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Silvicultural Management, Tree-Ring Analysis and Timber Quality Improvement in Zambian Forest Plantations: A Systematic Review

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Systematic Review

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Abstract

Forest plantations play a critical role in meeting demand for timber, poles, pulpwood, fuelwood and other forest products while reducing pressure on natural forests. In Zambia, plantation forestry is dominated by exotic species, particularly Pinus and Eucalyptus, but timber quality is influenced by silvicultural practices, site conditions, climate variability, pests, diseases and management interventions. This systematic review synthesizes evidence on silvicultural management, timber quality improvement and dendrochronological applications in Zambian forest plantations. Following the PRISMA 2020 framework, literature published between 1980 and 2026 was identified from Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, CAB Abstracts, Google Scholar and additional forestry and institutional sources. The review evaluates species–site matching, spacing, thinning, pruning, weed control, fertilization, fire management, pest and disease control, and the use of tree-ring analysis to understand growth dynamics, climate responses, wood formation and rotation-age decisions. A total of 1,624 records were identified, 1,310 were screened after duplicate removal, 382 full texts were assessed, and 142 studies met the inclusion criteria. Because of substantial heterogeneity among studies, thematic synthesis was used rather than quantitative meta-analysis. The evidence indicates that management interventions can influence stem form, diameter growth, knot development, wood density and timber value, while dendrochronology provides long-term information on growth patterns, climatic responses, disturbances and management effects. Integrating silvicultural management with tree-ring monitoring offers a practical framework for improving timber quality, growth modelling and climate-adaptive plantation management in Zambia.

Key points

• Silvicultural decisions influence growth, stem form, branch development and several indicators of timber quality.

• Spacing, thinning and pruning require balancing growth objectives with knot formation, stem quality and wood-property considerations.

• Fire, pests, diseases and climate stress can reduce plantation productivity and timber value if not integrated into management planning.

• Tree-ring analysis provides long-term evidence on growth variability, climate responses, disturbances and management effects.

• A combined silviculture–dendrochronology framework can support adaptive plantation management and timber-quality planning in Zambia.

Plain-language summary

Plantation trees are managed to produce wood efficiently and with the quality needed by different industries. This review brings together evidence on how practices such as spacing, thinning, pruning, weed control, fertilization and protection from fire, pests and diseases affect plantation growth and timber quality. It also examines tree rings as a record of past growth and environmental conditions. The review shows that long-term tree-ring information can complement routine plantation inventories by revealing growth changes, climate responses and management effects. For Zambia, combining good silviculture with systematic tree-ring monitoring may strengthen decisions about growth, timber quality, rotation planning and climate adaptation.

1. Introduction

1.1 Background

Forest plantations have become increasingly important in meeting global demand for wood products and reducing pressure on natural forests. Worldwide, planted forests contribute substantially to timber supply, industrial raw materials, carbon sequestration, ecosystem restoration, and rural livelihoods. As populations continue to grow and demand for forest products increases, plantation forestry has emerged as a strategic approach to sustainable wood production. (Evans and Turnbull, 2004; FAO, 2020)

In Zambia, plantation forestry forms an important component of the national forestry sector. The country's plantations are largely dominated by exotic species such as Pinus kesiya, Pinus oocarpa, Pinus patula, Eucalyptus grandis, and Eucalyptus cloeziana. These plantations provide saw timber, transmission poles, mining timber, pulpwood, fuelwood, and construction materials. Plantation forests are primarily concentrated in the Copperbelt Province, Muchinga Province, and other suitable agroecological regions.

The success of plantation forestry depends not only on tree growth and productivity but also on timber quality. Timber quality refers to the suitability of wood for specific end uses and is influenced by characteristics such as stem form, wood density, knot size, branch frequency, taper, straightness, growth rate, juvenile wood proportion, and the occurrence of defects. High-quality timber attracts premium market prices and improves industrial recovery, while poor-quality timber reduces profitability and utilization efficiency.

Silvicultural management plays a central role in determining plantation productivity and timber quality. Practices such as species-site matching, spacing, thinning, pruning, weed control, fertilization, fire management, and pest control influence tree growth, wood formation, and stand development. These interventions affect both the quantity and quality of timber produced.

In recent years, dendrochronology has emerged as an important tool for understanding forest growth dynamics. Dendrochronology involves the study of annual tree growth rings to reconstruct growth histories, assess climatic influences, evaluate management interventions, and predict future growth trends. Although traditionally associated with temperate forests, dendrochronological applications in

tropical and subtropical plantations are increasing. Tree-ring studies can provide valuable information regarding growth rates, climatic responses, disturbance histories, and timber quality development.

The integration of dendrochronology into plantation forestry offers opportunities to improve plantation management, optimize rotation lengths, assess climate sensitivity, and predict timber quality outcomes. Despite these benefits, dendrochronological applications remain relatively underutilized in Zambian plantation forestry.

1.2 Problem Statement

Forest plantations in Zambia have considerable potential to contribute to sustainable timber supply and economic development. However, timber quality remains a persistent challenge due to inappropriate silvicultural practices, inadequate plantation management, fire damage, pest and disease outbreaks, poor species-site matching, and climatic variability.

Many plantation management decisions continue to rely on short-term growth measurements and generalized silvicultural guidelines. As a result, opportunities to understand long-term growth patterns and their relationship with timber quality are often overlooked. Furthermore, dendrochronology remains underutilized despite its potential to provide valuable information regarding annual growth responses, management effects, and climate-growth relationships.

Without a comprehensive synthesis of existing knowledge, opportunities for integrating silvicultural management and dendrochronological approaches into plantation management remain limited. There is therefore a need for a systematic review that examines how silvicultural practices influence timber quality and how tree-ring analysis can support sustainable plantation management in Zambia.

1.3 Aim of the Review

The aim of this systematic review is to synthesize existing literature on silvicultural management, tree-ring analysis, and timber quality improvement in Zambian forest plantations.

1.4 Specific Objectives

The specific objectives of the review are:

To examine major silvicultural practices used in forest plantation management.

To assess factors influencing timber quality in Zambian plantations.

To evaluate the effects of spacing, thinning, pruning, weed control, fertilization, and fire management on timber quality.

To review the principles and applications of dendrochronology in plantation forestry.

To assess the contribution of tree-ring analysis to growth assessment and timber quality improvement.

To identify knowledge gaps and future research priorities for plantation forestry in Zambia.

1.5 Research Questions

The review seeks to answer the following questions:

What silvicultural practices influence timber quality in forest plantations?

What factors affect timber quality development in Zambian plantations?

How do thinning, pruning, spacing, and other silvicultural interventions affect wood quality?

What role can dendrochronology play in plantation growth assessment?

How can tree-ring analysis support sustainable plantation management and timber quality improvement?

What research gaps exist regarding plantation management, timber quality, and dendrochronology in Zambia?

1.6 Significance of the Study

This review is significant because it provides an integrated synthesis of plantation management, timber quality, and dendrochronological applications within the Zambian context.

The findings will benefit:

Plantation managers

Forestry researchers

Wood scientists

Policymakers

Forest industries

Forestry educators

Students

The review also contributes to sustainable forestry by identifying opportunities to improve plantation productivity, enhance timber quality, optimize management interventions, and strengthen climate adaptation strategies.

1.7 Structure of the Review

This paper is organized into five major sections.

Section 1 introduces the study.

Section 2 presents the systematic review methodology.

Section 3 discusses plantation management practices, timber quality determinants, and dendrochronological applications.

Section 4 identifies research gaps and future directions.

Section 5 presents conclusions and recommendations.

Graphical Abstract. Conceptual integration of silvicultural management, risk control, tree growth and dendrochronological evidence for timber-quality improvement.

2. Methodology

2.1 Review Design

This study employed a systematic literature review (SLR) approach to synthesize existing knowledge on silvicultural management, timber quality improvement, and dendrochronological applications in forest plantations, with particular emphasis on Zambia. Systematic reviews provide a transparent, reproducible, and evidence-based framework for identifying, evaluating, and synthesizing published research.

The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure methodological rigor and transparency throughout the review process (Page et al., 2021).

The review focused on three major thematic areas:

Silvicultural management practices in plantation forestry.

Timber quality determinants and improvement strategies.

Applications of dendrochronology and tree-ring analysis in plantation management.

2.2 Literature Search Strategy

A comprehensive literature search was conducted between January and June 2026.

The following databases were searched:

Scopus

Web of Science

ScienceDirect

SpringerLink

Wiley Online Library

CAB Abstracts

Google Scholar

Additional sources included:

Forestry Commission reports

FAO publications

CIFOR publications

IUFRO reports

Zambian forestry research reports

University repositories

Conference proceedings

Theses and dissertations

The search covered literature published between 1980 and 2026 to capture both historical and contemporary developments in plantation forestry and dendrochronological research.

2.3 Search Terms and Keywords

Searches were conducted using combinations of keywords and Boolean operators.

The primary search string was:

("forest plantation management" OR silviculture OR plantation forestry) AND ("timber quality" OR wood quality OR stem defects) AND (dendrochronology OR "tree-ring analysis" OR "tree growth") AND (Zambia OR "Southern Africa")

Additional search terms included:

Plantation management

Silvicultural practices

Tree growth

Wood density

Stem quality

Pruning

Thinning

Forest productivity

Growth rings

Climate-growth relationships

Rotation age

Timber defects

Pinus plantations

Eucalyptus plantations

Sustainable forestry

Reference lists from selected studies were also reviewed to identify additional relevant publications.

