Stalwarts who globally shaped the concept and science called agroforestry

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ABSTRACT: *Agroforestry is a sustainable and efficient land management system delibaretly combining crops, trees and sometimes livestock. Agroforestry is an age-old practice that has recently evolved as a scientific discipline to address the issues of land degradation, poverty and climate change in addition to the primary function of addressing the livelihood and economic security of the farming community. Nowadays, agroforestry is an alternate land use system for sustainability and acts as a platform for effectively harnessing the agriculture and forestry and livestock components. Several scientists shaped the agroforestry by addressing diverse kinds of practices involving tree-crop-animal combinations such as slash and burn agriculture, biological amelioration of degraded soil, soil-health improvement by alley cropping, benefits of different agroforestry system such as homegarden, agrisilviculture and silvopastures, species richness and ecosystem services, carbon sequestration and biodiversity conservation, provision of NTFP's, adaptation and mitigation of present and future climatic vulnerabilities, mitigation of GHG emission and delivery of ecosystem services.*

Despite the understanding of agroforestry as an age-old practice, recent decades has seen its transformation into a distinguished scientific discipline. This mainstreaming of agroforestry involve the collective efforts of number of scientists in the country of which the individual commitments and contribution from some stalwarts are worth mentioning. An insight into their contributions in the research and academic persuits in shaping up agroforestry will enlighten the academicians, policymakers and more importantly, students to get inspired to work for agroforestry. With this, snapshot of bibliometric analysis on "agroforestry" was carried out during the period 2001-2022 to understand the periodic progression in agroforestry research overtime and the associtated countries and scientists.

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1. INTRODUCTION

Planting trees has been regarded as a divine act for generations to meet primary needs *viz.* food, fodder, fuel and fibre. The multifarious benefits and services generated from tree-based systems are recognized as effective options to improve the livelihood status of dependent communities (Chavan *et al.*, 2015; 2016; 2021). Since the 1970s, agroforestry has come into the limelight for addressing various issue related to degradation of natural resources globally. The term 'agroforestry' was coined by a visionary study in the mid-1970s led by forester John Bene of Canada's International Development Research Centre (IDRC) Canada (Bene *et al.*, 1977). Agroforestry is a collective term for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos etc.) are deliberately introduced/used on the same land management unit as agricultural crops and/or animals, either in form of spatial arrangement or temporal sequence (Leaky, 2014). There are both ecological and economic interactions between the different components involved in the practices of agroforestry. Being an age-old practice evolved through intensification of traditional indigenous knowledge of many generations, agroforestry may not be recognized as a new concept but it emerged as new science. However, it will be interesting to observe the gradual evolution of agroforestry from the ancient traditional tree based landuse practices to more refined multiple component systems addressing the multidimensional challenges in the fast changing socio-economic fabric of the society.

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Slash and burn farming was commonly performed in Europe during the middle ages and was in practice in Finland until the end of the twentieth century and in a few locations in Germany as late as the 1920s (King, 1968). Farmers in Central America, have long planted a variety of crops with diverse growth habit tendencies to mimic the diverse nature of tropical forests. Hanunoo farming in SE Asia and shifting cultivation in Asia was practiced for ages. In African countries, agriculture under scattered trees and traditional homegardens have existed for millennia. Earlier, these practices were subsistence types, mainly focused on food production. However, towards the end of the nineteenth century, establishment of forest plantations assumed priority in many countires, the taungya system came into existence and spread to Burma, India and Africa (King, 1987). Randhava (1980) reported that tree domestication in South Asia dates back to the Mesolithic period (10,000 – 4000 BC) which include 63 fruits plants (including *bael*, goose berry, jujube, figs, *mahua* and mango).

In 1973, the Canadian International Development Agency (CIDA) collaborated with International Development Research Centre (IDRC) to organize an agrisilviculture fact-finding meeting in Ibadan, Nigeria and followed up with research in West Africa to figure out how to make the forest-fallow phase more productive. As a result, the IDRC Project Report recommended the formation of an internationally funded organization, now known as the International Council for Research in Agroforestry (ICRAF), to support, plan and coordinate research in agricultural and forestry combined land-management systems on a global scale. This was the first successeful effort for the institutionalization of agroforestry at global level. At the same time, International Institute of Tropical Agriculture, Ibadan also expanded its agroforestry research on alley cropping. Many research groups started working on animal integration with plantation tree crops like rubber and coconut (Nair, 1979). Meanwhile ICRAF has taken the lead in gathering information, conducting research, disseminating research results, pioneering new approaches and systems, although many individuals and institutions have made significant contributions to the knowledge and extension of the agroforestry concept (King, 1987). In addition, many other countries made efforts to identify and compile existing agroforestry practices all over the world.

Post Green Revolution era has witnessed the progression of agroforestry as a science and started attracting the world's attention as a prudent option for sustainable intensification of agriculture to address climate change and millennium developmental goals.

The systematic inventory of agroforestry systems was carried out by many scientists on various aspects of agroforestry and documented through large number of publications (Fig. 1). The contributions of Peter Huxley, Fergus L. Sinclair, PKR Nair, Meine van Noorddwijk, Ric Coe, BM Kumar, Götz Schroth, Chin K Ong, Anthony Young and GW Sileshi for the development of agroforestry as science are tremendous. Here is an attempt to recognize the contribution from these great stalwarts and highlight the trends of agroforestry research in the last two decades. This study document the number of periodic publications from 2001-2021, publication sources, eminent authors and their contributions, countries, and keywords. Such information were first identified, thematically mapped, conceptual structure and periodical topic evolution in agroforestry research were analyzed.

