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The development of an integrated herbicide financial risk model for plantation forests in South Africa

by

Jonathan Cecil Roberts

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Supervisor: Prof K.M. Little

Co-supervisor: Dr C.A. Rolando

DECLARATION BY CANDIDATE

NAME: Jonathan Cecil Roberts

STUDENT NUMBER: s211054801

QUALIFICATION: PhD in Forest Science

TITLE OF PROJECT: The development of an integrated herbicide financial risk model for plantation forests in South Africa

The work in this thesis was carried out under the supervision of Prof. Keith M. Little[1] and Dr Carol A. Rolando[2].

[1]School of Natural Resource Management, Nelson Mandela University, George Campus, Private Bag X6531, George 6530, South Africa
[2]Issues and Operations 2, Department of Conservation, 99 Sala Street, Fenton Park, Rotorua, 3010, New Zealand

DECLARATION:

In accordance with Rule G5.11.4, I hereby declare that the above-mentioned treatise/ dissertation/ thesis is my own work and that it has not previously been submitted for assessment to another University or for another qualification.

Jonathan Cecil Roberts
DATE: 30/11/2021

ABSTRACT

Vegetation management is a key component of silviculture in commercial forestry, ensuring that limited site resources (water, nutrients, light and physical growing space) are channelled into usable forest products rather than into non-desired plant species. To achieve this, various vegetation management options, are used within South Africa and include: physical and/or mechanical removal of non-crop vegetation; herbicide application using knapsacks or tractors with spray booms; cultural control methods that incorporate practices common to good land management such as manipulation of planting density, and biological control methods where pathogens or pests are used to regulate the population density of a target species. Even though a combination of appropriate control measures for the integrated management of vegetation is preferred, over the past five decades, the effectiveness and relatively low cost of herbicides has led to the dependence on their continued availability for improving tree growth. However, increasing global pressure to reduce or eliminate herbicides in commercial forestry, driven by factors such as growing public aversion to herbicide use in forests, forest certification requirements and governmental regulations restricting or prohibiting herbicide use, suggests that the continued dependence on herbicides alone is no longer viable.

Before making decisions related to vegetation management practices that use less herbicide, comprehensive data are required as to their commercial applicability, as well as outcomes from multiple long-term trials that accurately quantify any impacts on tree growth and financial return. The overall purpose of this dissertation was to examine herbicide use in commercial forestry in SA, and subsequently develop an herbicide use risk model or decision support system with the aim of reducing herbicide inputs without compromising tree growth. To achieve this, four inter-linked sub-objectives were determined, with each objective dealt with chronological.

The first objective was to examine herbicide use within the SA forest industry. This objective was achieved through conducting an herbicide survey which was completed by plantation managers. Results from this herbicide survey found that although 16 different active ingredients were applied, glyphosate-based products accounted for 97% of the total, with metazachlor and triclopyr butoxy ethyl ester combined, accounting for 2%. Regardless of climate zone (cool temperate, warm temperate, or sub-tropical), the highest number of herbicide applications and quantity of herbicide applied occurred

during the re-establishment phase (planting to canopy closure), with glyphosate-based products the most common herbicide. Data from this survey indicate similar levels of herbicide use (0.66 kg a.i. ha^{-1}) when compared to countries that also practice intensive plantation silviculture (New Zealand and the United States of America = 1.0 - 3.0 kg a.i. ha^{-1}; Chile = 2.0 - 2.5 kg a.i. ha^{-1}). The survey not only provided a benchmark of herbicide use in SA, but also highlighted areas where herbicides can be reduced depending on tree growth stages and climate zone.

The second objective was to investigate tree growth responses and herbicide use for various vegetation management treatments used in 19 pulpwood research trials (7 eucalypt and 12 pine). Tree growth responses obtained across these trials were a function of inherent site conditions, previous land use, species planted and the manner with which the competing vegetation were managed. Generally, the trials situated within the sub-tropical (ST) and warm temperate (WT) climate zones had better tree growth compared to the cool temperate (CT) climate zone, which can be attributed to the higher mean annual temperatures and increased number of growth days. As weed abundance and growth was also higher on the ST and WT sites, higher levels of weeding (higher use of herbicide was required) were required to optimise survival, yield and uniformity. The combined results from these 19 trials indicated the importance of vegetation management in terms of optimizing tree production, with higher weeding intensities resulting in better tree growth, albeit with higher herbicide use.

The third objective was focussed on understanding the financial implications of the various vegetation management treatments implemented across the 19 trials that formed part of objective two. This was achieved by calculating the total vegetation management cost for each of the various vegetation management treatments implemented and their rotation-end yield to determine cost-effectiveness. Compared with the *Weedy* treatments, vegetation control during the establishment phase resulted in significant improvements of ca. 53% in volume across the eucalypt and pine trials. This trend was similar for the net present value (NPV) that was calculated, with the outcomes illustrating the financial benefits of adequate vegetation management, confirming the importance of establishment vegetation control in both eucalypt and pine plantations managed on a pulpwood regime in SA. Within this trial series, there was a direct positive correlation between volume/NPV obtained and the intensity of vegetation management operations, particularly for those trials located within the ST and WT climate zones. For the trials within the CT climate zone, the variation between treatments was lower due to reduced competition from vegetation. If the objective is to optimise financial return, then complete vegetation management using herbicides is required whereby all competing vegetation is control (*Weedfree* treatments). However within ST and WT climate zones, competition can be managed through clearing any vegetation within a ≥1.2 m row width for eucalypts or within a ≥1.0 m diameter ring for pines. The planting of sweet potatoes within the interrow suppressed competing vegetation and could also be considered as a viable alternative to complete weeding, however within this trial series the actual cost of sweet potatoes was not considered and therefore the NPV relative the *Weedy* treatment could be lower if these costs were included

For objective four, various vegetation management treatments from 19 vegetation management trials were incorporated into an herbicide use risk model. The results indicated that the more intensive the weeding operation (such as the *Weedfree* treatments), the higher the tree volume, particularly on more productive sites. However, these methods also rely on the use of more herbicides. If reduced herbicide use is the main criterion, then either a manual weeding can be carried out (*Weedfree manual*) or *Weedy* treatments can be used. However, the manual weeding is more costly and labour intensive, with the *Weedy* treatment resulting in a significant loss in tree growth and profit, especially on the more productive sites in the WT and ST climate zones.

Overall, the outcomes from this dissertation provide benchmark data and derived information as to the necessity for various vegetation management options and associated herbicide use within the commercial forestry sector of SA. In addition, the herbicide use risk model will not only assist foresters with choosing the most appropriate site-specific vegetation management methods to use based on their management objectives, it will also provide them with an indication of the magnitude of loss in volume and profit, should a less intensive approach be followed.

PUBLICATIONS AND PRESENTATIONS RELATED TO THIS RESEARCH

Details of publications that form part of the research presented in this thesis.

Published reports and papers

Roberts JC, Little KM and Rolando CA. 2021. Estimated herbicide use within the commercial forestry sector in South Africa. *Australian Forestry* 84 (3): 108-121. DOI: 10.1080/00049158.2021.1935127

Conferences attended related to the thesis

Presented at the Combined Congress 2020 (January 2020) held at the University of the Free State, Bloemfontein (Topic presented: Herbicide use within the commercial forestry sector in South Africa).