2.4 Inclusion Criteria

Studies were included if they met the following criteria:

Published between 1980 and 2026.

Written in English.

Focused on plantation forestry, timber quality, or dendrochronology.

Examined silvicultural management practices.

Investigated timber quality characteristics.

Included tree-ring or growth analysis where relevant.

Published in peer-reviewed journals, books, conference proceedings, or institutional reports.

Provided sufficient methodological information.

2.5 Exclusion Criteria

Studies were excluded if they:

Focused exclusively on natural forests without plantation relevance.

Did not address timber quality or plantation management.

Were unrelated to forestry.

Lacked sufficient methodological detail.

Were duplicate records.

Were unavailable in full-text format.

2.6 Study Selection Process

The study selection process followed the four stages recommended by the PRISMA framework.

Identification

Database searches yielded 1,624 records .

Screening

After removal of duplicate records (n = 314), 1,310 studies remained for title and abstract screening.

Eligibility

A total of 382 full-text articles were assessed for eligibility.

Inclusion

Following detailed assessment, 142 studies met the inclusion criteria and were included in the final review.

2.7 Data Extraction

A standardized data extraction framework was developed to ensure consistency.

The following information was extracted from each study:

Table 1
Data-extraction variables used in the systematic review.

Variable	Description
Author(s)	Study authors
Year	Publication year
Country	Study location
Species	Tree species investigated
Plantation type	Pinus, Eucalyptus, mixed plantations
Silvicultural practice	Thinning, pruning, spacing, etc.
Timber quality variable	Density, knots, stem form, defects
Dendrochronological variable	Ring width, growth trends, climate response
Key findings	Major conclusions
Recommendations	Management implications
Note. Values and categories reproduced from the review manuscript.	

All information was compiled into a review matrix for thematic analysis.

2.8 Quality Assessment

Each study was evaluated for methodological quality based on:

Clarity of objectives.

Research design.

Data quality.

Statistical analysis.

Relevance to review objectives.

Reporting transparency.

Studies were classified as:

Table 2
Study-quality assessment categories.

Category	Description
High Quality	Strong methodology and reporting
Moderate Quality	Minor methodological limitations
Low Quality	Significant methodological limitations
Note. Values and categories reproduced from the review manuscript.	

Only studies categorized as high or moderate quality were included in the final synthesis.

2.9 Data Analysis and Synthesis

Due to variation in methodologies, species, plantation systems, and study objectives, quantitative meta-analysis was not feasible.

A thematic synthesis approach was therefore adopted.

The analysis involved:

Familiarization with extracted data.

Coding of recurring concepts.

Identification of thematic patterns.

Comparative analysis across studies.

Synthesis of findings.

The review identified six major themes:

Forest plantation management practices.

Timber quality determinants.

Effects of spacing on timber quality.

Effects of thinning and pruning.

Dendrochronology and growth assessment.

Climate-growth relationships and timber quality.

2.10 Limitations of the Review

Several limitations should be acknowledged.

First, only English-language studies were included.

Second, relatively few dendrochronological studies have been conducted in Zambia, requiring inclusion of broader Southern African and international plantation forestry literature.

Third, differences in measurement techniques limited direct comparison among studies.

Despite these limitations, the systematic approach adopted provides a robust synthesis of current knowledge regarding plantation management, timber quality, and dendrochronological applications.

3. Results and Discussion

3.1 Characteristics of Included Studies

A total of 142 studies met the inclusion criteria and were included in the final review. The selected studies covered a wide range of plantation forestry topics including silvicultural management, timber quality assessment, wood properties, growth modelling, forest productivity, and dendrochronological analysis.

The studies originated primarily from:

Southern Africa

Eastern Africa

Europe

North America

Australia

South America

Although relatively few studies were conducted specifically in Zambia, sufficient evidence was available from plantation forestry systems with similar species and environmental conditions.

Table 3
Characteristics of included studies by primary theme and plantation type.

Characteristic	Percentage (%)
Plantation management studies	35
Timber quality studies	28
Growth and yield studies	18
Dendrochronological studies	10
Climate-growth studies	5
Review papers	4
Pinus plantations	56
Eucalyptus plantations	34
Mixed plantations	10
Note. Values and categories reproduced from the review manuscript.	

The increasing number of studies after 2000 reflects growing interest in sustainable plantation management, timber quality improvement, and climate adaptation.

3.2 Forest Plantation Management and Timber Quality Development

3.2.1 Overview

Forest plantation management involves the application of silvicultural practices designed to optimize tree growth, stand productivity, wood quality, and economic returns.

The reviewed literature consistently demonstrates that timber quality is strongly influenced by management interventions throughout the plantation rotation.

Major management practices influencing timber quality include:

Species-site matching

Initial spacing

Weed control

Fertilization

Thinning

Pruning

Fire protection

Pest and disease management

Effective integration of these practices contributes significantly to the production of high-quality timber.

3.2.2 Species-Site Matching

Species-site matching refers to the selection of tree species best suited to local environmental conditions. (Evans, 1992; Gonçalves et al., 2013)

The reviewed studies indicate that appropriate species-site matching influences:

Survival rates

Growth performance

Stem form

Wood density

Timber quality

In Zambia, common plantation species include:

Pines

Pinus kesiya

Pinus oocarpa

Pinus patula

Eucalypts

Eucalyptus grandis

Eucalyptus cloeziana

Eucalyptus tereticornis

When species are poorly matched to site conditions, plantations often experience:

Reduced growth

Stem deformities

Increased disease susceptibility

Lower timber quality

Several studies emphasize that site quality remains one of the strongest determinants of plantation productivity.

3.2.3 Plantation Establishment and Early Stand Management

The establishment phase is critical for determining future plantation performance.

The reviewed literature identifies several important activities:

Site Preparation

Proper site preparation:

Improves root development.

Enhances water availability.

Reduces competition.

Seedling Quality

High-quality planting stock contributes to:

Improved survival.

Better growth.

Enhanced stem form.

Weed Control

Competition from weeds can significantly reduce:

Diameter growth.

Height growth.

Stem quality.

Effective weed control during the first three years after planting is particularly important.

3.2.4 Fertilization and Nutrient Management

Table 8

Evidence synthesis linking plantation management practices to timber-quality outcomes.

Management / evidence area	Primary quality or growth effect	Potential trade-off / risk	Management implication
Species–site matching	Survival, growth, stem form and wood-quality development	Poor matching may increase stress, deformity and disease susceptibility	Match species to site quality, climate and intended product.
Spacing	Competition, crown development, diameter growth and branch size	Wide spacing may increase branch and knot size; close spacing may suppress diameter growth	Select spacing according to species, site, product and rotation.
Thinning	Diameter growth, crown development, stand stability and timber value	Heavy thinning may increase branch growth, wind exposure and juvenile wood formation	Use intensity and timing appropriate to stand age and objectives.
Pruning	Knot reduction, clearwood production and sawlog quality	Excessive pruning can reduce photosynthetic capacity and growth	Prune early and avoid excessive live-crown removal.
Weed control & nutrition	Early survival, height/diameter growth and stand productivity	Excess nutrients or unmanaged competition may reduce quality or growth efficiency	Use site-specific weed and nutrient management.
Fire, pests & diseases	Protection of stem integrity, growth and recoverable timber	Damage can create scars, decay, defects and mortality	Integrate prevention, detection and control throughout the rotation.
Dendrochronology	Long-term growth histories, climate response and disturbance detection	Ring formation and comparability can vary among species and environments	Combine ring analysis with inventories and management records.

Note. Qualitative synthesis of relationships described in the review; no pooled effect size is implied.

Nutrient availability influences plantation productivity and timber quality.

Several studies reported positive effects of fertilization on:

Height growth.

Diameter increment.

Stem volume.

However, excessive fertilization may sometimes:

Promote rapid juvenile growth.

Reduce wood density.

Increase susceptibility to defects.

The review suggests that fertilization should be guided by site-specific nutrient assessments.

3.3 Timber Quality Determinants in Forest Plantations

3.3.1 Definition of Timber Quality

Timber quality refers to the characteristics of wood that determine its suitability for intended end uses. (Larson, 1969; Bowyer et al., 2007)

The reviewed studies identify several key timber quality indicators:

Stem straightness

Diameter growth

Wood density

Knot size

Branch frequency

Stem taper

Ring width

Defect occurrence

Mechanical properties

The relative importance of these indicators depends on the intended industrial application.

3.3.2 Stem Form and Straightness

Stem straightness is one of the most important timber quality characteristics.

Straight stems:

Improve sawmill recovery.

Increase product value.

Reduce processing losses.

Factors affecting stem form include:

Genetics

Spacing

Wind exposure

Site conditions

Silvicultural management

The reviewed literature demonstrates that poor stem form is often associated with inadequate plantation management.

3.3.3 Wood Density

Wood density is widely recognized as one of the most important indicators of timber quality. (Bowyer et al., 2007; Zobel and Van Buijtenen, 1989)

Wood density influences:

Mechanical strength

Pulp yield

Energy value

Durability

Table 4
Importance of wood density for different forest products.

Product	Importance of Density
Structural timber	Very High
Poles	High
Pulpwood	Moderate
Fuelwood	High
Charcoal	High
Note. Values and categories reproduced from the review manuscript.	

Several studies indicate that both genetics and management practices influence wood density development.

3.3.4 Knots and Branch Characteristics

Knots are among the most common defects affecting plantation-grown timber.