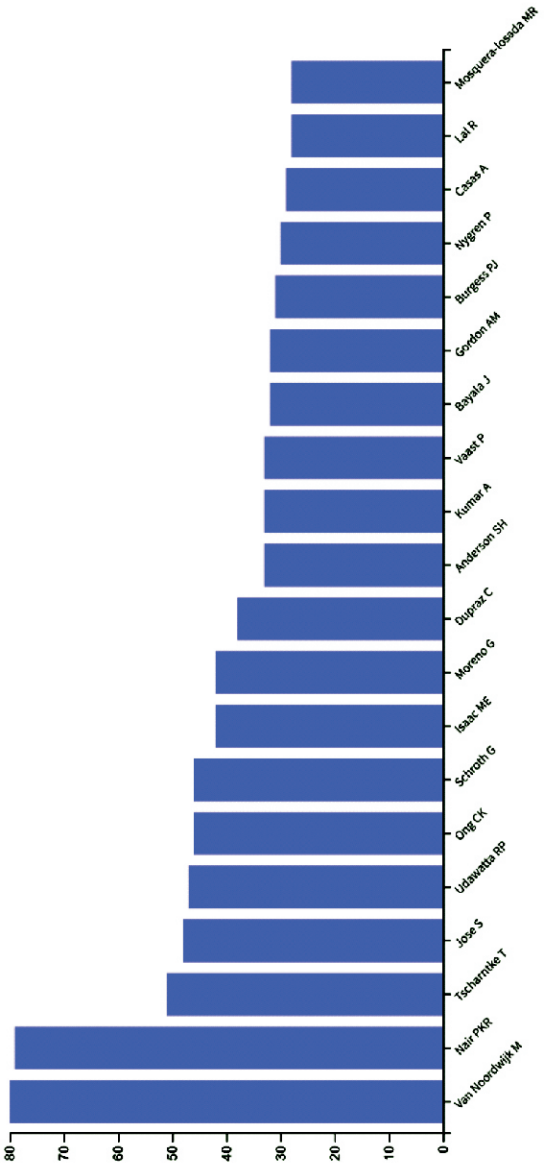

Fig. 1. The performance of the top 20 leading authors in agroforestry research worldwide from 1990- Jan 2022.

2. MATERIAL AND METHODS

2.1. Data collection

The data were collected from the ISI Web of Science Core Collection (WOS) database. WOS has been extensively used in bibliometric studies to offer high-quality academic publications and provide the most in-depth citation by source (Zheng *et al*., 2022). We performed single keywords search as 'agroforestry' topic in the WOS Core collection, and then we screened it out based on inclusion and exclusion criteria. Overall, firstly 8594 articles were identified and then we confined it to two recent decades from 2001-2022 (Jan, 2022) and the ten topmost categories that was related to forestry, agronomy, environmental science, ecology, agriculture multidisciplinary, soil science, plant science, environmental studies, green sustainable science technology and biodiversity conservation categories. Only research and review articles related to the 'agroforestry' topic and published in a peer-reviewed journal in the English language were considered. Book, book chapter, book review, proceedings paper, and the editorial material were excluded from the study. We manually screened 5841 articles to exclude those which are considered to be irrelevant and after assortment these publications were identified for further bibliometric analysis.

2.2. Bibliometric analysis method

Bibliometric analysis is a literature review methodology that analyses published papers statistically and quantitatively for ascertaining a specific kind of phenomenon or trend. It summarizes the content and structure of a particular research field. It analyses an extensive amount of published research using statistical tools to know which words-concepts and sub-topics are studied most? what are the most cited studies and journals? What are the studies that are most cited together? (Ozturk, 2021).

We performed a bibliometric analysis based on a sample article of 5841 retrieved from the WOS which intended to comprehend the systematic and holistic delineation of the existing structure in the agroforestry discipline and also to reveal research trends or provide an overview of evolution of the core themes (Zupic and Cater, 2015). The bibliometric analysis aims to analyze and visualize the structure of the research field by dividing the items (articles, authors, journals, keywords, or sub-topics) into different groups (Aria and Cuccurullo, 2017). In the current study, the bibliometric analysis of the agroforestry literature was performed in R using the biblioshiny for bibliometrix (Aria and Cuccurullo, 2017; Ramanan *et al*., 2021).

In addition, scientists with a higher impact on agroforestry research and citations were selected. Information regarding their contributions to agroforestry research was collected from google scholar, ResearchGate profiles, and other written media and compiled in this paper.

3. AGROFORESTRY SCIENTISTS

In the last four decades many scientists from different disciplines have contributed to the scientific expansion of agroforestry. In the long list of scientists, the contribution of a few stalwarts can't be ignored. The most prominent scientists who laid the scientific pillars of agroforestry are:

3.1. Peter A. Huxley

Peter A. Huxley was born in the year 1926 in Dulwich, East London. He joined the volunteer reserve in the Royal Auxiliary Navy at the end of the Second World War (1944–1946). Peter returned to Lloyds for a short while before concluding it wasn't for him. He received his PhD in Horticultural Botany in 1963 and his research focus was coffee physiology. Concurrently he nurtured strong passion for agriculture, climate, and tree phenology. Also, he had good understanding about agricultural education (Van Noordwijk *et al.,* 2021). Huxley's involvement with agroforestry began at the start of the modern research interest in its concept and practice. In 1979, he joined the newly instituted International Council for Research in Agroforestry (ICRAF) in Kenya making use of more than 20 years of tropical research experience in Uganda and Kenya. He noticed the ‘gap between the trees’ and ‘the trees commonly used in farmers’. Such observations helped to shape a new field of integrative science in support of farmers' practices. Huxly was instrumental in the creation of the journal Agroforestry Systems which helped to document various traditional agricultural landuse systems integrating trees and other crops (Huxley, 1985; 1987).

Peter Huxley was one of the "giants" of agroforestry research; one of his most enduring legacies is his consistant lobbying to convince the scientific community especially the CGIAR that a dedicated centre for agroforestry research might have a huge impact on improving the welfare of small-scale farmers. He was a key figure in the growth of ICRAF from a council to an international research centre (Lundgren *et al.,* 2020). Peter retired in 1990 while serving as head of the Research Development Division and left ICRAF in 1992. In 1996, in partnership with Chin Ong (Crops for The Future Research Centre, Malaysia), he compiled and edited a publication ‘Tree-Crop Interactions: A Physiological Approach’. Three years later, he published ‘Tropical Agroforestry’, which was mainly a reflection of his journey of discovery. This publication describes what is agroforestry, its complexities, and how to study and

develop it through reliable and credible research methods. Twenty years on, the book still stands out as the major textbook on agroforestry.

3.2 Maeine van Noordwijk

Before joining the Centre, Meine was a senior research officer in the Root Ecology Section at the DLO Institute for Soil Fertility Research in Haren, the Netherlands, concentrating on models of the relationships between soil fertility, nutrient use efficiency, and root development of crops and trees. He also worked for two years as a lecturer in botany and ecology at the University of Juba in Sudan. Meine has a PhD in Agricultural Science from the University of Wageningen, the Netherlands, and an MSc in Biology from the Rijksuniversiteit Utrecht, the Netherlands.