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CHAPTER 1. GENERAL INTRODUCTION

1.1. Background

Commercial forestry is an important sector within the South African economy. Although occupying less than 1.0% (1 212 383 ha) of the total land surface area and contributing 1.2% to the gross domestic product of South Africa, the forestry industry is estimated to indirectly support ca. 654 000 (or 1.4%) of the population in South African (**FSA 2020**). As a developing country with a rapidly increasing population, plantation forestry is essential to meet the increasing demand for timber for a variety of uses (**Siry et al. 2005; Bauhus et al. 2010; Edwards 2011**). South Africa (SA) has limited natural timber resources, and therefore the continual development and improvement of plantation forestry is fundamental to the growth of the country. Plantation forestry not only requires intensive inputs based on high levels of knowledge, but also needs to take into consideration various abiotic/biotic risks associated with all forestry management practices. For example, over the past 38-years ca. 669 439 ha of plantations within SA have been lost through fire alone (**FSA 2020**).

Maintaining sustainable production of wood is critical for long-term economic stability of the industry, and any potentially negative impacts to productivity arising out of abiotic/biotic risk factors first need to be understood, and then managed to reduce any long-term impact. There are numerous definitions related to sustainable forestry, but in principle they all aim to ensure that the resources utilized today, remain available in the future (**Smallidge 2003; Ryan 2010; FSC 2020; PEFC 2020**). **Chapman (1931)** described sustained yield as the actual net yield of a productive industry in which there is no permanent depletion of the capital resource, which in forestry is represented by the environment and growing stock. However, the principles associated with “sustained yield” are more far-reaching than conservation of the productive capacity of the forest only (**Little et al. 2006**), as environmental and social aspects should be considered as well. Consequently, the concept of sustainability has been expanded to include meeting the needs of the current generation without compromising the ability of the environment to meet the needs of future generations.

Understanding management options for sustained production not only requires an in-depth understanding of all the various components of the system, but also how these are inter-related, with the incorporation of economic, social and environmental forest management principles to ensure sustainable forest production (**Rametsteiner and Simula 2003; Smallidge 2003; Magin 2008**). Consequently, internal and external auditing processes are in place to ensure sustainable production is achieved without the over-exploitation of either social and/or environmental aspects. The South African forest industry makes use of various international, external auditing bodies (certification schemes) to ensure the basic principles around sustainable practices are adhered to. Some examples include the (**FSC 2020; PEFC 2020**):

- Forest Stewardship Council (FSC);
- Programme for the Endorsement of Forest Certification (PEFC);
- Sustainable Forestry Initiative (SFI); and
- International Standards Organization (ISO).

One of the components within any of these certification schemes in terms of the management of forest growth, relates to chemical use, with most of these chemicals incorporated within various silvicultural regimes for mitigating risk (e.g. through protection from pests). These silvicultural regimes make use of chemicals in a number of different areas, stages of stand development and are applied for different reasons, although most chemical use can broadly be grouped into those used for tree protection (pesticides: herbicides; insecticides; fungicides; rodenticides etc), for enhancing tree growth (fertilisers; fumigants; pesticides; sterilants; detergents; etc.), or for the amelioration of some site or environmentally limiting attribute (fertilisers; hydrogels; 'stress relievers'; etc.) (for example: **Ashton and Monaco 1991; Little and Eccles 2000; Veiga et al. 2001; Little and du Toit 2003; Rametsteiner and Simula 2003; Wagner et al. 2006; Little et al. 2006; Little 2007; Rolando et al. 2013; Little 2014; Baillie 2016; Little and Payn 2016**).

Pesticides are used world-wide to enhance and improve forest growth, especially in those countries that have limited natural timber resources that are reliant on planted forests (often comprising exotic species) for wood supply, such as South Africa, Europe, New Zealand and Brazil (**Little et al. 2006; Willoughby et al. 2009; GHS 2011; Baillie 2016; Rolando et al. 2017**). In contrast countries with an abundance of natural forest, such as Finland and Canada (**Hytönen et al. 2017; Rolando et al. 2017**), have a limited need for pesticides to enhance growth. For example, in Canada for the 2014 reporting year, ca. 779 577 ha (0.2% of the productive forest land base) was harvested with 413 373 ha of this replanted (commercial plantations), whereas the remaining areas were allowed to regenerate naturally as indigenous species (**NFD 2015**). In this same year, only 129 373 ha (31%) and 218 073 ha (53%) of the replanted area was treated with herbicides and insecticides respectively (**Figure 1.1**).

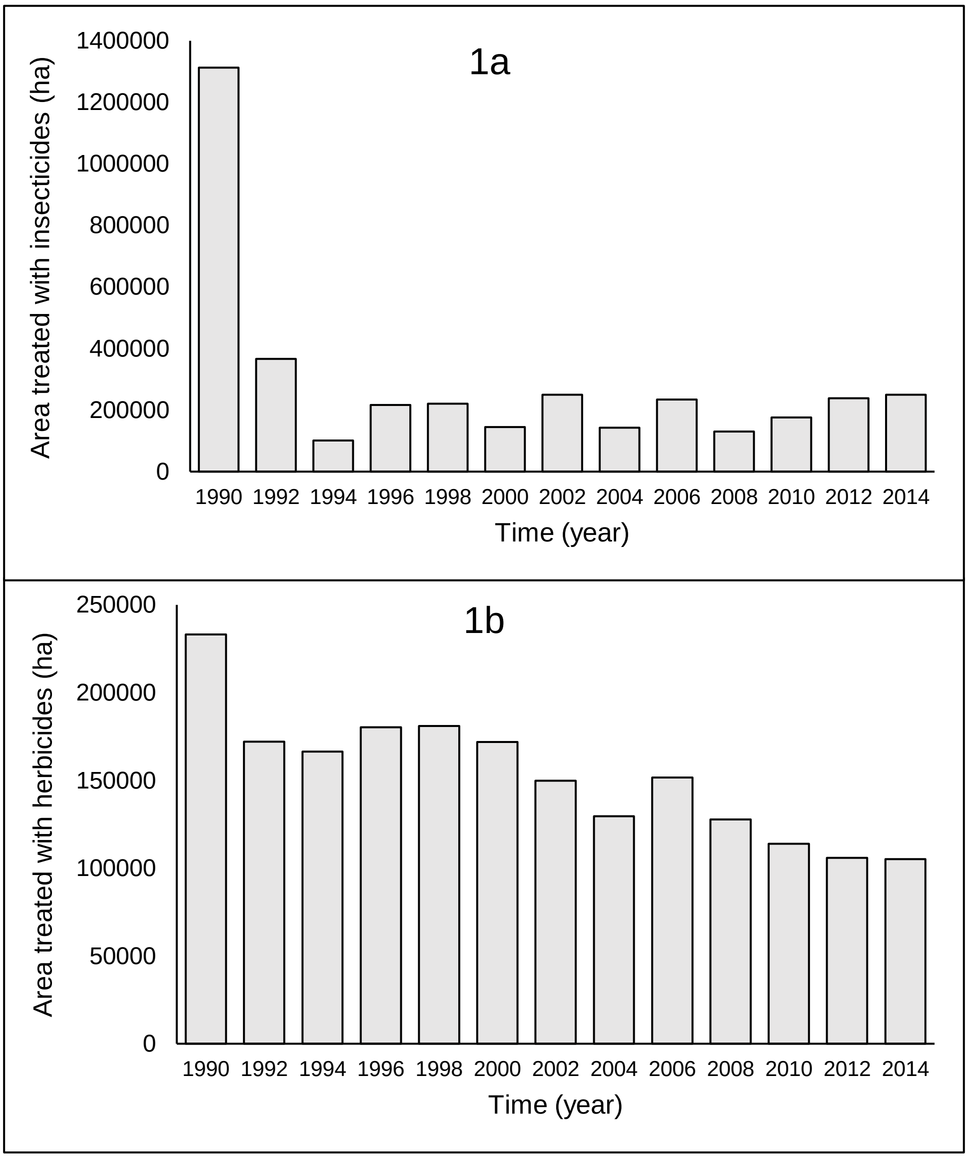


Figure 1.1. Total area treated by insecticides (1a) and herbicides (1b) over 25 years in Canada (extracted and adapted from **NFD 2017**).