Large knots may:

Reduce strength.

Lower visual quality.

Reduce market value.

The review demonstrates that knot development is strongly influenced by:

Initial spacing.

Pruning.

Growth rate.

Species characteristics.

Effective pruning is therefore essential for producing high-quality sawlogs.

3.3.5 Juvenile Wood and Timber Quality

Juvenile wood forms during the early years of tree growth and often differs from mature wood. (Cown, 1992; Zobel and Sprague, 1998)

Characteristics include:

Lower density.

Shorter fibres.

Reduced strength.

Rapid early growth may increase the proportion of juvenile wood within logs.

Several studies highlight the importance of balancing growth promotion with wood quality objectives.

3.4 Effects of Initial Spacing on Timber Quality

3.4.1 Introduction

Initial spacing is one of the most important silvicultural decisions in plantation forestry. (Smith et al., 1997; Evans and Turnbull, 2004)

Spacing determines:

Competition intensity.

Crown development.

Diameter growth.

Branch size.

Stem form.

The reviewed studies indicate that spacing influences both plantation productivity and timber quality throughout the rotation.

3.4.2 Wide Spacing

Wide spacing typically results in:

Advantages

Larger diameter growth.

Increased tree vigor.

Faster stand development.

Disadvantages

Larger branches.

Larger knots.

Reduced stem straightness.

Greater taper.

Consequently, wide spacing may reduce timber quality despite increasing growth rates.

3.4.3 Close Spacing

Closer spacing generally produces:

Advantages

Better stem form.

Smaller branches.

Reduced knot size.

Improved timber quality.

Disadvantages

Reduced diameter growth.

Increased competition.

Higher mortality.

The review suggests that optimal spacing should balance productivity and quality objectives.

3.4.4 Spacing in Zambian Plantations

Common spacing regimes reported for Zambian plantations include:
2.5 m × 2.5 m

3.0 m × 3.0 m

3.0 m × 2.5 m

Several studies indicate that spacing decisions should be tailored to:

Species

Site quality

Product objectives

Rotation length

3.5 Thinning and Timber Quality Improvement

3.5.1 Introduction

Thinning is the deliberate removal of selected trees from a stand to reduce competition and improve the growth of the remaining trees. It is one of the most important silvicultural practices used in plantation forestry and has significant implications for timber quality development. (Mäkinen and Isomäki, 2004; Smith et al., 1997)

The reviewed literature consistently demonstrates that properly planned thinning improves:

Diameter growth

Stem development

Crown expansion

Stand stability

Timber value

Thinning also influences wood formation, ring development, and long-term growth patterns that can later be examined through dendrochronological analysis.

3.5.2 Objectives of Thinning

The primary objectives of thinning include:

Growth Enhancement

Reducing competition for:

Light

Water

Nutrients

Growing space

Quality Improvement

Promoting development of:

Straight stems

Larger diameters

Better crowns

Stand Health

Reducing:

Disease incidence

Pest susceptibility

Competition-induced stress

Economic Returns

Increasing the proportion of trees capable of producing high-value timber products.

3.5.3 Types of Thinning

Several thinning methods are commonly used in plantation forestry.

Low Thinning

Removes suppressed and poorly performing trees.

Advantages:

Maintains dominant trees.

Improves stand uniformity.

Reduces competition.

Crown Thinning

Removes selected trees from upper crown classes.

Advantages:

Promotes growth of high-quality dominant trees.

Increases crown development.

Mechanical Thinning

Removes trees according to predetermined patterns.

Advantages:

Operational simplicity.

Lower costs.

Disadvantages:

May remove high-quality trees unintentionally.

3.5.4 Effects of Thinning on Diameter Growth

One of the most consistent findings in the reviewed literature is that thinning increases diameter growth.

Following thinning:

Competition decreases.

Resource availability increases.

Remaining trees grow faster.

Several studies on Pinus and Eucalyptus plantations report substantial increases in diameter increment after thinning interventions.

Improved diameter growth contributes directly to:

Higher timber volume.

Increased sawlog production.

Improved economic returns.

3.5.5 Effects of Thinning on Wood Density

The relationship between thinning and wood density is complex.

The reviewed studies reveal mixed results:

Positive Effects

Moderate thinning can:

Improve tree vigor.

Promote stable wood formation.

Maintain desirable density levels.

Potential Negative Effects

Heavy thinning may:

Accelerate growth excessively.

Increase juvenile wood formation.

Reduce wood density.

The effect often depends on:

Species

Site quality

Thinning intensity

Tree age

3.5.6 Effects of Thinning on Stem Form

Proper thinning improves stem form by concentrating growth on selected trees.

Benefits include:

Improved straightness.

Reduced competition-induced bending.

Better crown development.

Enhanced stem quality.

However, excessive thinning may expose trees to:

Wind damage.

Stem leaning.

Crown imbalance.

The reviewed literature emphasizes the importance of maintaining appropriate stand density following thinning.

3.5.7 Thinning and Knot Development

Thinning influences branch growth and consequently affects knot formation.

Following heavy thinning:

Crown expansion increases.

Branches become larger.

Knot size may increase.

Large knots reduce:

Timber strength.

Visual quality.

Product value.

Several studies recommend combining thinning with pruning to minimize knot-related defects.

3.5.8 Thinning and Timber Value

One of the principal reasons for thinning is to increase the production of high-value timber.

The reviewed literature indicates that thinning:

Increases average tree size.

Improves sawlog recovery.

Enhances market value.

Reduces harvesting costs per unit volume.

Consequently, thinning contributes significantly to plantation profitability.

3.5.9 Thinning Regimes in Zambian Plantations

Studies from Zambia and Southern Africa indicate that thinning regimes vary according to:

Species

Site productivity

Rotation objectives

Common thinning schedules involve:

First Thinning

Age: 6–10 years

Objective:

Remove suppressed trees.

Improve stand spacing.

Second Thinning

Age: 12–18 years

Objective:

Promote growth of selected crop trees.

Final Crop Development

Age: 18–25 years

Objective:

Produce large-diameter, high-quality sawlogs.

These schedules may vary according to plantation objectives.

3.5.10 Critical Discussion

The reviewed evidence demonstrates that thinning is one of the most effective silvicultural tools for improving timber quality.

Benefits include:

Increased diameter growth.

Improved stem quality.

Enhanced stand productivity.

Greater economic returns.

However, thinning intensity must be carefully managed to avoid undesirable effects such as:

Excessive branch growth.

Reduced wood density.

Wind damage.

Properly designed thinning regimes are therefore essential for sustainable plantation management.

3.6 Pruning and Timber Quality Improvement

3.6.1 Introduction

Pruning involves the deliberate removal of branches from standing trees to improve timber quality. It is widely regarded as one of the most effective silvicultural practices for producing high-value knot-free timber. (Evans and Turnbull, 2004; Smith et al., 1997)

The reviewed literature consistently identifies pruning as a critical management intervention for improving wood quality in plantation forests.

3.6.2 Objectives of Pruning

The primary objectives of pruning include:

Reducing knot size.

Producing clear wood.

Improving stem form.

Increasing timber value.

Enhancing sawlog quality.

Pruning is particularly important in plantations established for saw timber production.

3.6.3 Knot Formation and Timber Quality

Branches become embedded within the stem as trees grow, forming knots.

Knots are among the most significant defects affecting timber quality.

They can:

Reduce strength.

Lower visual quality.

Decrease processing efficiency.

Reduce market value.

The reviewed studies indicate that knot-related losses can substantially reduce sawmill recovery rates.

3.6.4 Effects of Pruning on Clear Wood Production

One of the greatest benefits of pruning is the production of clear wood.

Clear wood refers to wood free from knots and major defects.

Advantages include:

Improved appearance.

Higher strength.

Greater market value.

Better processing performance.

Several studies report that clear wood may command significantly higher prices than knotty timber.

3.6.5 Timing of Pruning

The timing of pruning strongly influences effectiveness.

Early pruning is generally preferred because:

Branches are smaller.

Wounds heal more rapidly.

Defect development is minimized.

The reviewed literature recommends that pruning should be conducted before branches become excessively large.

3.6.6 Pruning Height

Pruning height depends on intended product objectives.

Typical pruning heights include:

Table 5
Typical pruning heights by production objective.

Objective	Pruning Height
General timber production	2–4 m
High-quality sawlogs	4–6 m
Premium clearwood production	6–8 m
Note. Values and categories reproduced from the review manuscript.	

Higher pruning generally produces larger volumes of knot-free timber.

3.6.7 Pruning and Tree Growth

The reviewed studies indicate that moderate pruning generally has minimal effects on tree growth.

However, excessive pruning may:

Reduce photosynthetic capacity.

Slow diameter growth.

Stress trees.

Most researchers recommend avoiding removal of more than one-third of the live crown during a single pruning operation.

3.6.8 Combined Effects of Thinning and Pruning

The literature consistently demonstrates that thinning and pruning are most effective when applied together.

Thinning promotes:

Diameter growth.

Crown expansion.

Pruning improves:

Stem quality.

Knot reduction.

Together, these practices maximize production of high-value timber.

3.6.9 Pruning in Zambian Plantation Forestry

In Zambia, pruning is commonly practiced in:

Pinus kesiya

Pinus patula

Pinus oocarpa

Selected Eucalyptus plantations

The reviewed literature suggests that improved pruning programs could substantially enhance timber quality and economic returns within plantation forestry.