Trained as a biologist/ecologist at MSc level and with a PhD in agricultural sciences, his research focus centered on cross-scale linkages in socio-ecological systems (as in the 2015 volume "Climate- Smart Landscapes: Multifunctionality In Practice"); the synergy between local, scientific and public/policy knowledge systems (as summarized in the compilation of 49 methods in the 2013. Negotiation-support toolkit for learning landscapes" (2013); the development of synthetic models at tree (functional branch analysis, fractal scaling of allometry), tree-soil-crop interactions (WaNuLCAS), hydrological functions in landscape mosaics (GenRiver and FlowPer) and land use dynamics (FALLOW) scale, with associated databases. He led the RUPES program that reframed the debate on Payments for Ecosystem Services, recognizing a place for three complementary paradigms (commodification, compensation and coinvestment). Recent interests include the use of role play games for gender specific analysis of preferences and choices in a real-world context, complementing economic analysis of opportunity costs. He has a total citation of 36022 with a h-index of 90 and i10-index of 477.

3.3 P.K. Ramachandran Nair

P.K. Nair was born on March 12, 1942 in Trivandrum, Kerala, India and educated in India (BSc, MSc, and PhD), England (post-doctoral), and Germany (Dr. Sc. agr.). Then he worked as a post-doctoral fellow for a year at the Rothamsted Experimental Station in England and returned to India, joining the Plantation Crops Research Institute as an Agronomist. His path-breaking research on multistorey cropping *i.e.* home gardens in his native southern India during the 1970s led to his involvement as one of the founders of ICRAF in Kenya. At ICRAF where he worked for nearly 10 years, he played a key role in developing the discipline of agroforestry. He moved to the University of Florida as Professor of agroforestry in 1987, where he continues to train graduate students and visiting scientists from around the world, and provide global leadership in agroforestry research and education. As a world leader in the subject, he wrote the book, An Introduction to Agroforestry as the first college-level textbook in agroforestry in 1993 and recently the second edition, emphasizing current scientific developments.

He was the Editor-in-Chief of Agroforestry Systems journal for 11 years until 2005. In 2004, he started the book series "Advances in Agroforestry" (Springer), of which he was the editor. He showed exemplary leadership in organizing the World Congress's in Agroforestry: the first in Orlando, Florida, 2004; and the second in Nairobi, Kenya, 2009. He has received numerous awards and recognitions. He is a Fellow of the American Association for the Advancement of Science, and the American Societies of Agronomy, Crop Science, and Soil Science; he has received IUFRO (International Forestry Research) Scientific Award; multiple awards from the Society of American Foresters; four honorary Doctor of Science degrees (Kyoto, Japan; Kumasi, Ghana; Guelph, Canada; and Santiago de Compostela, Spain); the Hind Rattan (Jewel of India) and the Mahatm Gandhi Gold Medal Awards of India; and the Humboldt Prize of Germany. His famous quotes are agroforestry: a low-hanging fruit and Agroforestry - the future of global Land use.

Prof. Nair is a world leader in Agroforestry and his scientific experience extends internationally through more than 100 countries in Asia, Africa, Europe, and Latin America. His current research focuses on carbon sequestration and environmental quality under agroforestry systems. Other research interests include soil productivity, component interactions and agroforestry system design and evaluation.

3.4 Ric Coe

Ric coe is a specialist on research methods and has been working in ICRAF for long time. He is primarily associated with providing support research teams, scientists, students and partners in designing research projects and studies to improve their effectiveness. Similarly, he supports scientists in analyzing, interpreting, and communicating research data and results. Ric's background is in mathematics, biometry and statistics and during his long career with ICRAF, he has increasingly concentrated on the design phase of research, with particular interest in the design of research studies that are embedded in 'development' projects. Rics efforts has helped to resolve many methodological challenges in agroforestry research. He has been instrumental in developing experimental designs exclusively for agroforestry.

3.5 *Robert Zomer*

Prof Zomer is an acclaimed landscape ecologist with a broad background in the plant community, forest, and agricultural ecology and advanced skills in statistical analysis, geographic information systems (GIS), remote sensing, environmental modelling, and landscape-level spatial analysis. He is currently a visiting Professor at Kunming Institute of Botany and a Senior Landscape Ecologist at World Agroforestry in East and Central Asia.

Zomer has involved in projects on transboundary biodiversity conservation, wise-use of wetlands, small farmer timber production, application of advanced spatial tools at global to local levels and within participatory frameworks; integrated watershed management, characterization of marginal environments for livestock production, and water use dimensions of tree-based farming systems, agroforestry, and afforestation/reforestation for climate change mitigation. In-depth and practical experience in sustainable agriculture, tree crops, and Himalayan Mountain farming and forest ecosystems. His monumental work on assessing the contribution of agroforestry to global and national carbon budgets is worth aprecating.

3.6 *Fergus L. Sinclair*

Dr. Fergus Sinclair is Director of Research of science at World Agroforestry Centre (ICRAF) in Nairobi and was the faculty member in the school of Environment, Natural Resources and Geography at , Wales, UK. He received his bachelor's degree in agricultural systems from the University of Reading, where he began his career in applying systematic methods to agricultural development, inspired by Sir Colin Speeding. He did his Ph.D. on modelling agroforestry systems with Prof. Paul Jarvis at the University of Edinburg from where the University of Wales recruited him, Bangor to develop a new degree programme in Agroforestry. He is an honorary editor of Agroforestry Management Systems. He is Project team leader for the UN Committee on World Food Security (CFS), high–level panel of Experts (HLPE) report on agroecology, and lead author of background paper on agro-environmental approaches to realizing climate change- resilient agriculture for the global Commission on Adaptation (CGIAR, 2022).

Fergus Sinclair led the Center's study of how trees can contribute to the productivity of agricultural systems and rural livelihoods. Factors that influence a farmer's decisions about which trees to add to the farm and how to care for them (https://www.researchgate.net/profile/fergus-sinclair). He has also combined these interests by contributing to the development of interdisciplinary GIS tools for spatially explicit evaluation of ecosystem service synergies and tradeoffs at landscapes scales (Polyscapes). Fergus Sinclair is well known for pioneering the development of knowledge-based system methods for acquiring and using local agro-ecological knowledge; for using participatory modeling to better harness natural resources at the community level; and exploring tradeoffs between the impact of farm trees on productivity and biodiversity (GLF, 2022).

3.7 *Anthony Young*

He was born in London in 1932. After completing his education at St. Christopher School, Letchworth; he graduated from St. John's College, Cambridge, in MA Geography (Amazon, 2022). For his contribution to research on tropical soil and land evaluation, he was awarded a Doctoral degree at the University of East Angelia, Norwich, United Kingdom (Young, 1989).