Even though pesticide-use in most forest stands is highly regulated and forms part of a planned action to bring about a desired response, pesticides may still have the potential to accumulate within watersheds or catchments despite low rates of applications in such areas – often referred to as off-target or off-site impacts (**Ashton and Monaco 1991; Michael and Neary 1993; Cooper and Dobson 2007; Willoughby et al. 2009; Little et al. 2006; Little 2014; Baillie 2016; Rolando et al.**

2013, 2017). As a result, various countries and organisations have developed laws and regulations regarding the use of these pesticides, with increasing pressure in recent years to reduce reliance on pesticides globally. According to **Willoughby et al. (2009)**, policy drivers for pesticide reduction can be grouped into three main categories, often occurring in combination:

- national policies restricting pesticide-use;
- internationally independent forest certification schemes such as those approved by the Programme for the Endorsement of Forest Certification schemes (PEFC) and the Forest Stewardship Council (FSC);
- international policy on pesticide approvals that has led to a review of the safety and efficacy of registered pesticides with either the lack of data, adverse data, or commercial decisions resulting the withdrawal of many active ingredients from the market.

In response to the risks associated with pesticide use, increased public concern and compliance associated with forest certification standards and/or countries national policies, there is an increased need to identify and avoid the use of pesticides where possible. At the same time, there is also a need to provide alternative methods that can reduce reliance on pesticides together with the appropriate recommendations on use thereof when applied (**Little et al. 2006; Willoughby et al. 2009; FSC 2020**).

In some instances, even where alternative practices exist, or where a reduction in the requirement for pesticides has been demonstrated (without compromising tree growth), these practices have not always been adopted commercially. For example, effective vegetation management practices in SA that focus on reduced herbicide use have been demonstrated through research yet few of these operations have been commercial adopted. Such practices include reducing the area treated (spot or strip spraying), a reduced frequency of weeding operations, the targeted control of specific/competitive vegetation types, the development of standards for cover-cropping, the adjustment of weed control standards according to altitude and improving the efficiency of herbicides through use of adjuvants (**Little and Schumann 1996; Little and Rolando 2001; Tu et al. 2001; Little et al. 2002; Little et al. 2006; du Toit et al. 2010; Little 2014**). Although several papers and conference proceedings highlighting these research results have been produced and can be considered successful from a research perspective, not all are applied commercially (**Little and Dyer 2002**), or when they are applied, it is by default rather than design.

According to **Little and Dyer (2002)**, possible reasons for why these pesticide research findings have not been commercially implemented could be due to the following:

- an inability to incorporate the research findings as company structures are inflexible, in combination with research results lacking coherence;
- an inability to understand and therefore use the research findings (too complicated);
- the economic return for the company is not perceived to be worth the additional resources to implement the recommendations; and/or
- there is no system/model in place whereby all the relevant research findings are illustrated in one document (difficulties in information transfer to companies).

Overall, poor implementation is mainly due to the lack of a systematic and holistic approach to classify potential risk in terms of impacts to economic, environmental and social outcomes, as well as their incorporation into practical strategies easily adopted by the end-user. As such, there is a need for an integrated, yet holistic approach to pesticide risk assessment as well as the development of a strategy for the incorporation of current pesticide knowledge into practical management tools. This strategy should also focus on the economic, environmental and social aspects of forest management to ensure sustained production of forest resources.

1.2. The research problem

Forestry research within SA has primarily focused on maximising sustainable production, with ca. 70 years of co-ordinated and planned research conducted towards achieving this goal (**ICFR 2020**). Most vegetation management research conducted within plantation forestry in SA is related to short-term tree growth impacts (up to 3 years), with proportionally fewer studies dealing with either longer-term growth and/or economic risk (anything from 3 years to rotation end) (**Little and Rolando 2008; Rolando and Little 2009; Roberts et al. 2016**). To fulfil the global trend regarding reduced herbicide-use and/or the use of alternative practices that reduce reliance on herbicides, comprehensive vegetation management data is required from commercial use as well as results from multiple long-term trials, where all treatment inputs are known (herbicide type, rates and frequency of use; input costs; tree performance etc.). However, few countries have such comprehensive data or systems for the detailed recording of herbicide use within forests (as is done in Canada for example) (**NFD 2015**). The benefits of having an up-to-date system recording herbicide use are many, some of which include: an understanding of the types and amounts of product applied; the linking of product type and amount to tree growth stage; transparency in reporting; changes in herbicide use over time; the ability to benchmark local with international use; the ability to highlight areas where herbicide use can be reduced without a loss of production; and the linking of herbicide use with any economic, social and environmental impacts in terms of sustainable forest management (**Cooper and Dobson 2007; Rolando et al. 2017**).

Even though herbicide use data is collected by individual companies involved with forestry in South Africa, this data is fragmented in that there is no commonality in terms of the manner it is collected, nor the collation of this data into one comprehensive data base. Annually the Timber Industry Pesticide Working Group (TIPWG) provides an updated list of which herbicides can be used in nurseries and plantations according to the Fertilizers, Farm Feeds, Agricultural Remedies and Stock Remedies Act of 1947 (Act No. 36 of 1947) and FSC criteria, however this information does not contain the level of detail required for the determination of best operating practice regarding the use of herbicides for the optimisation of vegetation management practices or reduction of herbicide use (**FSA 2020**).

1.3. Overall research aims and objectives for the research

The overall aim of this dissertation is to develop an herbicide financial risk model for vegetation management within commercial eucalypt and pine pulpwood plantations of South Africa. The model will assess the environmental and economic risk associated with various vegetation management treatments through quantifying the total amount of herbicides applied throughout the growth of a stand, while considering the financial return and rotation-end growth responses obtained from application of that treatment. To do this, four key objectives were identified.

Objective 1: Quantify herbicide use within the commercial forestry sector of South Africa

Purpose: To determine the types and quantities of herbicides applied within plantations of South Africa, and to link this information with that of stand development.

Method: A herbicide survey was carried out to quantify herbicide use within commercial forestry plantations in SA.

Outcome: Quantified current status of herbicide use in commercial forestry SA with a specific focus on:

- key herbicide active ingredients (a.i.) currently used by the industry;
- stages of stand development where these a.i. are applied; and
- actual quantities used.

To meet this objective an herbicide database was developed which provides a detailed overview of herbicide use within forestry, as well providing a basis upon which future herbicide use can be assessed.