3.6.10 Critical Discussion

Pruning remains one of the most cost-effective silvicultural investments for improving timber quality.

Its benefits include:

Reduced knot formation.

Increased clear wood production.

Enhanced timber value.

Improved processing efficiency.

The next section examines the influence of fire management, pests, diseases, and environmental factors on timber quality development in plantation forests.

3.7 Fire Management, Pests, Diseases and Timber Quality

3.7.1 Introduction

Beyond thinning and pruning, timber quality is also influenced by environmental disturbances and biological agents. Fire, pests, diseases, and climatic stresses can significantly reduce plantation productivity and timber value.

The reviewed literature demonstrates that these factors contribute to:

Stem defects

Reduced growth

Wood degradation

Mortality

Economic losses

Effective management of these risks is therefore essential for sustainable plantation forestry.

3.7.2 Fire and Plantation Timber Quality

Fire remains one of the most significant threats to plantation forestry in Zambia and many parts of Southern Africa. (Agee, 1993)

Plantation fires may result from:

Agricultural burning

Charcoal production

Hunting activities

Accidental ignition

Arson

Effects of Fire on Timber Quality

Fire damage can cause:

Stem scars

Bark injuries

Growth reductions

Heartwood defects

Increased susceptibility to decay

Several studies report that even low-intensity fires may influence wood quality by altering growth patterns and creating internal defects.

3.7.3 Fire Scars and Wood Defects

Fire scars create openings that allow entry of:

Fungi

Bacteria

Insects

Consequently, damaged trees often develop:

Stem decay

Discoloration

Structural weaknesses

These defects reduce:

Timber recovery

Product quality

Market value

Dendrochronological studies frequently use fire scars to reconstruct historical disturbance events.

3.7.4 Fire Management Strategies

The reviewed literature identifies several effective fire management practices:

Firebreak Construction

Reduces fire spread between plantation compartments.

Early Burning

Reduces fuel accumulation.

Community Awareness

Promotes fire prevention.

Fire Detection Systems

Improve rapid response capabilities.

Firefighting Preparedness

Reduces plantation losses.

Effective fire management contributes directly to timber quality preservation.

3.7.5 Pests and Plantation Timber Quality

Pests represent another major challenge affecting plantation productivity and wood quality.

Common plantation pests include:

Bark beetles

Defoliators

Termites

Wood borers

Sap-sucking insects

Pest attacks may reduce:

Growth rates

Stem quality

Wood strength

Several pest species create defects that remain visible in processed timber.

3.7.6 Termite Damage

Termites are particularly important in tropical plantation systems.

Damage may include:

Stem hollowing

Root destruction

Structural weakening

Termite damage significantly reduces timber quality and increases mortality risk.

Young plantations are especially vulnerable.

3.7.7 Disease Impacts on Timber Quality

Forest diseases can affect:

Growth performance

Stem form

Wood properties

Tree survival

Common plantation diseases include:

Fungal Diseases

Root rots

Stem cankers

Needle blights

Bacterial Diseases

Stem infections

Tissue degradation

Disease-related defects often reduce timber utilization potential.

3.7.8 Plantation Diseases in Zambia

Several studies have documented disease problems in Zambian plantation forests.

Affected species include:

Pinus kesiya

Pinus patula

Pinus oocarpa

Eucalyptus grandis

Disease outbreaks can result in:

Reduced growth

Stem deformities

Timber defects

Increased harvesting losses

Integrated disease management remains essential for maintaining timber quality.

3.7.9 Climate Stress and Timber Quality

Climate variability increasingly affects plantation performance. (Allen et al., 2015; Kozlowski and Pallardy, 2002)

Important stressors include:

Drought

Heat waves

Extreme rainfall

Windstorms

Climate stress may influence:

Growth rate

Wood density

Ring formation

Stem quality

Understanding climate-growth relationships has become increasingly important for plantation management.

3.7.10 Critical Discussion

The reviewed evidence demonstrates that fire, pests, diseases, and climatic stressors significantly influence plantation timber quality.

While silvicultural interventions improve growth and stem quality, failure to manage these risks can negate potential benefits.

Integrated plantation management should therefore combine:

Silvicultural practices

Fire management

Pest control

Disease management

Climate adaptation strategies

3.8 Dendrochronology and Tree-Ring Analysis in Plantation Forestry

3.8.1 Introduction

Dendrochronology is the science of dating and interpreting annual growth rings in trees. It provides a powerful tool for reconstructing growth histories, evaluating management interventions, and understanding environmental influences on tree development. (Fritts, 1976; Speer, 2010)

Although traditionally associated with temperate forests, dendrochronology is increasingly applied in tropical and subtropical plantation systems.

The reviewed literature demonstrates growing interest in using tree-ring analysis to support plantation management and timber quality improvement.

3.8.2 Principles of Dendrochronology

Tree rings form through annual growth processes.

A typical annual ring consists of:

Earlywood

Produced during periods of rapid growth.

Characteristics:

Larger cells

Lower density

Latewood

Produced during slower growth periods.

Characteristics:

Smaller cells

Higher density

Together, these structures form annual growth rings that record environmental conditions and growth performance.

3.8.3 Tree Rings as Historical Records

Tree rings provide valuable records of:

Annual growth

Climate variability

Disturbance events

Silvicultural interventions

Unlike short-term inventories, dendrochronology allows researchers to reconstruct growth histories spanning decades.

This information is valuable for:

Growth modelling

Rotation planning

Timber quality assessment

3.8.4 Dendrochronology in Tropical Forests

Historically, tropical trees were considered unsuitable for dendrochronological analysis because of less distinct annual rings. (Creber and Chaloner, 1984; Gourlay, 1995)

However, recent studies demonstrate that many tropical species form annual growth rings under seasonal climatic conditions.

Examples include:

Baikiaea plurijuga

Pinus kesiya

Pterocarpus angolensis

Several Eucalyptus species

These findings have expanded opportunities for tropical dendrochronology.

3.8.5 Dendrochronological Research in Zambia

The reviewed literature indicates growing interest in dendrochronological research in Zambia.

Studies have successfully developed tree-ring chronologies for:

Indigenous Species

Baikiaea plurijuga

Plantation Species

Pinus kesiya

These studies demonstrate that tree-ring analysis can provide valuable insights into:

Growth trends

Climate responses

Forest productivity

3.8.6 Tree Rings and Growth Assessment

One of the most important applications of dendrochronology is growth assessment.

Tree rings allow researchers to evaluate:

Annual diameter increment

Growth fluctuations

Productivity trends

Responses to management

This information can improve plantation planning and management decisions.

3.8.7 Dendrochronology and Climate-Growth Relationships

Tree-ring records provide valuable information regarding climate influences on growth.

The reviewed studies indicate strong relationships between ring width and:

Rainfall

Temperature

Drought events

These relationships can help identify climate-sensitive periods and improve adaptive management strategies.

3.8.8 Dendrochronology and Timber Quality Assessment

Tree-ring characteristics often influence timber quality.

Important variables include:

Ring width

Ring uniformity

Earlywood-latewood ratios

Growth rate

Table 6
Dendrochronological variables and timber-quality indicators.

Tree-Ring Variable	Timber Quality Implication
Ring width	Growth rate
Ring uniformity	Wood consistency
Latewood proportion	Density
Growth interruptions	Stress indicators
Ring anomalies	Disturbance history
Note. Values and categories reproduced from the review manuscript.	

These variables provide valuable information regarding wood formation processes.

3.8.9 Dendrochronology and Rotation Age Determination

Tree-ring analysis can assist in determining optimal rotation ages. (Speer, 2010; Rinn, 2003)

Benefits include:

Improved yield estimation.

Better growth forecasting.

Enhanced economic planning.

Dendrochronological evidence may reveal whether current rotation ages are appropriate for maximizing timber quality and economic returns.

3.8.10 Dendrochronology and Sustainable Plantation Management

The reviewed literature demonstrates that dendrochronology can support sustainable forestry through:

Long-term growth monitoring.

Climate adaptation planning.

Productivity assessment.

Timber quality prediction.

Integration of dendrochronology into plantation management represents a significant opportunity for improving forestry decision-making in Zambia.

3.9 Climate, Growth Dynamics and Timber Quality Development

3.9.1 Introduction

Climate is one of the most important environmental factors influencing tree growth, plantation productivity, and timber quality. Temperature, rainfall, humidity, solar radiation, and extreme weather events affect physiological processes such as photosynthesis, respiration, water uptake, and cambial activity, all of which influence wood formation.

The reviewed literature indicates that climate variability significantly affects:

Tree growth rates

Ring formation

Wood density

Stem form

Timber quality

Dendrochronology provides a valuable tool for understanding these relationships because annual growth rings preserve historical records of climate-growth interactions.

3.9.2 Rainfall and Tree Growth

Rainfall is often the most important climatic variable affecting plantation growth in Zambia and other tropical regions.

The reviewed studies consistently show positive relationships between rainfall and:

Diameter growth

Height growth

Stand productivity

Ring width development

During years of adequate rainfall:

Cambial activity increases.

Trees produce wider growth rings.

Biomass accumulation improves.

Conversely, prolonged droughts may reduce annual growth and affect timber quality.

3.9.3 Drought Stress and Timber Quality

Drought represents one of the most significant threats to plantation productivity under climate change.

The reviewed literature indicates that drought may result in:

Reduced ring width

Lower growth rates

Increased mortality

Stem defects

Reduced wood quality

Several studies reported that severe drought conditions can influence wood density and alter anatomical characteristics.