During 1958-62, he worked as a Soil Surveyor under the Department of Agriculture, Malawi (HM Overseas Civil Service) and as a Lecturer in Geography at the University of Sussex from 1963 to 1968 (Amazon, 2022). He was a consultant for the Food and Agriculture Organization and World Bank and worked in 31 developing countries (Young, 1989). He worked as a professor of environmental sciences at the University of East Angelia, Norwich, United Kingdom (1962-82). He also worked as Principal Scientist of Soils and Land Evaluation with ICRAF for nine years during 1983-92 (Young, 1989). He was awarded Cuthbert Peek Award in 1972 by the Royal Geographical Society, 1995 Leverhulme Emeritus Fellowship, and Rockefeller Residency in 1995 for his contribution to research (Amazon, 2022; Young, 1989). His works not only include university-based study in constraints of natural resources development but also included practical contributions to resource-use planning in developing African and Asian nations as he was trained soil scientist and geographer as well (Young, 1989). He was co-authored the FAO standard textbook on the evaluation of land and land use planning. His world renouned books entitled "Agroforestry for soil conservation" and "Agroforestry for soil management and soil survey and land evaluations" provided eye-opening information on role of trees to combact land degradation and nutrient cycling. He also authored 23 monographs, ten books, and more than 130 articles in journals. He is currently working as an Honoury research fellow at in university of east Angelia (Amazon, 2022; Young, 1989).

3.8 *Gotz Schroth*

Schroth has greatly contributed to agroforestry through his studies on the biophysical interactions and

component management in agroforestry. He completed Masters in Geoecology (Environmental Sciences) in 1989 on the topic "Agroforestry System of Kazaboua, Central Togo - an Analysis on the Basis of Multiple Approaches" and received a doctoral degree in Natural Sciences in 1994 for his study on above- and below-ground interactions in alley cropping with *Gliricidia sepium* as compared to conventional and mulched sole cropping on a high base status soil in the West African rain forest zone and Ph.D. degree in Soil Sciences in 2000 from the University of Bayreuth, Germany. He is currently working as Senior Director at Conservation International, USA. His research focused chiefly on agroforestry systems, family farming, biodiversity of agricultural landscapes, sustainable use conservation units, and climate change (https://www.escavador.com/sobre/564287/gotz-schrot). He is also co-authored in the book "Tree, Crops and Soil fertility". He authored many books such as 'Agroforestry and Biodiversity Conservation in Tropical Landscapes', 'Economics and Ecology of Diversification'. He has published three books, three special issues of journals, and more than 156 articles and book chapters related to sustainable agriculture and natural resource management especially on cocoa-based agroforestry (Escavador, 2022) with 9037 citations (https://www.researchgate.net/profile/Goetz-Schroth).

3.9 Gudeta Weldesemayat Sileshi

Sileshi is an Ethiopian ecologist with over 25 years of long and diverse experience in research, management and teaching in agriculture in Africa. He graduated in BSc Biology and completed an MSc degree in Agriculture and a doctoral degree in Ecology. He held the post of Research Scientist at ICRAF, Lilongwe, Malawi during 2002-11 and as a Regional Representative at World Agroforestry Centre, Nairobi during 2010-14. He also worked as a Research Associate for Plant and Animal Health at International Centre for Insect Physiology and Ecology (ICIPE), Nairobi, during 2000-2001. The focus of his research areas was production ecology, emphasizing plant and soil health, biodiversity, and sustainability, including ecological modelling. He is also fascinated about life of termites. He oversaw the Malawi Agroforestry Food Security Programme. He created the Building a Large Evergreen Agriculture Network for Southern Africa, a thriving multi-stakeholder AR4D initiative that was executed in Malawi, Zambia, Mozambique, Botswana, and South Africa. His works particularly focused on carbon sequestration, allometric equation, ecological modelling and tree crop interaction in agroforestry. Till date he has published more than 320 articles including books, book chapters and research articles with 8203 citations. In 2008, he co-edited Indigenous Fruit Trees in the Tropics, and in 2016 and 2020, he co-authored two books' Termite Management in Agroforestry' and 'Bamboo: Climate Change Adaptation and Mitigation'.

He has also served as the International Union of Forest Research Organizations' Deputy Coordinator of Experiment Design, Performance, and Evaluation since 2017. In appreciation of his extraordinary contribution to research on the creation of Fertilizer Trees and his excellent leadership in promoting green technologies to combat land degradation, climate change impacts, and improve productivity and food security in Africa, he was nominated as an African Academy of Science Fellow (AAS, 2022).

3.10 Mohan Kumar, B

Mohan Kumar, B currently holding the position of Vice-Chancellor of Arunachal University of Studies, India, is a leading researcher in agroforestry. Earlier, he worked as Assistant Director General (Agronomy, Agroforestry & Climate Change) in Indian Council of Agriculture and Research. He was Professor and Dean (Ecology & Environment Studies) at Nalanda University and Associate Dean (Forestry) in the Kerala Agricultural University, Thrissur in India.

He also served as visiting professorship at the University of Missouri in the United States, the University of Toulouse (CNRS Visitor), Bangor University in the United Kingdom (Erasmus Mundus Scholar), the University of Tokyo in Japan (IR3S Visiting Fellow), the University of Florida in the United States (Fulbright Award), Tokyo University of Agriculture and Technology in Japan (JSPS Scholar), Utah State University in the United States (USAID Sponsorship) and many universities in Indonesia. In appreciation to his dedication and contribution in agroforestry field, he was awarded the first Dr. KG Tejwani Award for Excellence in Agroforestry Research & Development in India by Indian Society of Agroforestry. (https://vidwan.inflibnet.ac.in/profile/43831#personal_information panel). Mohan Kumar has also figured listed in the newest database of the world's top 2% scientists, compiled by Elsevier Publishers and Stanford University in the United States.

His research area focused on agroforestry, silviculture, sustainability, data analysis, and agrobiodiversity. He also contributed to the first and only study on stand density management of teak in India. He has strong professional background, including a postdoctoral fellowship at Utah State University in Forest Ecology and Silviculture. He also co-authored book titled' Carbon Sequestration Potential of Agroforestry Systems: opportunities and challenges' along with PKR Nair (Kumar and Nair, 2011). He has also the

coauthor of the revised edition of the monumental book on agroforestry 'An Introduction to Agroforestry- Four Decades of Scientific Developments by Dr. P.K. Ramachandran Nair. Dr. Mohankumar has more than 200 per reviewed publications, including books, book chapters, reviews, research articles, and 5800 citations to his credit (https://www.researchgate.net/ profile/B-Mohan-Kumar-2).