Objective 2: Link vegetation management treatments to herbicide use and forest productivity (survival, growth and uniformity) for eucalypt and pine pulpwood regimes

Purpose: To investigate the longer-term impacts of various vegetation management treatments on tree growth and link the response to the quantity of herbicides applied to achieve these growth responses.

Method: Based on the presence of comprehensive vegetation management and tree growth data available in South Africa, seven eucalypt and 12 pine vegetation management trials were selected and used for the linking of treatment to tree performance and herbicide use.

Outcome: By linking long-term tree growth responses (obtained from various vegetation management treatments) to quantity of herbicides applied, an herbicide-use-to-benefit risk profile for the different treatments/species/sites could be determined for both pines and eucalypts.

Objective 3: Understanding of financial implications of various vegetation management treatments

Purpose: To determine the financial implications associated with vegetation management for pines and eucalypts grown in South Africa.

Method: The financial returns for the various vegetation management treatments that were used in **Objective 2** were determined, and from this the cost-effectiveness for each treatment calculated.

Outcome: Besides the development of a comprehensive understanding of the financial implications associated with various vegetation management treatments, the costs-benefits of herbicide-dependant treatments could now be compared to alternative treatments where herbicides are either used at reduced quantities or not at all.

Objective 4: Development of an herbicide use risk model specific to eucalypt and pine pulpwood regimes in South Africa

Purpose: The development of an herbicide use risk model for vegetation management to assist forest managers to make an informed choice of vegetation treatment (and herbicide-use) and link this to tree growth and financial risk.

Method: Various risk models (or decision-support systems) were sourced and compared using data obtained from **Objectives 2 and 3**, with the most appropriate one adapted for use on pine and eucalypt stands grown in SA.

Outcome: An herbicide use risk model incorporating herbicide use and costs was developed for use within commercial plantations in South Africa. A working example of this vegetation management risk model can be used by forest companies to make informed decisions around the responsible and reduced use of herbicides as part of a planned and informed process.

General note to the reader:

Although this dissertation is centred around a common theme, a paper-based structure has been used, whereby each chapter is standalone (i.e. each chapter deals with one objective/sub-objective **Chapters 2-7**). As such there is some repetition between chapters, in particular the Introduction and Material and Methods sections. To assist with an understanding as to how the various components contained within this thesis are linked, an organogram (**Dissertation at a glance**) has been provided.

Dissertation at a glance

The development of an integrated risk model for plantation forests in South Africa

Chapter 1

General introduction

Chapter outline
- Background
- The research problem
- Overall research aims and objectives for the research
- Significance of the research

Chapter 2

Objective 1:
Herbicide use within the commercial forestry sector in South Africa

Chapter outline
- Introduction
- Materials and methods for industry herbicide survey
- Results
- Discussions
- Conclusion

Main outcome
Glyphosate-based products accounted for 97% of herbicide use, with the re-establishment phase receiving the highest number of herbicide applications across the climate zones.

Chapter 3

Objective 2a:
Linking eucalypt rotation end data to vegetation management treatments and herbicide use: results from 7 pulpwood trials, South Africa

Chapter 4

Objective 2b:
Linking pine performance to vegetation management treatments and herbicide use: results from 12 pulpwood trials, South Africa

Chapters outline
- Introduction
- Materials and methods used for eucalypt/pine trials
- Tree performance risk associated with reduced levels of vegetation management for both eucalypt and pine trial data sets
- Significance of the research
- Results and Discussion
- Conclusion

Main outcome
The combined results from the 19 trials indicates the importance of vegetation management in terms of ensuring tree production, with a higher intensity of weeding favoured, albeit with higher herbicide use as well

Chapter 5

Objective 3:
Linking pulpwood tree volume and financial performances to different methods of vegetation management within commercial forestry South Africa

Chapter outline
- Introduction
- Materials and methods
- Cost assumptions used for all vegetation management treatments in both eucalypt and pine trial series
- Results and Discussion
- Conclusion

Main outcomes
Volume directly linked to weeding intensity (and hence cost). If the aim is to maximise volume and financial return, then complete vegetation management required. If the focus is on reducing herbicide use, then no vegetation management required, albeit with negative impacts on both tree growth and financial returns.

Chapter 6

Objective 4:
Development of an integrated economical vegetation management risk model

Chapter outline
- Introduction
- Examples of integrated risk models
- Description of integrated economic vegetation management risk model
- Worked example of the model
- Conclusion

Main outcomes
The results of the research showed that the integrated risk model can be used by foresters to select the appropriate vegetation method for both eucalypt/pine pulpwood plantations

Chapter 7

Overall conclusions

Chapter outline
- Summary of major findings
- Limitations and future research direction
- Value of research findings to the forestry industry

CHAPTER 2. ESTIMATED HERBICIDE USE WITHIN THE COMMERCIAL FORESTRY SECTOR IN SOUTH AFRICA

2.1. Introduction

Natural (or indigenous) forests occur over a small percentage of the area (0.4%) of South Africa, with the reliance on timber plantations (1% of the land area) to supply the need for wood and timber products (**Edwards 2011; FSA 2020**). Timber plantations contribute 1.2% towards the gross domestic product of South Africa, and also contribute significantly to employment (**FSA 2020**). As a developing country with a rapidly increasing population, timber plantations are essential to meet the increased demand for forest products within both the formal and informal wood-production sectors (**Edwards 2011**). Timber plantations in SA occur mainly within the north-eastern (Mpumalanga, 40.6%) and eastern regions (KwaZulu-Natal, 39.9%), with smaller areas planted in the south-east (Eastern Cape, 11.6%) and west regions (Western Cape, 3.6% and Limpopo, 4.3%) (**FSA 2020**). Currently, more than half (61.9% or 755 629 ha) of the timber plantations in SA are owned by 11 private companies.

The main tree species grown for commercial wood production in SA include *Acacia mearnsii* De Wild (7.1% of total commercial plantation area) and various species and inter-specific hybrids of the genera *Eucalyptus* and *Pinus* (49.8% and 42.7% of total commercial plantation area, respectively) (**FSA 2020**). Various timber products are produced from these species, including sawn timber (used for building and construction timber), pulpwood (fibre for pulp and paper production), mining props and transmission poles. In South Africa, softwoods (*Pinus* species and inter-specific hybrids) are grown predominantly for sawn timber (73.5%) and pulpwood (26.1%), whilst hardwoods (*A. mearnsii* and *Eucalyptus* spp. and inter-specific hybrids collectively) are grown for pulpwood (87.2%) and mining timber (4.6%), poles (4.1%) and sawn timber (2.9%) (**FSA 2020**).

Timber plantations occur over diverse sites, with rotations ranging from 6-33 years depending on a combination of site productivity, choice of species and end-product (**Smith et al. 2005a, 2005b; du Toit and Norris 2011; Little et al. 2018a**). Specific species are matched to site based on their suitability to climate and susceptibility to site-specific abiotic and biotic risk factors (**Swain and Gardner 2003; Smith et al. 2005b**), with three broad climatic zones used for the categorization of forest growing regions in SA (**Smith et al. 2005a, 2005b)**. These three climatic zones are defined as: cool temperate (CT): mean annual temperatures (MAT) <16°C with snow and frost risk across the landscape; warm temperate (WT): MAT 16-19°C with frost risk confined to low-lying areas only; and sub-tropical (ST): MAT >19°C which is frost-free. Since rainfall is closely related to productivity and drought risk, the classification is further sub-divided into mean annual precipitation (MAP) classes corresponding to dry, moist and wet sites.