Drought Effects on Timber Quality

Table 7
Drought impacts and timber-quality consequences.

Drought Impact	Timber Quality Consequence
Reduced growth	Smaller log dimensions
Growth interruptions	Ring irregularities
Physiological stress	Stem defects
Increased mortality	Reduced plantation productivity
Note. Values and categories reproduced from the review manuscript.	

Understanding drought responses is therefore essential for adaptive plantation management.

3.9.4 Temperature and Growth Dynamics

Temperature influences:

Photosynthesis

Respiration

Cell division

Wood formation

The reviewed studies indicate that moderate temperatures generally promote growth, while extreme temperatures may reduce productivity.

High temperatures may contribute to:

Water stress

Reduced growth

Increased vulnerability to pests and diseases

Temperature-related changes in growth patterns are often detectable through tree-ring analysis.

3.9.5 Climate Variability and Ring Formation

Tree rings provide valuable records of past climatic conditions.

Several reviewed studies demonstrated strong correlations between annual ring width and climatic variables.

Climate Signals Recorded in Tree Rings

Wet years → wider rings

Dry years → narrower rings

Disturbance events → growth anomalies

Climate extremes → growth suppression

These relationships enable reconstruction of historical climate conditions and growth responses.

3.9.6 Climate Change and Plantation Forestry

Climate change is expected to influence plantation forestry through:

Rising temperatures

Altered rainfall patterns

Increased drought frequency

Extreme weather events

Potential consequences include:

Reduced productivity

Increased pest outbreaks

Greater fire risk

Changes in timber quality

The reviewed literature suggests that adaptive management strategies will become increasingly important under future climate scenarios.

3.9.7 Dendrochronology and Climate Adaptation

Dendrochronological methods can support climate adaptation by:

Identifying climate-sensitive species.

Evaluating drought responses.

Assessing resilience.

Improving growth predictions.

Tree-ring records provide long-term data that can strengthen evidence-based plantation management decisions.

3.9.8 Critical Discussion

The reviewed evidence demonstrates that climate strongly influences growth dynamics and timber quality development.

Rainfall variability appears particularly important in tropical plantation systems such as Zambia.

Integrating climate analysis with dendrochronological monitoring can improve:

Plantation planning

Species selection

Rotation management

Climate adaptation strategies

3.10 Integrated Framework for Timber Quality Improvement in Zambian Plantations

3.10.1 Introduction

The review demonstrates that timber quality is influenced by complex interactions among silvicultural management, environmental conditions, genetics, and growth dynamics.

An integrated management framework is therefore necessary to maximize plantation productivity and timber quality.

3.10.2 Components of the Framework

Species-Site Matching

Appropriate species selection remains the foundation of successful plantation management.

Silvicultural Management

Key interventions include:

Spacing

Thinning

Pruning

Weed control

Fertilization

Risk Management

Protection against:

Fire

Pests

Diseases

Climate stress

Growth Monitoring

Regular assessment of:

Diameter growth

Height growth

Stem quality

Stand productivity

Dendrochronological Analysis

Tree-ring studies provide:

Growth histories

Climate information

Management response data

3.10.3 Benefits of the Framework

Implementation of this framework can contribute to:

Increased timber quality.

Improved plantation productivity.

Better climate adaptation.

Enhanced economic returns.

Sustainable forest management.

3.10.4 Synthesis of Findings

The review demonstrates that:

Plantation management strongly influences timber quality.

Spacing, thinning, and pruning are critical quality-improvement tools.

Fire, pests, and diseases significantly affect timber value.

Climate variability influences growth and wood formation.

Dendrochronology provides valuable information for growth assessment and management.

Integration of silviculture and tree-ring analysis can improve sustainable timber production.

4. Research Gaps and Future Research Directions

4.1 Introduction

Despite substantial progress in plantation forestry research, important knowledge gaps remain regarding plantation management, timber quality development, and dendrochronological applications in Zambia.

Addressing these gaps is essential for improving plantation productivity and supporting sustainable timber production.

4.2 Research Gaps

Limited Dendrochronological Research in Zambia

Few studies have examined:

Tree-ring formation

Growth chronologies

Climate-growth relationships

for major plantation species.

Timber Quality Studies

More research is needed on:

Wood density development

Knot formation

Stem defects

Mechanical properties

Climate Change Impacts

Limited information exists regarding:

Future climate effects

Drought sensitivity

Adaptive management strategies

Plantation Species Comparisons

Comparative studies among:

Pinus kesiya

Pinus oocarpa

Pinus patula

Eucalyptus grandis

remain insufficient.

4.3 Future Research Priorities

Priority areas include:

Development of long-term tree-ring chronologies.

Climate-growth modelling.

Timber quality prediction using dendrochronology.

Wood density and ring-width relationships.

Effects of silvicultural treatments on tree-ring characteristics.

Climate adaptation strategies for plantation forestry.

Growth and yield modelling using tree-ring data.

Economic analysis of quality-improvement interventions.

4.4 Critical Discussion

Future forestry research in Zambia should increasingly integrate:

Silviculture

Wood science

Dendrochronology

Climate science

Such interdisciplinary approaches can improve understanding of plantation growth processes and support evidence-based management.

5. Conclusion

5.1 Overview

This systematic review synthesized literature on silvicultural management, tree-ring analysis, and timber quality improvement in Zambian forest plantations.

A total of 142 studies were reviewed, providing evidence regarding plantation management practices, timber quality determinants, climate-growth relationships, and dendrochronological applications.

5.2 Major Findings

The review demonstrates that:

Effective silvicultural management is fundamental to timber quality improvement.

Appropriate spacing influences stem form, growth rates, and knot development.

Thinning improves diameter growth and stand productivity.

Pruning is essential for producing knot-free, high-value timber.

Fire, pests, diseases, and climate variability significantly influence timber quality.

Dendrochronology provides powerful tools for assessing growth dynamics and management responses.

Tree-ring analysis can improve growth prediction, climate adaptation, and rotation planning.

5.3 Final Conclusion

The review concludes that integrating silvicultural management with dendrochronological monitoring offers significant opportunities for improving timber quality and plantation productivity in Zambia. Tree-ring analysis provides long-term growth information that complements traditional forest inventories and supports adaptive management under changing climatic conditions.

The incorporation of dendrochronology into plantation forestry research and practice has the potential to strengthen sustainable timber production, improve forest planning, and enhance the economic value of plantation forests in Zambia.

Declarations

Conflict Of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Ethics Statement

Ethical approval

was not required for this study because it involved the review and synthesis of published literature and did not involve human participants, animals, or primary data collection.

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Author Contributions

Mulenga Brian Nsofu and Kasamba Hatimbula contributed to the development, literature synthesis, manuscript preparation, critical review and final approval of the manuscript.

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Data Availability Statement

No new datasets were generated during this study. All data supporting the findings of this review are available within the published literature cited in the manuscript.

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Figures

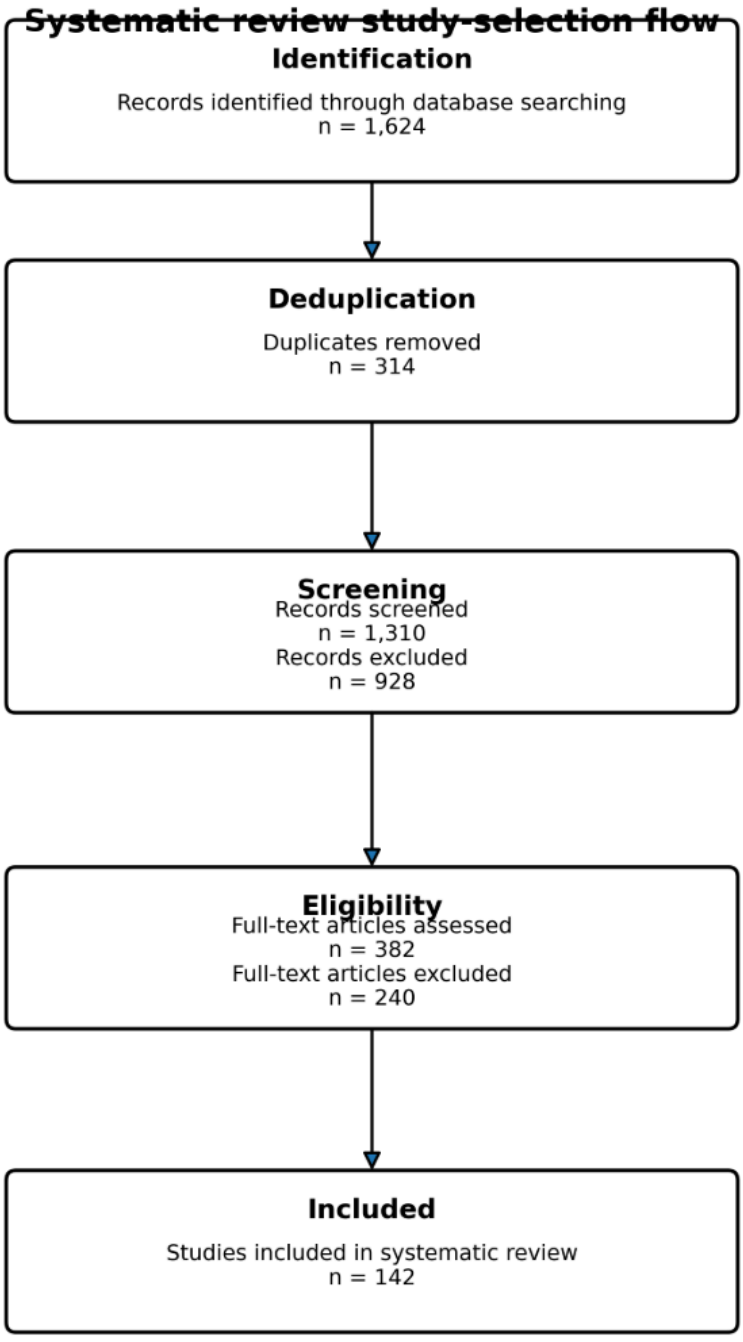


Figure 1

PRISMA 2020 study-selection flow for the systematic review.