4. RESEARCH TREND IN AGROFORESTRY DURING 2001-2022

Research on agroforestry has started in mid-twentieth century throughout the world. The countries most active in agroforestry research include United States, India, France, Germany, Australia, China, Brazil, Kenya, Ethiopia, and some Southeast Asian countries, which is likely due to a research boom in line with agroforestry projects and policies (Fig. 2). Papers based on multi-functionality, carbon sequestration, biodiversity conservation, soil improvements, maintenance of soil fertility and nutrient cycling of homegardens are mainly featured from India. Institutions like ICAR-Central Agroforestry Research Institute, Jhansi and other ICAR institutes along with All India Coordinated Research Project on Agroforestry contributed substantially to build research in agroforestry in India. In African countries, most studies focused on cocoa-based and coffee-based agroforestry and silvipastoral systems for easy access to nutritious food, poverty reduction, and ecosystem conservation and rehabilitation. Due to presence of ICRAF in Kenya and many projects' initiatives, research in Kenya and Cameroon is booming. To combat deforestation in the Amazon, agroforestry is one of the most essential land-use types in Latin America. In this region particularly Brazil, research is primarily focused on ways to support farmers' short- and long-term economic needs while also preventing deforestation. As a result, the most pastoral and shaded tree-crop systems. To utilize limiting natural resources sustainably to meet growing demand of food of increasing population, agriculture components is given attention in SE Asia and thus most of the studies focused on homegardens, taungya, shelterbelts, and windbreaks. Due to high living standards in USA, France and Germany, most of the studies focused on ecosystem services, landscape aesthetics construction, and the role in response to the global environment change and phytoremediation. Research on agroforestry during 2001 to Jan, 2022 and summerrised in table 1. About 5841 scientific documents were published in the form of articles, book chapter & porceedings and a total of 16295 authors contributed with an average of 0.358 documents per author, 2.79 authors per documents and a collaboration index of 2.89. Interestingly, there were about 249 authors who published single-authored input indirectly indicating the level of collaboration among authors.

4.1 Thematic map

We examined themes according to the quadrant in which they are positioned on a thematic map, which is a highly intuitive plot: (1) upper-right quadrant: motor themes; (2) lower-right quadrant: fundamental themes; (3) lower-left quadrant: developing or vanishing themes; (4) upper-left quadrant: extremely specialized/niche themes. According to our analysis intercropping and alley cropping fall into the agroforestry niche theme which is very suitable for research and could succeed over time. Coffee and cocoa based agroforestry research is either emerging or in declining trend now a days. Climate change-based agroforestry research is the motor theme, inferring the importance of the agroforestry in the era of climate change. Additionally, size of circle denotes the relative relevance or scope of work with reference to other thematic topics. However, after climate change, ecosystem services and in particular carbon sequestration potential of agroforestry has been most relevant topic of research in last two decades. These themes are important for a research field and concern general topics transversal to the different research areas of the field. In synthesis, the themes are clustered and classified by their centrality, representing the importance of the theme within the research field and their density, representing their stage of development.

Table 1. Summary of literature (metadata) on Agroforestry between 2001-2022

Description	2001-2022
Total Number of Scientific Documents	5841
Average years from publication	7.74
Article	5246
Book chapters	315
Proceedings papers	173
Average citations per documents	18.72
Authors	16295
Involved in single-authored documents	249
Involved in multi-authored document	16046
Documents per Author	0.358
Authors per Document	2.79
Co-Authors per Documents	4.68
Collaboration Index (CI)	2.89
Study Sources (Journals, Books, *etc.*)	533

Country Scientific Production

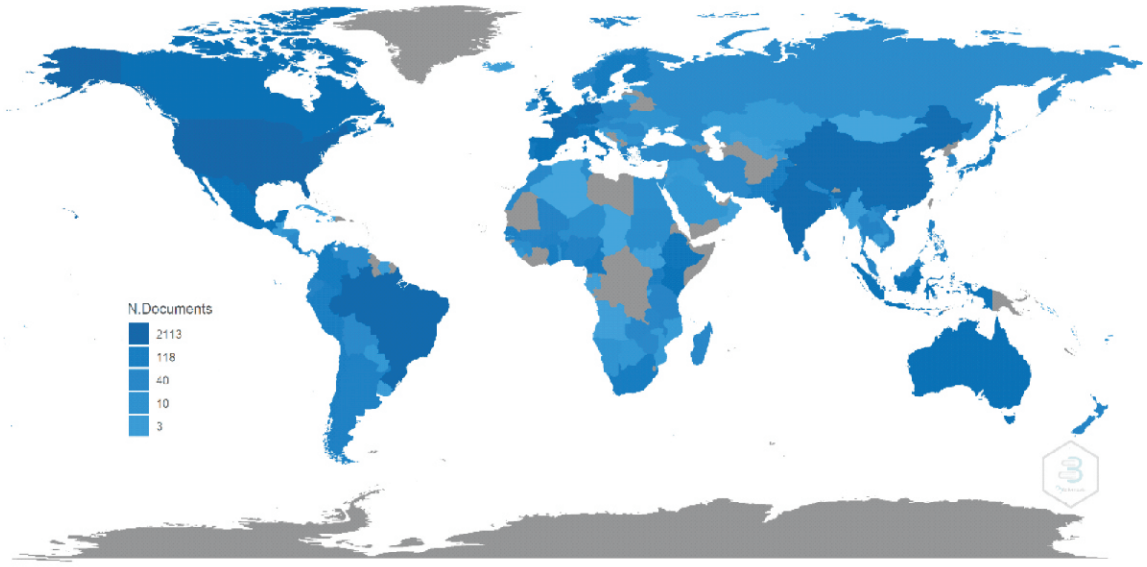

Fig. 2. The most productive countries, based on aggregate of the documents published in the agroforestry research (Intensity of blue color is relative to number of documents published).

