emphasis on the limitations of available data and the constraints of resources. The article concludes by discussing future directions, including the potential for emerging technologies and global initiatives to improve forest inventories for conservation purposes. This comprehensive overview highlights the crucial role of forest inventory in gaining insights, effectively managing, and preserving the world's forests.

Keywords: *Forest inventory, conservation, sustainable management, ecosystem management*

1. Introduction

Forests play a crucial role in maintaining the delicate balance of Earth's ecosystems and are essential for the well-being of both the planet and its inhabitants. Central to the preservation of these natural treasures is the crucial practice of forest inventory - a methodical process aimed at collecting data on the composition, health, and structure of forests. Over time, forest inventory has grown beyond its original purpose of timber management and resource assessment, becoming an essential tool for forest conservation[3, 4]. Figure 2 illustrates that between 1990 to 2021, there were notable variations in forest cover worldwide, which may be attributed to several international initiatives aimed at conserving and managing forests. By 1990, the global forest cover was substantial, however it was increasingly threatened by deforestation[5], mostly driven by the need for agricultural development and wood exploitation. This time marks the start of increased consciousness and efforts towards the preservation of forests.

In the following years, several nations adopted measures to decrease deforestation and encourage the growth of new forests through reforestation and afforestation. Forest inventory, an essential instrument in this undertaking, played a crucial role in providing information for policy choices. The data supplied precise information on the size, composition, and condition of forests, which was essential for the implementation of efficient management and conservation plans. By 2021, the endeavours had yielded discernible alterations in certain areas, as reforestation and the spontaneous growth of forests played a role in partially restoring forest coverage. Nevertheless, the overall situation worldwide remained complicated, since substantial declines continued to take place in tropical areas. Figure 1 illustrates the global forest cover. The period emphasised the crucial function of forest inventory in directing and assessing the effects of forest conservation strategies, highlighting its significance in the continuous task of reconciling human requirements with environmental sustainability.

The complexity of forest inventory in the context of conservation is manifold. The collection and analysis of data concerning various forest attributes, including tree species, sizes, densities, age classes, and health

*Corresponding author's ORCID: 0009-0001-1571-9259
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conditions, requires meticulous attention to detail. This abundance of knowledge serves as the foundation for conservation initiatives, providing a transparent glimpse into the essence of the forest. Through the careful examination of forest landscapes, inventory data sheds light on the intricate workings of forest ecosystems, helping us gain a deeper understanding of their complex dynamics.

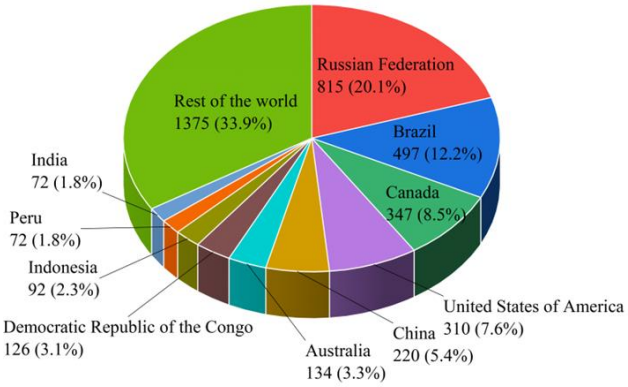

Figure 1 Global Forest cover 2021 in million hectares[2]

The figure 1 illustrates the distribution of forests across different countries and regions. The largest segment “rest of the world" makes up 33.9% of the total with 1375 million hectares. Following closely is the Russian Federation with 815, Brazil with 497, and Canada with 347 million hectares. Other countries that have a significant number of units include the United States of America with 310 million hectares (7.6%), China with 220 million hectares (5.4%), and Australia with 134 million hectares (3.3%). Smaller percentages ranging from 1.8% to 3.1% are also represented by other countries such as the Democratic Republic of the Congo, Indonesia, Peru, and India. The chart offers a concise and visually appealing representation of the data from various nations, showcasing the respective contributions of each.