To meet an increasing demand for timber, plantation managers make use of intensive silvicultural practices to optimise productivity per unit land area (**Rametsteiner and Simula 2003; Smallidge 2003; Magin 2008; Little et al. 2018a, 2018b**). This is achieved through the use of intensive silvicultural practices that are based on comprehensive research implemented within forestry, which is designed to realise the productivity potential of each site (and includes practices such as site preparation, vegetation management, fertilization etc.) (**Zutter et al. 1987; Wagner et al. 2006; du Toit et al. 2010; Ndlovu et al. 2019a**). Globally, the outcomes from this silvicultural research have resulted in the optimization of productivity on a site-specific bases, be that for timber volume, pole length and/or tree form (**Wagner et al. 2006; Willoughby et al. 2009; du Toit et al. 2010; Rolando et al. 2017**). Of the various silvicultural practices, the appropriate management of competing vegetation is necessary to reduce both the short- and long-term negative impacts of on-site vegetation on timber/wood production (**Wagner et al. 2006; Willoughby et al. 2009; Rolando and Little 2009; Little et al. 2018b; Roberts et al. 2018; Ndlovu et al. 2019a**).

Vegetation management practices are used to channel limited site resources (water, nutrients, light and physical growing space) into usable forest products rather than into non-target plant species, or weeds (**Richardson 1993; Wagner et al. 2006; Little and Rolando 2008; Willoughby et al. 2009**). A type 1 growth response is obtained as a result of controlling competing vegetation, whereby there is an advancement of stand development but no change in the inherent productivity of the site (**Snowdon 2002**). The management of vegetation through a rotation is divided into the three distinct phases, namely: pre-establishment - the phase between harvesting and re-planting (which includes all pre-planting operations); re-establishment - the phase between planting and canopy closure; and post-establishment - the phase between canopy closure and harvesting (**Wagner et al.**

1996, 2006; Willoughby et al. 2009; Rolando et al. 2013; Weatherford et al. 2015). The intensity of vegetation management operations (type, frequency and duration) is adjusted within each of these three phases to take into consideration the relative importance of the impacts of the competing vegetation on the planted tree species. As commercial plantations are planted across diverse climatic zones in South Africa, vegetation management duration and intensity across the three phases varies widely (**Little et al. 2007; Little and Rolando 2008; Rolando and Little 2009; Little et al. 2018b**). For example the time taken to canopy closure varies according to site productivity, genera planted (pines versus eucalypts), planting density, and management objective, with vegetation management operations following canopy closure (post-establishment) reduced due to shading by the tree crowns (**Little and Rolando 2002; Little et al. 2018b**).

Various vegetation management options (mostly labour intensive), are used within SA to ensure that competing vegetation is kept to a minimum and include: physical and/or mechanical removal of non-crop vegetation using agricultural hoes or bush-knifes (slashing), or tractor drawn implements such as discing within the inter-row; herbicide application using knapsacks (and to a lesser extent tractors with spray booms) to either the foliage, basal stem or cambium layer of weeds; cultural control methods that incorporate practices common to good land management such as manipulation of planting density (planting at higher density to achieve earlier canopy closure to shade out possible competing vegetation), maintenance of critical 'weed free' periods, the retention of post-harvesting residues to suppress weed germination and development, or the use of cover cropping (suppressing weeds through planting of a desirable cover crop in areas which are open to invasion) (**Zutter et al. 1987; Little et al. 2006; Wagner et al. 2006; Little and Payn 2016; Roberts et al. 2016, 2018; Ndlovu et al. 2019a, 2019b and 2019c**). Due to the range of competing weed species that occur within South African plantations (**van Heerden and Masson 1991**), biological control methods where pathogens or pests are used to regulate the population density of a target species, although important, are not as effective as manual, chemical and/or cultural control (**Saunders 2011; Watson et al. 2011**).

Even though a combination of appropriate control measures for the integrated management of vegetation is preferred, over the past five decades, the effectiveness and relatively low cost of herbicides (**Dales and Golob 1997; Baylis 2000; Cooper and Dobson 2007; Little 2014**) has led to the dependence on their continued availability for improving tree growth (**Little et al. 2006; Wagner et al. 2006; Willoughby et al. 2009; Baillie 2016; Rolando et al. 2017**). Worldwide there have been increased concerns regarding pesticide-use (herbicides included) in terms of human health and environmental impacts (**Wagner et al. 1998; Rolando et al. 2017**). Studies have shown that within forest management areas, herbicides are generally applied at low rates of application, seldom exceeding the maximum allowable rates or thresholds, and infrequently with most operations occurring during the pre- and re-establishment phases (**Jenkin and Tomkins 2006; Wagner et al. 2006; NRD 2015; Weatherford et al. 2015; Baillie 2016; Rolando et al. 2013, 2017**). Even so there is still the potential that the active ingredients may move either in surface flow or leach through the soil profile and thereby accumulate within watersheds or catchments (referred to as off-site impacts) (**Baillie 2016**). However, few studies have indicated off-site impacts that have had long-term negative impacts to soil/water quality (**Willoughby et al. 2009; Little 2014; Baillie 2016; Rolando et al. 2017**).

These concerns, together with increasing global pressure to reduce or eliminate herbicides, driven by factors such as increasing public aversion to herbicide use in forests, forest certification requirements and governmental regulations restricting or prohibiting herbicide use, means that the continued dependence on herbicides alone is no longer viable (**Baillie 2016; PEFC 2020; FSC 2020**). As such, herbicide use in forests will need to comply with national policies, forest certification standards (for example >80% of timber plantations in SA are certified according to Forest Stewardship Council (FSC) standards), as well as taking into consideration the environment and social wellbeing **(Little et al. 2006; FSC 2020**). In addition to FSC, other certification systems such as the Programme for the Endorsement of Forest Certification (PEFC) and International Standards Organisation (ISO-14001) all have similar goals related to responsible pesticide-use: avoiding the use of designated “highly hazardous” herbicides; promoting alternative methods for vegetation management; and/or reducing the rate of herbicide application for those herbicides where no alternatives are available (**Little et al. 2006; Willoughby et al. 2009; PEFC 2020; FSC 2020**).

In South Africa, herbicide use in commercial forests is managed through a combination of government legislation, third party certification and operational cost-effectiveness, with any pesticide application forming part of a planned practice to achieve a specific management goal (**Little 2014; FSA 2020; FSC 2020**). Although timber companies keep accurate records of herbicide use, this data is often fragmented, and stored in different formats depending on forest company making it difficult to accurately determine the total amounts used on an annual basis, including the main active ingredients applied and rates used per hectare. In contrast, countries such as Canada have quantitative information on annual herbicide use which allows for (**NFD 2015**):

- benchmarking of past, current or future herbicide use;
- identification of areas of high-risk where herbicides are used;
- identification of areas where reduction in herbicide use can be achieved; and
- transparency in reporting to external auditors or certification bodies.