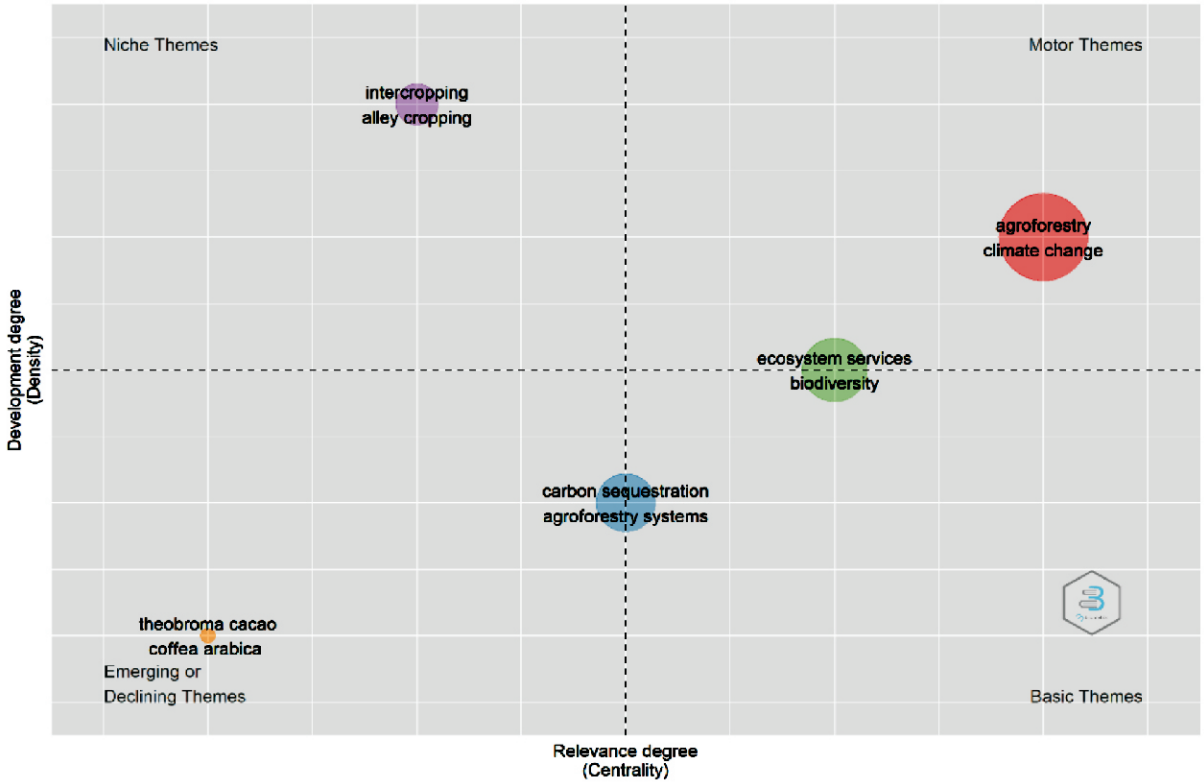

Fig. 3. Thematic map based on author keywords (interpretation is based on relevance of topic and development of topic over period of time *i.e.*, present, past and future scope of work).

4.2 Three-field-plot

Three-field-plot, as depicted in figure 4 showed interactions among the most relevant journals (left), most productive countries (middle) and keywords (right). The three field plots reported that most of the papers were published in the 'Agroforestry system' followed by 'Agriculture ecosystem & management' and 'Sustainability'. Articles published in the journal "Agroforestry systems' were mostly contributed by authors from the USA, majority of them have the keyword as agroforestry. On an average USA, India, Germany, France, China and Brazil have great interest in agroforestry research. Authors from the most of the countries used broad range of keywords, out of which agroforestry is commonest. From India, agroforestry research published in Range Management &

Agroforestry journal published by Range Management Society of India, Jhansi. The research journal such as Indian journal of Agroforestry, Indian Journal of Ecology, Indian Journal of Agricultural Sciences and Current Science are not covered in web of scince. Recently, Suresh *et al.* (2021) analysed research output of ICAR-CAFRI, Jhansi by using Scopus database and found that journals like Current Science, Indian Journal of Agricultural Sciences and Indian Journal of Ecology published majority of research papers about agroforestry.

Thematic and three-fold maps were analyzed to understand the research trend of agroforestry to draw the future need of the researchers.

4.3 Conceptual structure

Figure 5 shows a bird's eye perspective of articles published in agroforestry study domains from 2001 to 2022. During 2001-2005, silvi-pastoral system, agroforestry system, legume tree and cropping systems were most commonly used titles for publication. In 2006-2010, silvi-pastoral system and carbon storage were most common terms used as titles in papers. Production systems and carbon sequestration were the most familiar titles used in publications during 2011-15, while soil organic and carbon sequestration were the most typical terms used as titles in 2015-20. In 2020-22, carbon storage, silvi-pastoral system, and agroforestry system were the commonest. The share of carbon storage and sequestration as a title increased from 2006 to 2022, as shown in Fig. 5. With the increased awareness of climate change and environmental issues in the world and its potential impact on agricultural sector, agroforestry research has become increasingly involved in those areas with a focus on carbon

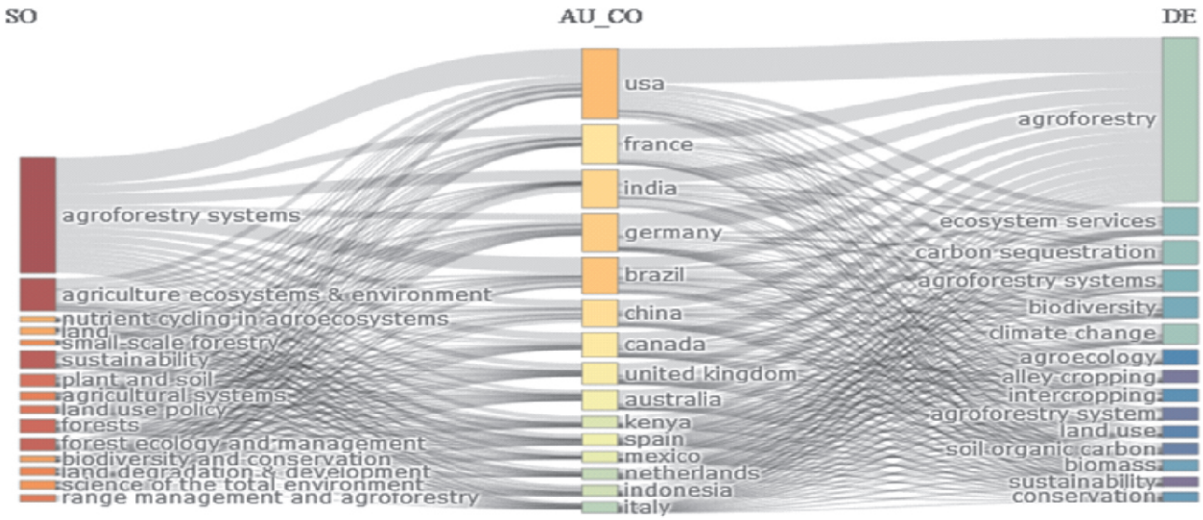

Fig. 4. Three field plots *i.e.*, source-country-keyword in agroforestry research (2001 to 2022).