The figure 2 illustrates the global forest cover between 1990 to 2021 while figure 3 clearly illustrates a concerning decline, with a steady decrease in the percentage of forest area over the span of 30 years. The data points exhibit a distinct downward trend. The percentage of global forest area has decreased from around 32.4% in 1990 to slightly above 31.0% in 2020, indicating a loss of approximately 1.4% over the course of three decades. This visual representation showcases the concerning decline in forest coverage across the globe, potentially caused by various factors including deforestation, climate change, and changes in land use for agriculture and urbanisation. The graph highlights the pressing concerns surrounding forest conservation and the importance of responsibly managing our forest resources.

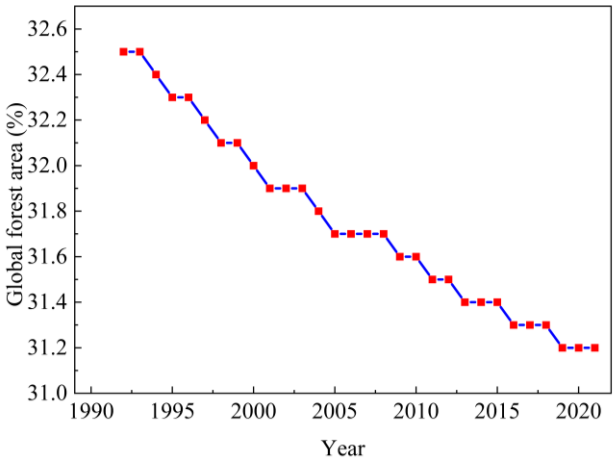

Figure 2 Changes in the global forest cover between 1992 - 2021[1]

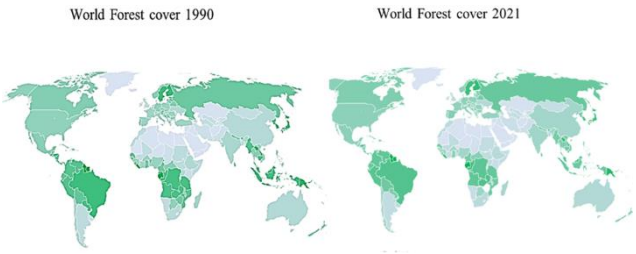

Figure 3 Global forest distribution between 1990 - 2021[1]

Forest inventory plays a crucial role in the preservation of forests. In a time where the world faces numerous ecological challenges, such as climate change, deforestation, and habitat loss, the demand for precise, thorough, and prompt data has become increasingly urgent. Forest inventory plays a crucial role in guiding conservation strategies, informing policy decisions, and aiding in the sustainable management of these critical ecosystems. It empowers conservationists and forest managers to make well-informed decisions, striking a balance between human needs and ecological integrity, guaranteeing the long-term flourishing of forests.

This article explores the important role of forest inventory in conservation efforts, discussing its methodologies, applications, and the challenges it encounters in the mission to protect our planet's valuable green heritage. Through this investigation, we strive to illuminate the broader significance of forest inventory, highlighting its crucial role in the preservation of our precious forests.

2. Forest classification

Forests, which span approximately 30% of the Earth's land, are crucial ecosystems that support a wide range of biodiversity[6]. They contain a vast array of terrestrial species and a staggering number of tree varieties. Various factors, such as the geographical location, climate conditions, types of trees, and amount of rainfall, play a significant role in determining their

classification. Forests are classified into Boreal, Temperate, and Tropical types, each with distinct characteristics.

2.1 Boreal forests

These forests are located between 50° and 60° North, Boreal Forests experience harsh winter conditions, with temperatures dropping as low as -30°C. Due to the extensive presence of permafrost covering 80% of the land, the biodiversity in this region is quite restricted[7]. These forests experience a relatively short growing season of approximately 130 days, with conifers being the predominant tree species. They play a crucial role in absorbing carbon and are essential for combating climate change. There are two subtypes: Open Canopy Boreal, which tends to be colder and have fewer species, and Closed Canopy Boreal, which is generally warmer and has higher species diversity and denser tree growth.