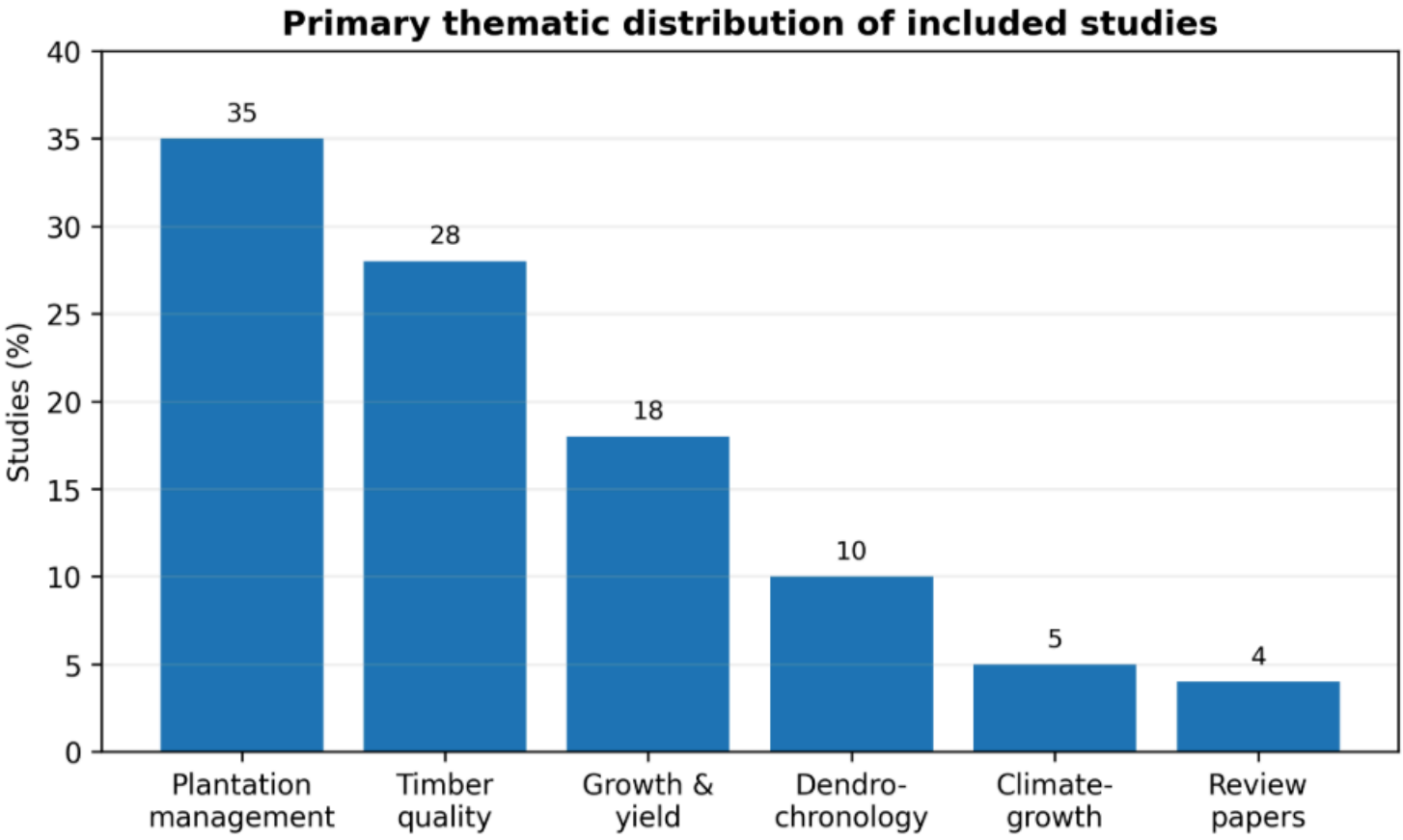


Figure 2

Primary thematic distribution of the 142 included studies.

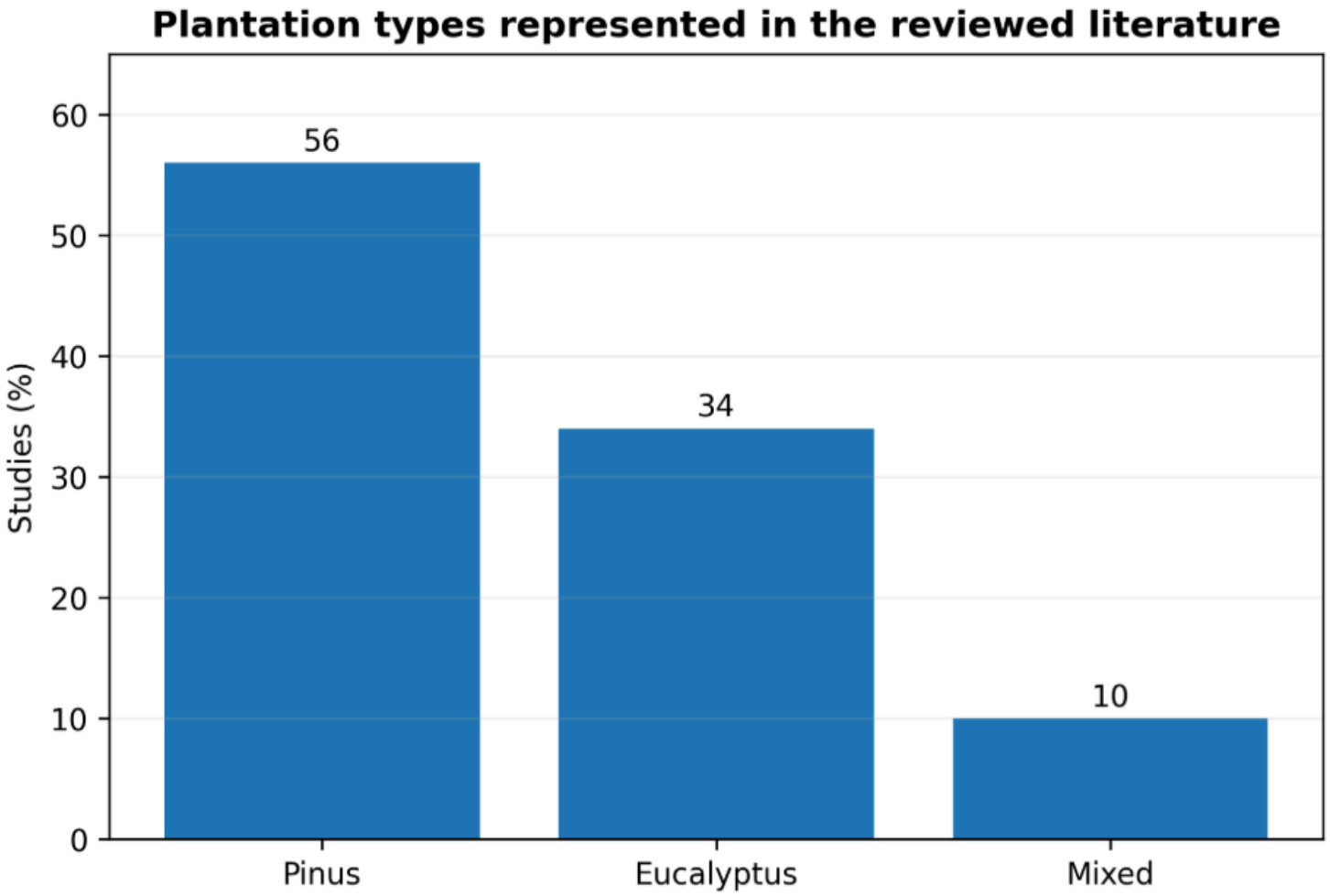


Figure 3

Plantation types represented in the reviewed literature.