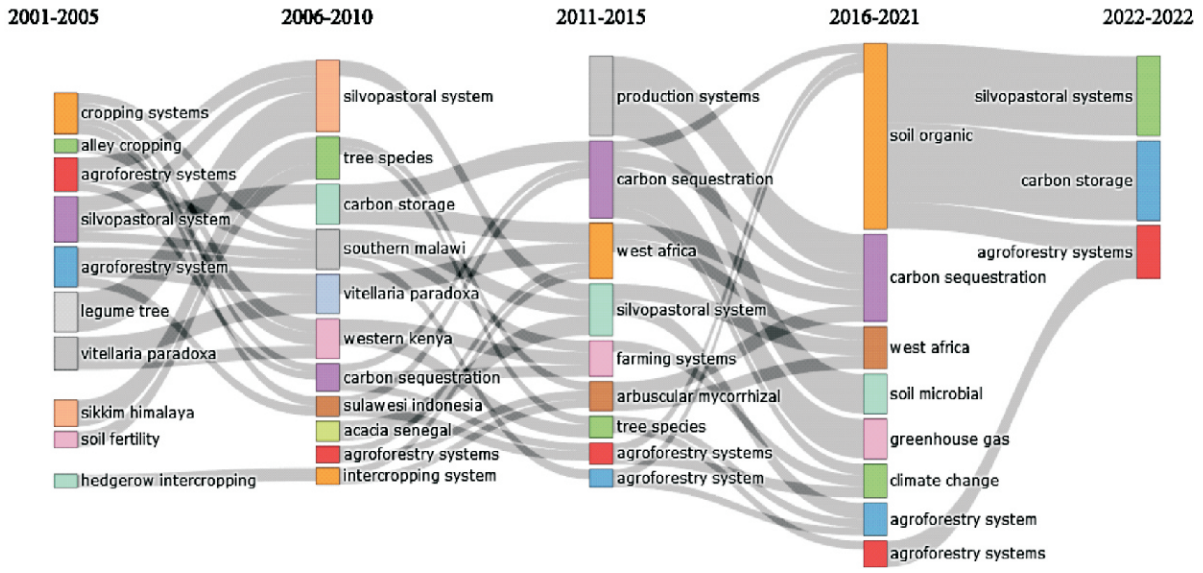

Fig. 5. Conceptual structure *i.e.*, thematic evolution of title in agroforestry publication (inclusion index)

sequestration, greenhouse gases mitigation, and climate change (Fig. 6). Under climate change scenarios, research keywords or climate related topics were biomass production, carbon storage, carbon stock, soil carbon, carbon sequestration, adaptation & mitigation of climate change, climate change, ecosystem services and more recently regenerative agriculture, climate-smart agriculture and carbon neutral agriculutre. After 2020, research on regenerative agriculture and climate-smart technologies are more published in reputed journals (Fig. 6).

The word cloud analysis showed that the authors' most frequent keywords in agroforestry publications are agroforestry system, carbon sequestration, climate change, ecosystem services, and biodiversity (Fig. 7). It is a proxy of research done in the past and the present time, which flags a future research line in agroforestry. The large letter in the word cloud indicates the most researched area or favorite topic, which follows the line of investigation at present. However, the small letter indicates either an emerging or declining exploration theme. Overall, it showed a corridor for potential and opportunities in the research time ahead.

4.4. Future lines of works

Agroforestry science paradigms have altered in response to global forest policy discourses. In the realm of agroforestry, policy and science discourses are intertwined. Between 2010 and 2018, the most studies focused on biodiversity conservation, soil formation, soil composition, soil fertility and nutrient cycling, with a few studies focusing on cultural services, spiritual and religious, and recreational or aesthetic values of agroforestry (Shin *et al*., 2020). Ecosystem services provided by agroforestry were considered to be seldom understood in the field of social science. Farmer's choice to adopt agroforestry is influenced by a variety of factors, including income,

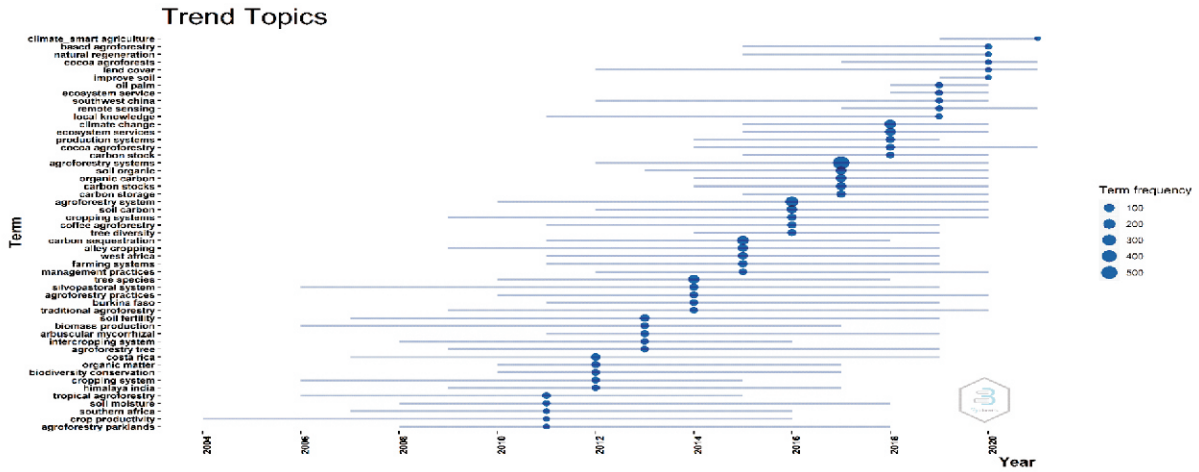

Fig. 6. Periodical topic evolution in agroforestry research (Circle size indicate the frequencies of keyword for determination of trend topic).