2.2 Temperature forests

Temperate Forests are found in mid-latitudes and go through four distinct seasons. The temperatures in these forests can range from -30°C to 30°C. The annual precipitation ranges from 75 cm to 1.5 m. The forests are categorized into different types based on their characteristics. There are Deciduous Forests, where trees shed their leaves during colder months. Coniferous Forests consist of evergreen trees that are well-adapted to colder climates. Temperate Rainforests, on the other hand, are characterized by their moderate temperatures and abundant rainfall[8].

2.3 Tropical forests

Tropical forests are located between the Tropics of Cancer and Capricorn, providing a consistently warm (20°C to 30°C) and humid environment. With their vast array of habitats, these areas are home to an astonishing variety of species, far surpassing what one might expect from their relatively small size. The soil, on the other hand, lacks essential nutrients because they are quickly used up. These forests are facing significant threats due to human activities. There are different types of forests that exist in various environments. These include rainforests, which receive a lot of rainfall and are home to a wide range of plant and animal species. There are also moist forests, which have less rainfall and consist of semi-evergreen trees. Dry forests, on the other hand, have adapted to survive in areas with prolonged dry periods. Cloud forests are found at higher altitudes and are characterized by their misty atmosphere. Lastly, mangroves are coastal ecosystems that thrive in brackish water[9].

These various forest types provide habitats for countless species. Conservation efforts, such as those undertaken by Operation Wallacea, play a vital role in safeguarding the remarkable ecosystems found in tropical rainforests, dry forests, cloud forests, and mangroves.

3. Methods for Assessing Forest Inventory and Their Applications in Conservation

Forest inventory is crucial for effective forestry management and conservation, utilising a range of methods to evaluate and track forest resources[4]. Over time, scientists have broadened their methods to encompass a wide range of traditional and advanced techniques, each with its own valuable contribution to the field of conservation[10].

3.1 Conventional Survey Techniques

Traditional forest inventory methods rely heavily on ground-based survey techniques. These measurements include direct assessments of forest attributes like tree diameter, height, species identification, and age estimation. Plot sampling, a widely used method, involves measuring specific areas and then applying those measurements to larger regions. The significance of these methods in conservation cannot be overstated. The data they provide is crucial for gaining insights into the composition and well-being of specific forest areas, which is of utmost importance for conservation planning and assessing biodiversity[11].

3.2 Remote Sensing and GIS

The advancements in satellite imagery and Geographic Information Systems (GIS), forest inventory has been transformed, allowing for more efficient and comprehensive monitoring and mapping on a large scale[12, 13]. Through the use of remote sensing technology, scientists have been able to gather data across expansive and hard-to-reach regions, providing a more comprehensive understanding of forest coverage and its fluctuations throughout time. This technology is vital for monitoring deforestation, forest degradation, and land-use changes, which are critical for implementing broad conservation strategies. The capabilities of GIS are further enhanced through the integration and analysis of spatial data, which greatly aids in conservation planning and decision-making[14].

3.3 Lidar and Advanced Technologies

LiDAR technology has revolutionised forest inventory, particularly in its ability to accurately map forest structure and biomass. LiDAR technology offers precise and detailed information about forest canopies, enabling scientists to analyse forest density, vertical structure, and canopy characteristics with great accuracy[15, 16]. This information is of utmost importance for habitat conservation, as it aids in the identification and preservation of crucial habitats and biodiversity hotspots. The use of LiDAR in conservation biology is growing, providing valuable information on wildlife habitats, forest succession stages, and ecosystem services. In a study conducted by Lefsky[17], A new map of global forest canopy height has been created using data

from the Moderate Resolution Imaging Spectroradiometer and the Geoscience Laser Altimeter System. A study published in Geophysical Research Letters has provided new insights. Various forest inventory methods, each with their own unique applications and strengths, contribute to a more comprehensive understanding and effective management of forest resources for conservation purposes.