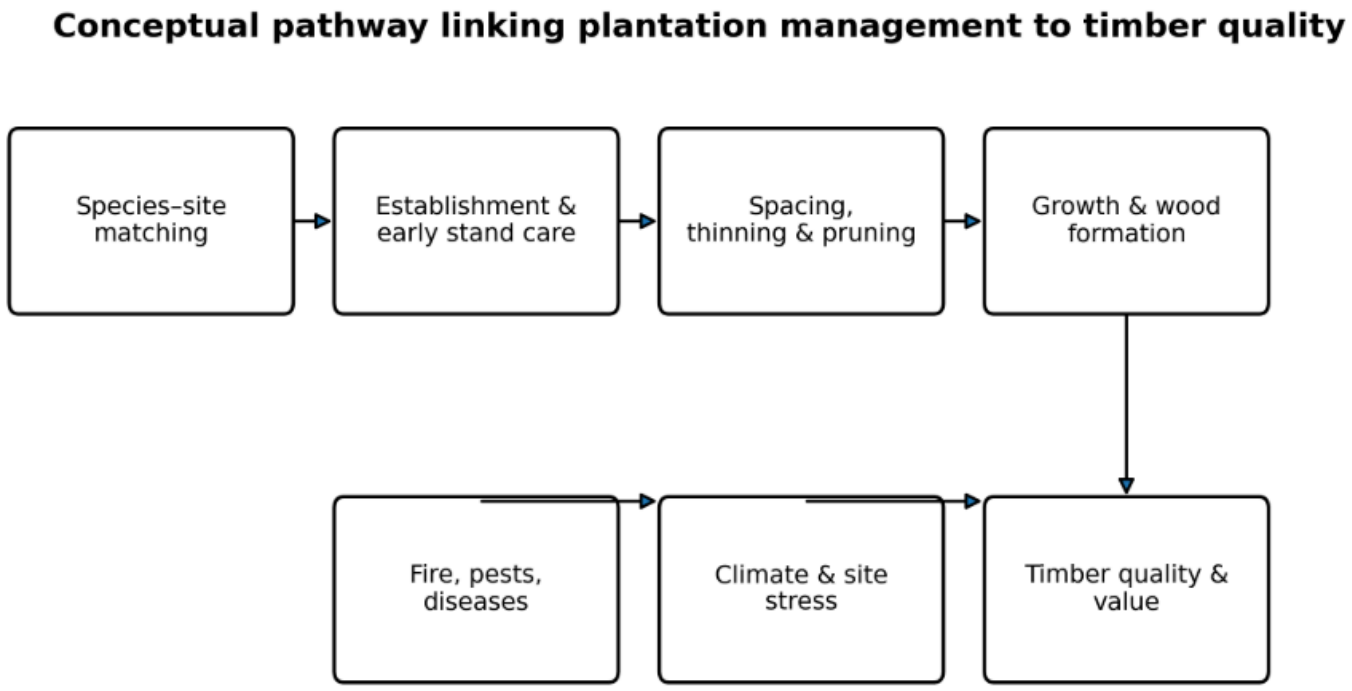


Figure 4

Conceptual pathway linking species–site matching, establishment, silvicultural management, risk control and timber quality.

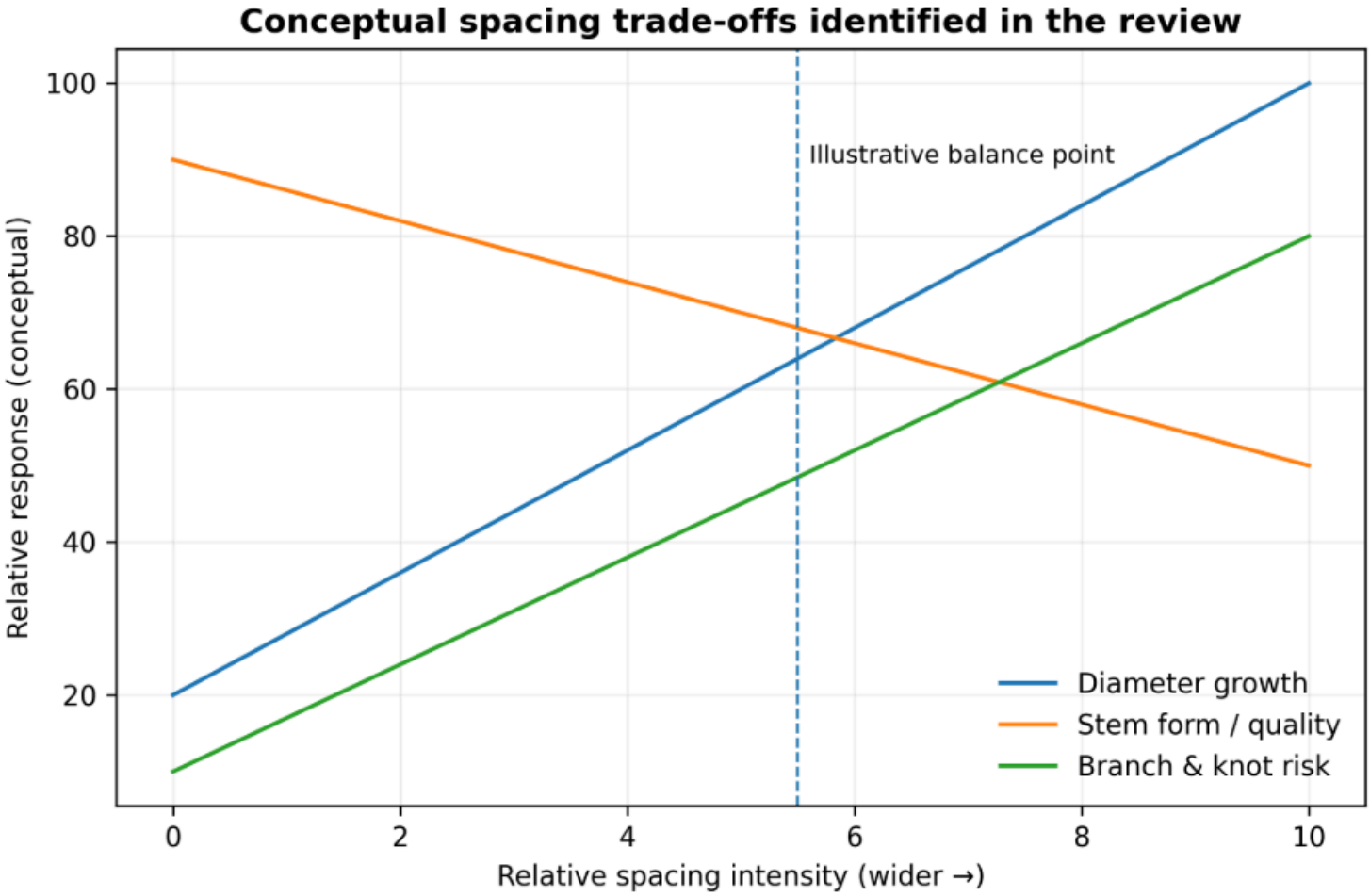


Figure 5

Conceptual spacing trade-offs identified in the reviewed literature; curves are illustrative rather than quantitative estimates.

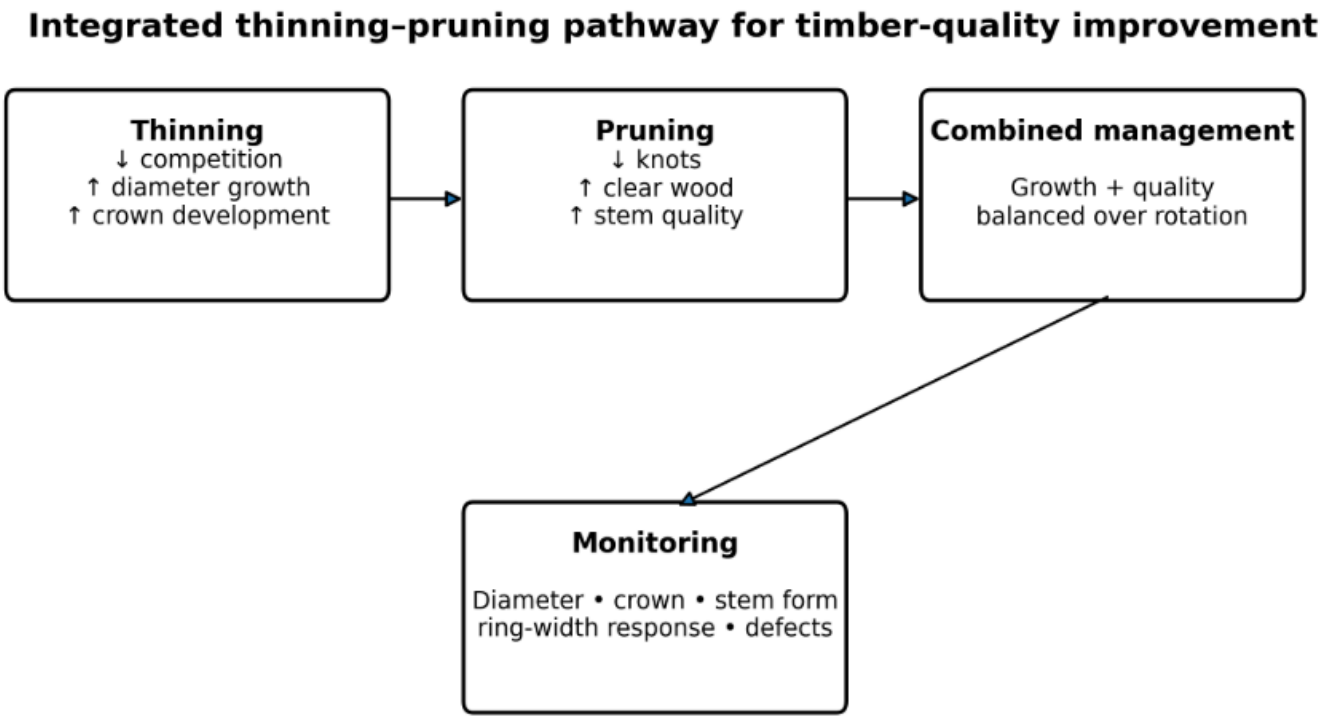


Figure 6

Integrated thinning–pruning pathway for balancing growth and timber-quality objectives.