As part of the research an herbicide survey was undertaken in 2017-2018 within the South African forestry industry, specifically to quantify the herbicide type and quantities used. By linking the quantity of herbicides applied to timber species grown, end-product produced and vegetation management phases within and across the three climate zones, a better understanding of herbicide use can be obtained. In addition, this information may also highlight possible areas where herbicide use can potentially be reduced.

Note: Ethical clearance was obtained for the herbicide use survey from Nelson Mandela University based on the Act 26 of 1996 (**Annexure 2**). This National Research Act (known as the Belmoth Report) relates to ethical principles and guidelines for the protection of human subjects of research.

2.2. Materials and methods for industry herbicide survey

An herbicide use survey (**Annexure 3**) was sent to 72 timber plantations managers owned by 6 of the 11 major forestry companies in South Africa, requesting details of their herbicide use over the period from February 2017 to February 2018. The herbicide use survey consisted of two sections: (i) general background information and (ii) herbicide information.

2.2.1. General background information

(i) Background information, consisted of:

- location of plantation (co-ordinates);

- climate zones within which each plantation was situated (together with MAT, MAP and altitude);
- genera planted (*Acacia*, *Eucalyptus* and *Pinus*); and
- main timber product produced (sawn timber or pulpwood), together with the average rotation-length.

Using this background data, the plantations could be partitioned into different climate zones, genera planted and end-product. This partitioning resulted in 13 different scenarios (**Table 2.1**), against which more detailed herbicide data could be compared.

Description of scenarios

Global Köppen climate classes were adapted to timber growing regions of SA by **Smith et al. (2005a)**, with three climate zones (CT, WT and ST), three main genera (*Acacia*, *Eucalyptus* and *Pinus*), and two main timber products (sawn timber and pulpwood) occurring within the areas surveyed (**Kottek et al. 2006; FSA 2020**). As rainfall is closely related to productivity and drought risk, the classification system upon which the three climate zones were based also incorporates mean annual precipitation to take into consideration dry, moist and wet sites (**Smith et al. 2005a**), resulting in a total of 39 potential scenarios. The increased difficulty associated with partitioning and interpreting the data within these 39 classes, meant that the scenarios (13 in total) were restricted to three climate zones only.

Climate zones

Jarvel and Pallett (2002), Little et al. (2007), **Little and Rolando (2008)** and **Rolando and Little (2009)** highlighted the importance of site (in terms of physiographic and climatic variables) when linking the growth response of eucalypts and pines to competing vegetation. They found that vigorous weed–tree competition required earlier, and more frequent intervention on the more productive, sub-tropical sites than on the moderately productive warm temperate sites, with little competition detected on the cool-temperate sites (lower productivity). Based on these findings, it was expected that herbicide use would be related to weed growth, with more vegetation management operations required on an annual basis on more productive sites (subtropical > cool-temperate sites).

Table 2.1. Thirteen scenarios created to quantify herbicide use throughout the South African forestry industry. These scenarios are based on the three climate zones and main genera planted for pulpwood or sawn timber.

[1]Climate zones	*MAT (°C)	*MAP (mm)	Altitude (m a.s.l.)	Scenario number	Commercial genera planted or coppiced	End-product	Pre-establishment phase[2/3] (yrs)	Re-establishment phase[2/3] (yrs)	Post-establishment phase[2/3] (yrs)
Cool temperate (CT)	<16	725 to 925	900 to 2 250	1	wattle	pulpwood	-1 to 0	3	10
				2	eucalypts	pulpwood		2	9
				3	eucalypt coppice	pulpwood		2	9
				4	pines	pulpwood		4	18
				5	pines	sawn timber		6	30
Warm temperate (WT)	16-19	850 to 1 000	50 to 1 600	6	wattle	pulpwood	-1 to 0	2	10
				7	eucalypts	pulpwood		1.5	8
				8	eucalypt coppice	pulpwood		1.5	8
				9	pines	pulpwood		3	18
				10	pines	sawn timber		5	27
Sub-tropical (ST)	19-22	925 to 1 075	0 to 1 050	11	eucalypts	pulpwood	-1 to 0	1	8
				12	eucalypt coppice	pulpwood		1	8
				13	pines	pulpwood		2	18

*MAT (Mean annual temperate) and MAP (Mean annual precipitation)
[1]Smith et al. (2005a.b)
[2]Little and Rolando (2008) = time to canopy closure for eucalypts
[3]Roando and Little (2009) = time to canopy closure for pines

Main genera grown in South Africa

Due to the diversity of site types, over 40 pure species or hybrid combinations of mainly *Pinus* and *Eucalyptus* are grown in SA (**FSA 2020**). For simplicity, an assumption that trees within the same genus would likely respond to competition in a similar manner across climatic zones was made and data were grouped according to genus as follows: *Acacia* spp., *Eucalyptus* spp. and *Pinus* spp; hereafter referred to as wattle, eucalypts and pines, rather than by the Latin name (**Little and Rolando 2001, 2008; Little et al. 2007**).

Main timber products

As 94.8% of the timber grown in SA was used for either pulpwood (56.8%) or sawn timber (38%) (**FSA 2020**), the data were partitioned into, and based on these two end-products.

2.2.2. Herbicide information

For each timber plantation included in the 2017/18 survey, comprehensive compartment-level, herbicide-related data were obtained for each of the 13 scenarios (**Table 2.1**) and included:

- date of herbicide application;
- method of application (manual, mechanical, aerial);
- herbicides applied;
- area treated; and
- quantity applied.

2.2.3. Data analysis used for industry herbicide survey

Descriptive statistics in the form of tables and figures were used to describe the herbicide-data obtained (means, ranges, standard deviation = sd). In addition to total amount of herbicide active ingredient (a.i. in kg), the rates of application ha^{-1} for each climate zone and treatment period were calculated as the quantity of kilograms (kg) a.i. applied divided by the area that received treatment. Due to differences in the periods (time) associated with the different phases, genera and end-products (for example, the re-establishment phase for pines grown for sawn timber in a CT region is longer than eucalypts grown for pulpwood in a ST region (6 years compared to 1 year respectively) (**Table 2.1**), for comparative purposes it was necessary to standardize/normalise the data. Even though kg of herbicide a.i. applied ha^{-1} provides an indication of overall herbicide use, this does not include the risk associated with the use of herbicides over time. Risk is a function of inherent toxicity of a particular herbicide and the frequency of application thereof (or exposure under the specific working conditions to this toxicity over time) (**Machado-Neto 2015**). To standardize/normalise herbicide use for comparative purposes, the annual rate of herbicide a.i. application per unit area (kg a.i. ha^{-1} yr^{-1}) for each of the three major herbicide application phases was calculated as follows (**Table 2.1**):

(i) Pre-establishment phase

$$\text{Equation 1} = \left(\frac{\text{quantity a.i. applied (kg)}}{\text{area (ha)}}\right) / \text{ period between harvesting and planting (yrs)}$$

(ii) Re-establishment phase

$$\text{Equation 2} = \left(\frac{\text{quantity a.i. applied (kg)}}{\text{area (ha)}}\right) / \text{ period between planting and canopy closure (yrs)}$$

(iii) Post-establishment phase

$$\text{Equation 3} = \left(\frac{\text{quantity a.i. applied (kg)}}{\text{area (ha)}}\right) / \text{ period between canopy closure and harvesting (yrs)}$$

2.2.4. Data limitations and assumptions for industry herbicide survey

- Due to the variability associated with forestry in SA (sites types/productivity, climate, species planted, end-product, rotation-length etc.), the data were partitioned into 13 scenarios (linked to vegetation management within South Africa). Although this partitioning would assist with interpretation and management, it may also result in the loss of detail for those timber species/products not included, as well as for those scenarios which were not well represented in terms of area planted and/or data not surveyed.
- The sampling strategy was designed to obtain data relating to the growth of timber grown within the commercial forestry sector in SA over one year. By doing this, one would obtain data associated with all plantation ages/management activities, thus allowing for an estimation of herbicide use related to the 13 scenarios. Although there are likely to be minor variations from year to year in terms of the actual areas used, FSA data related to timber area planted by species/age etc. shows little variation in the proportions relative to the total area planted over the years with an increase of ca. 58 000 ha (or 5.1%) over a period of 38 years (1980-2018) (**FSA 2020**).