4. Key Parameters in Forest Inventory for Conservation

4.1 Biodiversity Indices

Biodiversity, an essential component of conservation, encompasses the wide range and diversity of life found on our planet. Forest inventories are essential for evaluating the wide range of species present in an ecosystem. Through the collection of data on species presence, abundance, and distribution, inventories offer valuable insights into the diversity of species within a forest. Metrics like the Shannon-Weiner Index or Simpson's Diversity Index are commonly used to measure the richness and evenness of species in a given area. Collecting such data is crucial in order to identify regions with high biodiversity and determine which areas should be prioritised for conservation efforts. In addition, forest inventories can provide valuable biodiversity indices that help monitor changes over time. This information is crucial for informing conservation strategies and guiding actions[18].

4.2 Ecosystem Health Indicators

A forest ecosystem's health can be assessed by examining different parameters recorded in forest inventories, including forest density, age distribution, and indications of degradation or resilience. Forest density is a crucial factor in understanding the forest's ability to support wildlife and maintain ecological balance. It offers valuable insights into the number of trees per unit area. Age distribution data provide valuable insights into the forest's growth stages and succession patterns, enabling accurate predictions of future dynamics and resilience. In addition, it is crucial to observe signs of degradation, such as reduced canopy cover or increased prevalence of invasive species, as well as signs of resilience, such as the ability to recover after disturbances. These indicators provide valuable insights into the overall health and sustainability of forest ecosystems. These parameters help evaluate the effects of changes in the environment and human activities, providing guidance for conservation and restoration efforts[19]

4.3 Habitat Quality Assessment

Assessing the quality of habitats for wildlife conservation is another important use of forest inventory. Assessing various factors like the availability of food resources, water, shelter, and breeding sites is crucial for the survival of wildlife. Frameworks such as the Habitat Suitability Index (HSI) and Landscape Fragmentation Tools offer methods to evaluate the appropriateness of forest habitats for particular wildlife species. These tools make use of data on forest structure, composition, and connectivity, which are collected through forest inventories. Such assessments are crucial for identifying important habitats, creating wildlife corridors, and implementing measures to address habitat fragmentation and degradation. Ensuring the preservation of biodiversity and ecological functions relies heavily on the maintenance of high-quality habitats[20].

The importance of forest inventories in conservation is highlighted by key parameters such as biodiversity indices, ecosystem health indicators, and habitat quality assessments. They contribute essential data for making informed decisions to protect and manage forests in a sustainable manner, safeguarding biodiversity and ecosystem health.

5. Case Studies: Forest Inventory in Conservation Action

5.1 Success Stories

5.1.1 The Brazilian Amazon Monitoring Project

The National Institute for Space Research (INPE) in Brazil has effectively employed satellite-based forest inventory to track deforestation in the Amazon. The project showcased a remarkable decrease in deforestation rates, with a reduction of almost 80% between 2004 and 2017. This achievement is credited to the timely provision of data, which allowed for swift law enforcement actions and policy implementations. The approach exemplifies a model for extensive monitoring in tropical forests around the globe addressing the issue of Amazon deforestation through the implementation of public policies and interventions in beef and soy supply chains. Science has been expanded[21].

5.1.2 Restoration in Costa Rica's Guanacaste conservation area

Forest restoration efforts in Guanacaste, Costa Rica, have greatly benefited from a comprehensive forest inventory approach. The project centred around reforestation of native species and the implementation of natural regeneration techniques, which were guided by thorough forest inventories. The results show a greater variety of species, improved functions provided by the ecosystem, and better connections between habitats, illustrating the significance of thorough inventories in the field of restoration ecology (Chazdon, R. L. (2008). Exploring new frontiers: Revitalising forests and ecosystem services on depleted lands. Science).

5.2 Lessons Learned

5.2.1 Challenges in Madagascar's Rainforests

Madagascar's conservation efforts shed light on the difficulties of conducting inventories in dense, biodiverse, and frequently hard-to-reach rainforests. Despite facing challenges, the application of integrated ground and remote sensing techniques has significantly enhanced our comprehension of the island's distinct ecosystems, contributing to the conservation efforts for its native species. This case highlights the importance of tailoring inventory techniques to suit different environmental conditions and the value of incorporating local knowledge[22]

5.2.2 Breakthroughs in the Boreal Forests of Canada:

LiDAR technology has been integrated with traditional inventory methods to enhance conservation efforts in the Canadian boreal forest. Thanks to the scientist's efforts, the integration of data has resulted in more precise assessments of forest structure and carbon stocks. Canada's experience highlights the immense benefits of integrating advanced technologies into conventional inventory practices, resulting in enhanced conservation planning[23].