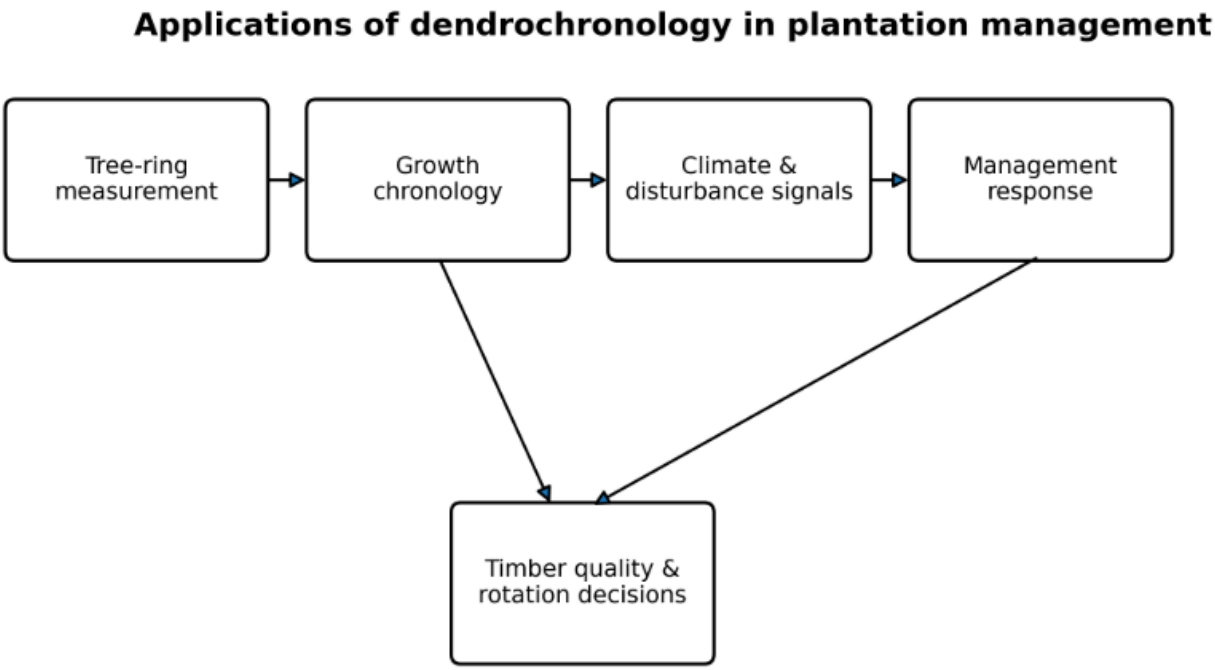


Figure 7

Applications of dendrochronology in plantation management.

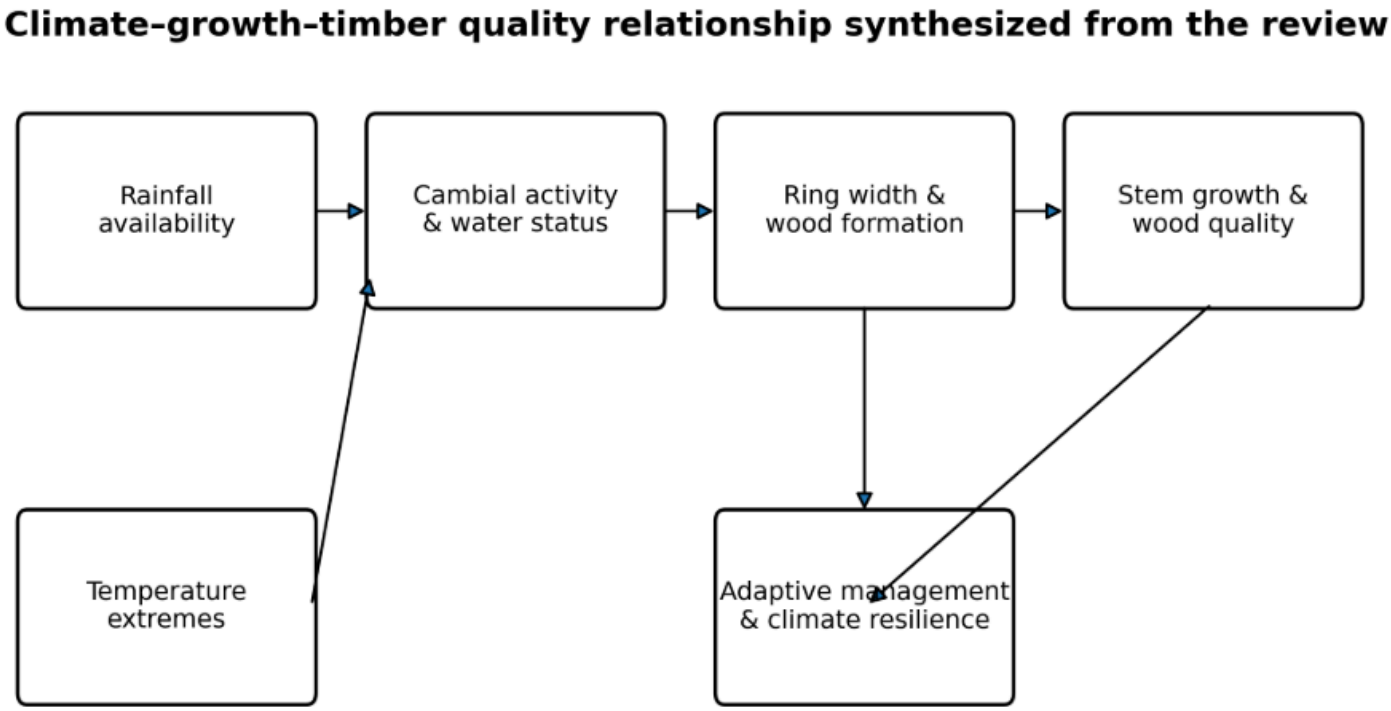


Figure 8

Conceptual climate–growth–timber quality relationship synthesized from the review.

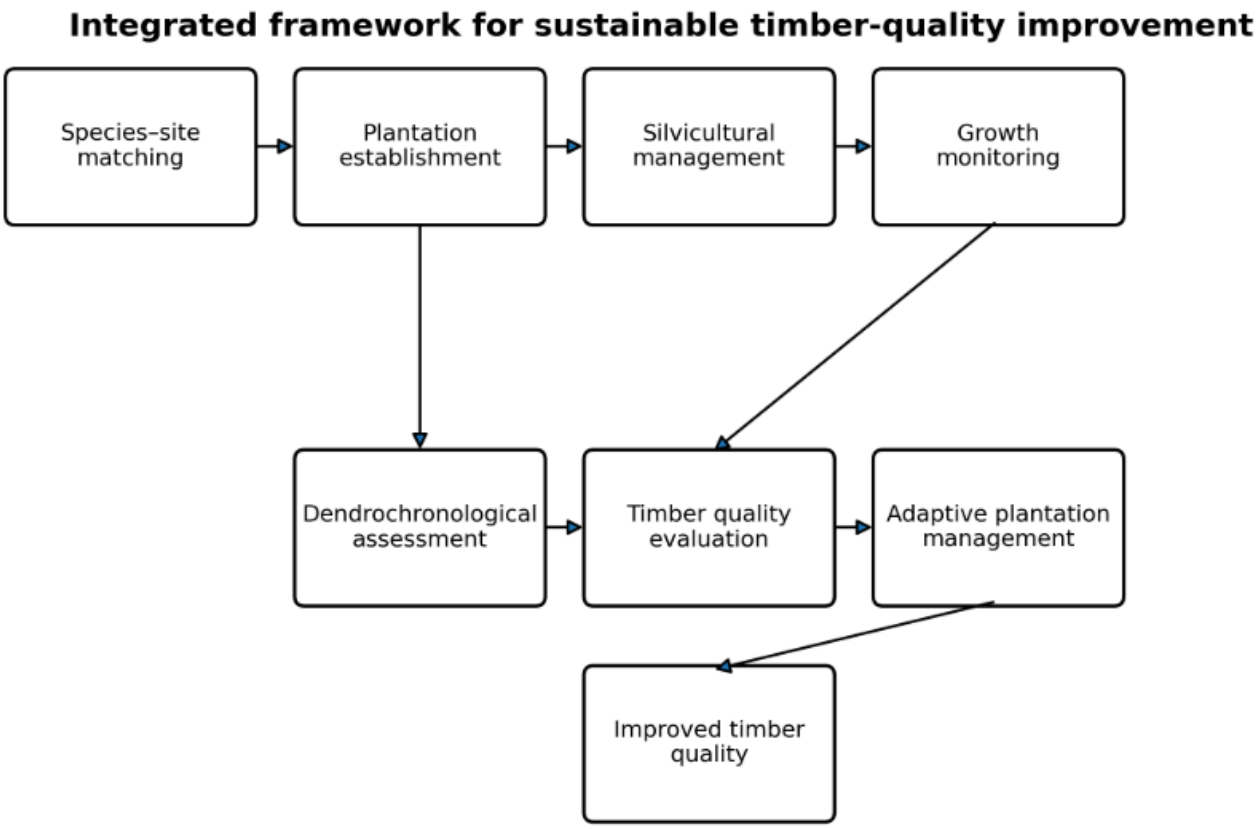


Figure 9

Integrated framework for sustainable timber-quality improvement in Zambian plantations.

Supplementary Files

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