- Due to the scope of the project, herbicide-related data was restricted to planted areas (possibly the most important in terms of total herbicide use), thus total use for the whole forestry sector could not be determined (for example herbicide use in conservation areas, along road verges, within fire breaks etc.).

For estimation of total herbicide used on an annual basis, products with the same active ingredient (glyphosate), but where different formulations were used (200 – 700 g a.i. per litre), the most common formulation (obtained from the survey 360 g a.i. in this case with over 81% of the total applied) and thus the total glyphosate used was calculating using the 360g a.i. calculations.

2.3. Results

2.3.1. South African forest industry

The aim of the survey was to obtain a good representation of herbicide use data related to the area used by the South African forestry industry to grow trees. Little information could be found as to the ideal sample-size, however for a similar study carried out in New Zealand in 2012 by **Rolando et al. (2013)**, herbicide use within 41% of forestry regions of New Zealand were surveyed (**Rolando et al. 2013**). Over the data collection period (2017-2018) 46 of the 72 timber plantations completed the survey, equating to 28.5% (or 343 959 ha) of the total timber plantations area (ca. 1.2 million ha) within the South African forestry industry surveyed (**Table 3.1**). This area consisted of a good representation of data for the three main genera grown over the three climate zones across the three vegetation management phases.

Table 2.2. Total area according to main purpose for which trees were grown in 2018 within the forestry industry in South Africa, and surveyed area across all scenarios and vegetation management phases, grouped by climatic zone for the period of 2017-2018.

a. Area surveyed based on genera and end-product

Genera	Area according to main purpose for which trees were grown in 2018 for whole industry (ha)[1]				Area surveyed 2017-2018 (ha)		Area surveyed relative to actual industry areas (%)	
	Sawn timber	Pulpwood	Mining Timber	Other roundwood products	Sawn timber	Pulpwood	Sawn timber relative to industry (%)	Pulpwood relative to industry (%)
Pines	437 701	146 287	n/a	350	15 212	53 865	3.5	36.8
Eucalypts	13 720	449 508	26 489	31 332	n/a	269 840	n/a	60.0
Wattle	153	77 187	709	3 894	n/a	4 955	n/a	6.4
Other hardwoods	358	3 184	81	685	n/a	n/a	n/a	n/a
Total area	451 932	676 166	27 279	36 261	15 212	328 660	3.4	48.6
Grand total area	1 191 638				343 872		28.9	

b. Area surveyed based on climate zones

Climate Zone	Scenario number	Genera	Product produced	Area Surveyed (ha)	Percentage relative to climate zone (%)	Percentage relative to total area sampled (%)
Cool Temperate (CT) MAT (°C): <16 MAP (mm): 725 to 925 Altitude (m a.s.l.): 900 to 2 250	1	wattle	pulpwood	927	0.9	0.3
	2	eucalypts	pulpwood	54 241	53.4	15.8
	3	eucalypt coppice	pulpwood	2 140	2.1	0.6
	4	pines	pulpwood	37 727	37.2	11.0
	5	pines	sawn timber	6 480	6.4	1.9
		Total CT		101 515	100	29.5
Warm Temperate (WT) MAT (°C): 16 to 19 MAP (mm): 850 to 1 000 Altitude (m a.s.l.): 50 to 1 600	6	wattle	pulpwood	4 028	6.7	1.2
	7	eucalypts	pulpwood	25 238	41.7	7.3
	8	eucalypt coppice	pulpwood	6 464	10.7	1.9
	9	pines	pulpwood	16 050	26.5	4.7
	10	pines	sawn timber	8 732	14.4	2.5
		Total WT		60 511	100	17.6
Sub-tropical (ST) MAT (°C): 19 to 22 MAP (mm): 925 to 1 075 Altitude (m a.s.l.): 0 to 1 050	11	eucalypts	pulpwood	145 540	80.0	42.3
	12	eucalypt coppice	pulpwood	36 217	19.9	10.5
	13	pines	pulpwood	88	0.1	0
		Total ST		181 845	100	52.9
		Total area sampled across climate zones		343 872		100

[1]Based on Forestry South Africa values for the year period of 2017 to 2018

More eucalypt timber plantations were surveyed relative to both pine and wattle plantations (58.3%, 11.8% and 6.4% relative to industry areas). Of the total area planted to pulpwood (676 166 ha), 48.6% (or 328 660 ha) was included, with 3.4% (or 15 212 ha) of the total area planted to sawn timber surveyed (**Table 2.2**). More pine pulpwood plantations were surveyed compared to pine sawn timber plantations (36.8% and 3.5%). No eucalypt or wattle sawn timber plantations were surveyed due to the small areas managed for these purposes within SA (3% and 0.03% respectively) (**Table 2.2**) **(FSA 2020)**. According to the areas planted (**FSA 2020**), pine plantations are seldom established in the ST climate zone (scenario 13), and therefore as a scenario it was excluded from further discussions (**Table 2.1 and 2.2**).

In terms of the total area surveyed, 29.5% was situated within the CT climate zone, 17.6% within the WT climate zone and 52.9% for the ST climate zone (**Table 2.1**). Eucalypt pulpwood was sampled the most across all three climate zones (CT: 15.8%; WT: 7.3%; ST: 42.3%), followed by pine pulpwood (CT: 11.0%; WT: 4.7%; ST: 0.0%), eucalypt coppice (CT: 0.6%; WT: 1.9%; ST: 10.5%), and wattle (CT: 0.3% and WT: 1.2%).

The timber plantation area surveyed within the pre-establishment phase accounted for 12% (or 39 751 ha) of the total plantations area surveyed (343 872 ha). The re-establishment phase accounted for 48% (165 766 ha) while the post-establishment phase accounted for 40% (138 355 ha) of the total plantations area surveyed.

2.3.2. Herbicide kg a.i. ha^{-1}

An estimated 188 288 kg (or 0.55 kg ha^{-1}) of herbicide active ingredient (a.i.) was applied on the 343 784 ha surveyed (excluding scenario 13) (**Table 2.3 and Table 2.4**). These herbicides were mostly applied manually using knapsack sprayers (either as a broadcast spray, inter-tree row spray or spot spray), across the different climate zones, genera grown, end-product produced and three vegetation management phases (**Figure 2.1**).

Table 2.3. List of active ingredients and main products applied across the sampled area for the period of 2017-2018 within the South African forestry industry.