These case studies highlight the diverse applications and valuable insights gained from forest inventory in conservation efforts. The importance of adaptability, integration of new technologies, and data-driven approaches in effective conservation planning and action is emphasised.

6. Integrating Forest Inventory with Conservation Strategies

6.1 Policy and Management

The data from inventories are extremely important in the process of formulating environmental policies and management strategies. By way of illustration, the United States Forest Service incorporates inventory data into the National Forest Management Act, which enables efficient management of forest resources. The information that is presented is helpful in guiding decisions on sustainable harvesting, the protection of habitat, and initiatives to reforest regions. In addition, the European Union's Forest Strategy makes use of inventory data in order to provide background information for policy choices. The strategy's primary goals are to encourage sustainable forest management and to protect biodiversity. For the purpose of supporting evidence-based policymaking and adaptive management techniques, which are designed to enhance ecological, economic, and social sustainability, both situations rely on inventory data[11].

6.2 Community Involvement

When it comes to assisting local conservation initiatives, community-led forest inventories play a significant role, particularly in developing nations. For example, community forestry projects in Nepal make it possible for local people to conduct their own forest inventories. This leads to more community engagement and improved forest management. The relevance of community participation in conservation initiatives is shown by the fact that these programmes have been shown to be effective in increasing the amount of forest cover and improving households' standard of living. Furthermore, the participation of local people in inventory procedures for forest management has led to enhanced forest governance and conservation outcomes in specific parts of Africa. This contribution has been made possible by the inclusion of local communities. Through this, the need of incorporating local knowledge and involving stakeholders in conservation efforts is brought into sharper focus[24].

6.3 Monitoring and Evaluation

It is essential to conduct a continuous forest inventory in order to monitor the results of conservation efforts and make adjustments to tactics as required. The effort known as REDD+, which stands for "Reducing Emissions from Deforestation and Forest Degradation," is an excellent example of how continuing inventory data is employed to monitor forest carbon stocks and biodiversity. This monitoring is essential for determining how effective the programme is. The use of these inventories is extremely beneficial since they allow for the monitoring of changes over time, the evaluation of the efficiency of conservation efforts, and the modification of management plans as required. The use of this strategy ensures that conservation efforts continue to be flexible and open to new ideas and conditions as they emerge[25].

The incorporation of forest inventory into conservation plans is ultimately one of the most important factors that determines whether or not forest ecosystems can be successfully and sustainably preserved. In order to accomplish this goal, there are a variety of approaches that may be taken, including policy and management, engagement of the community, and ongoing monitoring and assessment. The use of these principles ensures that conservation efforts are well-informed, inclusive, and adaptable, which ultimately leads to environmental results that are more effective and sustained over time.

7. Challenges in Aligning Inventory with Conservation Goals

Table 1 presents a comprehensive view of the difficulties encountered when trying to integrate the forest inventory with conservation objectives. It highlights the diverse range of challenges, including technological and resource constraints, environmental shifts, and socio-political influences. Every challenge is supported by a logical explanation and a reliable source, ensuring a thorough grasp of the matter at hand.