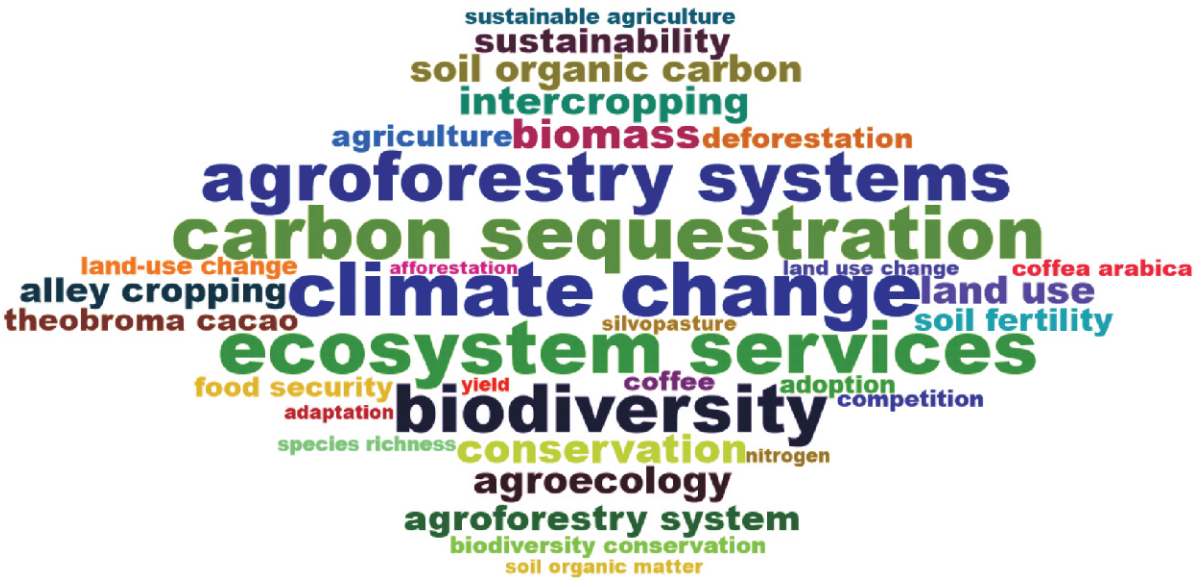

Fig. 7. Graphical display of World cloud formation based on frequency of author's keywords in agroforestry research.

expertise, policy, and gender; as a result, more social science studies in the field of agroforestry is highly recommended to uncover the elements that impact the adoption of agroforestry. Although many studies on ecosystem services published, valuation of ecosystem services especially regulating services and intangible ecological benefits need to be done to incorporate in the payment for ecosystem services (PES) mechanism. Further studies to identify existing or new successful intercropping combinations with high value crop such as sandalwood, red sanders, agarwood, ebenum, African blackwood and *Litsea* spp. are needed within the framework of climate-smart agriculture. Considerable emphasis has been given to research on precision farming, water and nutrient budgeting in agriculture but relatively very few studies in these focused areas in the the field of agroforestry. The focus of agroforestry research has shifted in recent years from the plot or field scale to the landscape scale, revealing enormous benefits that trees give in agricultural landscapes. Trees on farms play an important role in forest transition beyond the conventional forest boundaries. More concerted efforts are required for harnessing various policies with agroforestry in meeting the the INDC commitments of the country and based on decisions in the recent climate negotiations.

Agroforestry is one of the most promising components for adapting to climate-related anomalies in the smallholder sector which while ensuring economic, nutritional and livelihood security, also takes care of the ecological resilience of the agroecosystems. Hence, agroforestry should be central to all such policies intented to improve the resilience of the most vulnerable populations. Some of the identified future researchable issues based on the summarized four decades of rigorous research in agroforestry are :

1. A global consortia leading agroforestry research dedicated towards studies on the effect of climate change on current land use systems and contribution of agroforestry as a resilient system and quantification of its ecosystem services and impact of climate change on phenology of trees.
2. Advanced modelling techniques to overcome long gestation period associated with woody perrenials to understand impact of tree-based systems' and early adoptions.
3. Precision silviculture techniques specific to important agroforestry tree species to provide farmer centric and friendly techniques.
4. Eco-physiological studies on agroforestry species to provide deeper insight into their climate resilience ability.
5. Developing digital signature of important woody perennials using remote sensing and GIS tools to identify trees and areas under agroforestry.
6. Emphasis on tree genomics and next-generation sequencing and omics will expand our knowledge to detect molecular and physiological pathways in agroforestry species.
7. Long term experiments to understand the impact of agroforestry on soil health
8. Socio-economic impact analysis of agroforestry systems to understand its role in livelihood security and meeting sustainable development goals
9. Documentation of traditional agroforestry knowledge and systems (khejri, kangyam, Acacia, alder *etc*.) needs to be scientifically characterized and explored to understand their biodiversity conservation, livelihood security, and climate resilience
10. The valuation of agroforestry ecosystem services, is still in the infancy stages. More social scientists have to focus research on payment of ecosystem services to farmers. Mechanism for premium pricing of agroforestry products has to be developed.
11. Tree improvement programmes should focus on wood quality and product-based research (solid wood, plywood, particle board *etc.*)
12. Research on compatibility and designing of silvopastoral systems, tree fodder and value addition as animal feed to meet the growing fodder requirement at the micro- and macro-level will be needed in the future.
13. High-value (sandalwood, red sanders, agarwood) agroforestry systems must be standardized.
14. Research on the impact of practicing agroforestry on REDD+, carbon credits, NDC, forest conservation, and management.
15. A viable and vibrant extension network and mechanism to disseminate the agroforestry knowledge aming various stake holders.
16. Studies on agroforestry as potential strategy for the ecorestoration of agro-ecosystems in the fast changing agro-climate of the country.

5. CONCLUSION

Agroforestry as a scientific discipline has evolved over the years from a simple field trial to complex models like WaNuLCas or more. In the last decade, the role of agroforestry in generating or creating

ecosystem services has been primarily acknowledged. Agroforestry is considered a panacea to address the maladies of intensive agriculture and land degradations. Over the years, agroforestry has created its niche among the scientific communities as it has proven itself as a climate-resilient and climate-smart practice. Thousands of agroforestry researchers are working around the clock to understand and master the centuries-old idea of agroforestry. The fruits of scientific recognition of agroforestry that we are reaping today are the seeds sown by our predecessors and stalwarts like Peter Huxley, Fergus L. Sinclair, PKR Nair, Meine van Noordwijk, Ric Coe, BM Kumar, Gotz Schroth, Chin K Ong, Anthony Young and GW Sileshi. Their contributions helped immensely to systematically identify the fundamental problems, designing the experimental trials and documenting the scientific findings. Their efforts largely helped in laying the foundation for many agroforestry specialists throughout the world to pursue agroforestry as a scientific career. Agroforestry is the future of sustainable farming on the planet, and the contributions of these scientists will be remembered and appreciated in the future. Agroforestry touch upon many sectors of agricultural and forestry relevance which calls for collaborative approach for resolving larger issues of productivity decline in the context of climate change. Hence, there is an urgent need to focus on collaboration with institutes at the national and international level in the future.

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