Table 1 Difficulties in synchronizing forest inventory for the purpose of forest preservation

Challenge	Reasons	References
Data Limitations	Challenges arise when gathering data in remote or densely populated regions. Potential inaccuracies caused by the dense canopy or complex terrain. There is a pressing need to update data on forest ecosystems due to their rapid changes. Exploring the complexities of species identification and tree density measurement.	26
Resource Constraints	Financial constraints can have a significant impact on the extent and regularity of inventories, particularly in less developed nations. Insufficient access to cutting-edge technological tools, such as high-resolution satellite imagery or GIS software. Lack of skilled individuals in the field of forest inventory techniques and data analysis.	27
Technological Limitations	Current remote sensing technology faces challenges in accurately capturing the intricate details of forest structures. Addressing the complexities of merging various data sources and technologies to achieve a holistic perspective.	28
Environmental Changes	The effects of climate change on forest ecosystems may cause data quickly obsolete. The forest structure and composition are being impacted by a rise in natural disturbances such as fires and storms.	29
Political and Social Factors	Shifts in political agendas and policies impacting the allocation of resources and attention to conservation efforts. Conflicts arising from differences in conservation goals and the needs or land use practices of local communities.	30

7.1 Future Directions and Innovations

7.1.1 Exploring new technological advancements

In the field of forest conservation, new technologies are making a significant impact on transforming forest inventories. These advancements offer the potential to improve the precision of data collection and optimize the process for greater efficiency and minimal disruption. Important technologies to consider include: The application of remote sensing technology has revolutionized forest inventory methods, thanks to the utilization of satellites, drones, and LiDAR (Light Detection and Ranging) systems. These tools offer the ability to capture detailed images and collect data on the terrain, allowing for more accurate measurements of forest canopy, biomass, and even the identification of specific tree species from a distance.

AI and machine learning algorithms are being used more and more to analyze the large amounts of data produced by remote sensing technologies. These systems are capable of detecting patterns and variations in forest landscapes, which can be helpful in identifying illegal logging activities, forest degradation, and disease outbreaks.

Implementing blockchain technology can ensure the integrity of forest inventory data, providing a transparent and reliable system. Through the development of a secure and distributed ledger, individuals involved can effectively monitor and authenticate conservation initiatives, fostering a culture of openness and responsibility in the administration of forests.

The incorporation of mobile technology in forest inventories allows for the empowerment of local communities and individuals interested in scientific research. Mobile apps have the potential to gather and report data on forest health, species diversity, and environmental threats, providing crucial on-the-ground information.

7.2 Global Initiatives

Global conservation objectives are greatly supported by international collaboration in utilising forest inventories. One of the significant global initiatives is the Global Forest Watch (GFW). An innovative web application that harnesses the power of satellite technology, AI, and crowdsourcing to provide real-time updates on the state of forests worldwide. This initiative helps in monitoring changes in forest cover and offers support to policy-makers in making well-informed decisions.

REDD+ is a programme spearheaded by the United Nations that aims to motivate developing nations to reduce emissions from forested regions and foster sustainable[31] development through low-carbon initiatives. Precise forest inventories are essential for measuring and monitoring changes in carbon stock within the framework of REDD+.

A global partnership has been established among space agencies, conservation organisations, and research institutions. The objective of this partnership is to improve worldwide forest monitoring through the use of satellite technologies. This collaboration fosters the sharing of knowledge, technological progress, and the implementation of effective methods worldwide[32].

The Forest Carbon Partnership Facility (FCPF) is a global initiative that aims to assist countries in their preparations for the implementation of REDD+. This involves enhancing forest inventories and monitoring systems to efficiently evaluate and control forest carbon stocks.

Conclusion

The importance of forest inventories in the preservation and sustainable management of forest ecosystems is highlighted by the progress made in inventory methods. Through a wide range of techniques, including advanced

technologies such as remote sensing and LiDAR, our capacity to observe and control forests has been significantly improved. These methods are essential for evaluating biodiversity, ecosystem health, and habitat quality, which is critical for developing effective conservation strategies. The case studies provided highlight the practical application of these methods in real conservation projects, showcasing the accomplishments and valuable knowledge gained. The article also recognises the difficulties encountered in aligning inventory efforts with conservation goals, emphasising the importance of creative solutions and ongoing adaptation. Considering the future, advancements in technology and increased global cooperation hold great potential for improving the efficiency of forest inventories in support of conservation efforts. This article explores the importance of forest inventories in preserving our planet's valuable green heritage. It highlights how they serve as a foundation for informed decision-making and sustainable forest management.

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