Active ingredient	Chemical class	Formulation		Trade name	Registration holder	Weeds targeted		
		Type	Active ingredient (g kg^{-1} or g kg^{-1})			Grasses	Broadleaf	Woody
clethodim	Cyclohexanedione oxime	Emulsifiable concentrate	120	Select®	Arysta LifeScience SA	✓		
clopyralid	Pyridinecarboxylic acid	Soluble (liquid) concentrate	100	Lancer®	Future Farm & Forest Serv.		✓	✓
cycloxydim	Cyclohexanedione oxime	Emulsifiable concentrate	100	Focus Ultra®	BASF South Africa	✓		
fluroxypyr meptyl ester	Pyridinecarboxylic acid	Emulsifiable concentrate	200	Starane®	Dow AgroSciences SA			✓
glufosinate ammonium	Phosphinic acid	Soluble (liquid) concentrate	200	Bound®	Villa Crop Protection	✓	✓	✓
glyphosate ammonium salt	Glycine derivative	Water dispersible granules	680	Roundup Max®	Monsanto	✓	✓	✓
glyphosate dimethylamine salt	Glycine derivative	Soluble (liquid) concentrate	480	Mamba DMA®	Dow AgroSciences SA	✓	✓	✓
glyphosate isopropylamine salt	Glycine derivative	Soluble (liquid) concentrate	360	Roundup®	Monsanto	✓	✓	✓
glyphosate potassium salt	Glycine derivative	Soluble (liquid) concentrate	540	Slash Plus®	Universal Crop Protection	✓	✓	✓
glyphosate sodium salt	Glycine derivative	Water dispersible granules	700	Kilo Max®	Arysta LifeScience SA	✓	✓	✓
Imazapyr*	Imidazolinone	Soluble (liquid) concentrate	240	Spear®	Adama South Africa	✓	✓	✓
Imazapyr isopropylamine salt*	Imidazolinone	Soluble (liquid) concentrate	100	Hatchet®	Volcano Agroscience	✓	✓	✓
metazachlor*	Chloroacetamide	Suspension concentrate	500	Sultan®	Adama South Africa	✓	✓	
metsulfuron-methyl*	Sulfonylurea	Water dispersible granules	600	Brush-Off®	Du Pont de Nemours Int SA		✓	
triclopyr butoxy ethyl ester	Pyridine carboxylic acid	Emulsifiable concentrate	270	Garlon Max®	Dow AgroSciences SA			✓
triclopyr triethylamine salt	Pyridine carboxylic acid	Soluble (liquid) concentrate	360	Timbrel®	Dow AgroSciences SA			✓

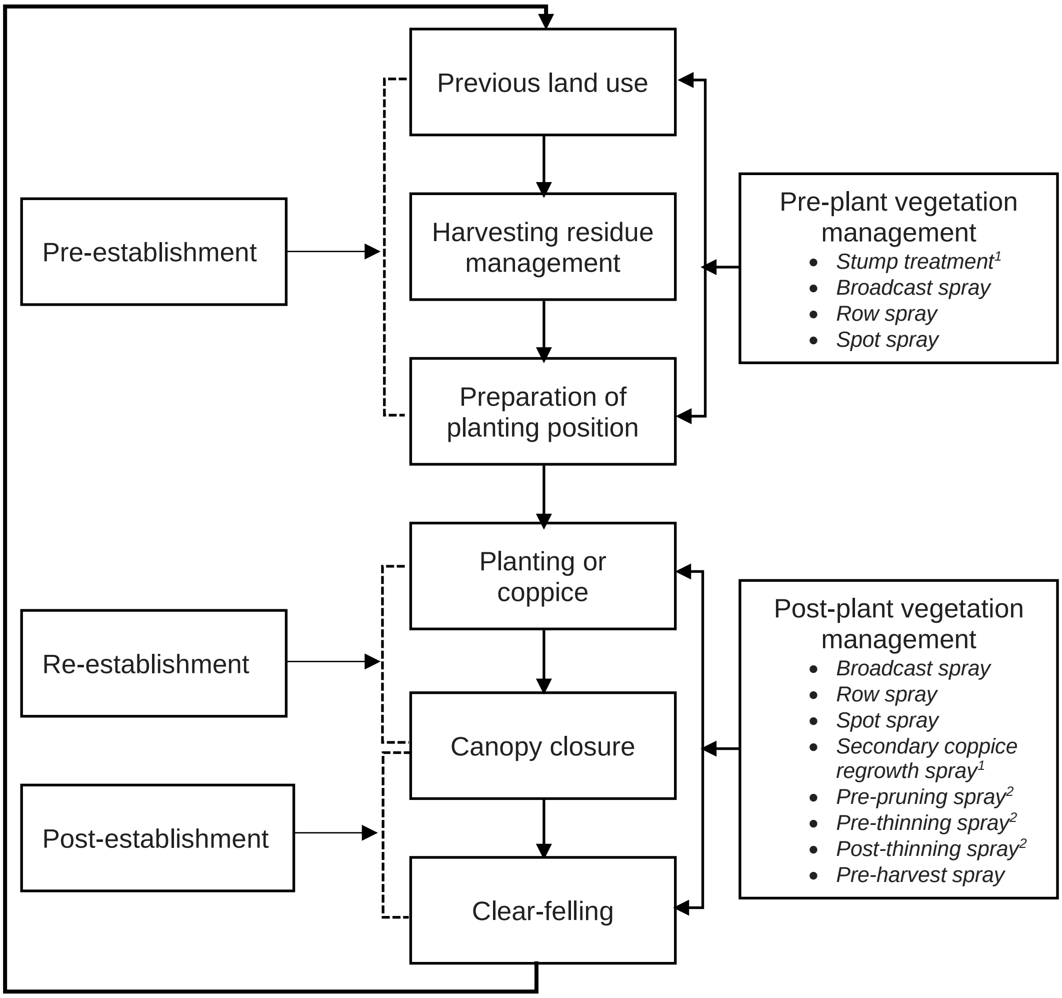
*Pre-emergence herbicide

Table 2.4. Total area surveyed across vegetation management phases, grouped by climatic zone, that received herbicide treatments for the period of 2017-2018 within the commercial forestry industry in South Africa. Also shown are the total quantities of active ingredient (a.i.) applied, and derived rates per hectare.

Climate zone	Treatment period	Area (ha)	Quantity a.i. applied (kg)	a.i. applied ha^{-1} (kg)	Area Relative to Climate zone Total (%)	Quantity applied Relative to Climate zone Total (%)
CT	Pre-establishment	8 357	6 644	0.80	8	11
	Re-establishment	75 320	49 205	0.65	74	81
	Post-establishment	17 838	4 900	0.27	18	8
	Average (Total)	**101 515**	**60 749**	**0.60 (1.72)**	**100**	**100**
WT	Pre-establishment	12 349	12 061	0.98	20	26
	Re-establishment	28 183	25 574	0.91	47	56
	Post-establishment	19 980	7 914	0.40	33	17
	Average (Total)	**60 512**	**45 549**	**0.75 (2.29)**	**100**	**100**
ST	Pre-establishment	19 045	15 641	0.82	10	19
	Re-establishment	62 263	51 816	0.83	34	63
	Post-establishment	100 449	14 532	0.14	55	18
	Average (Total)	**181 757**	**81 989**	**0.45 (1.79)**	**100**	**100**
		343 784*	**188 288***	**0.55**		

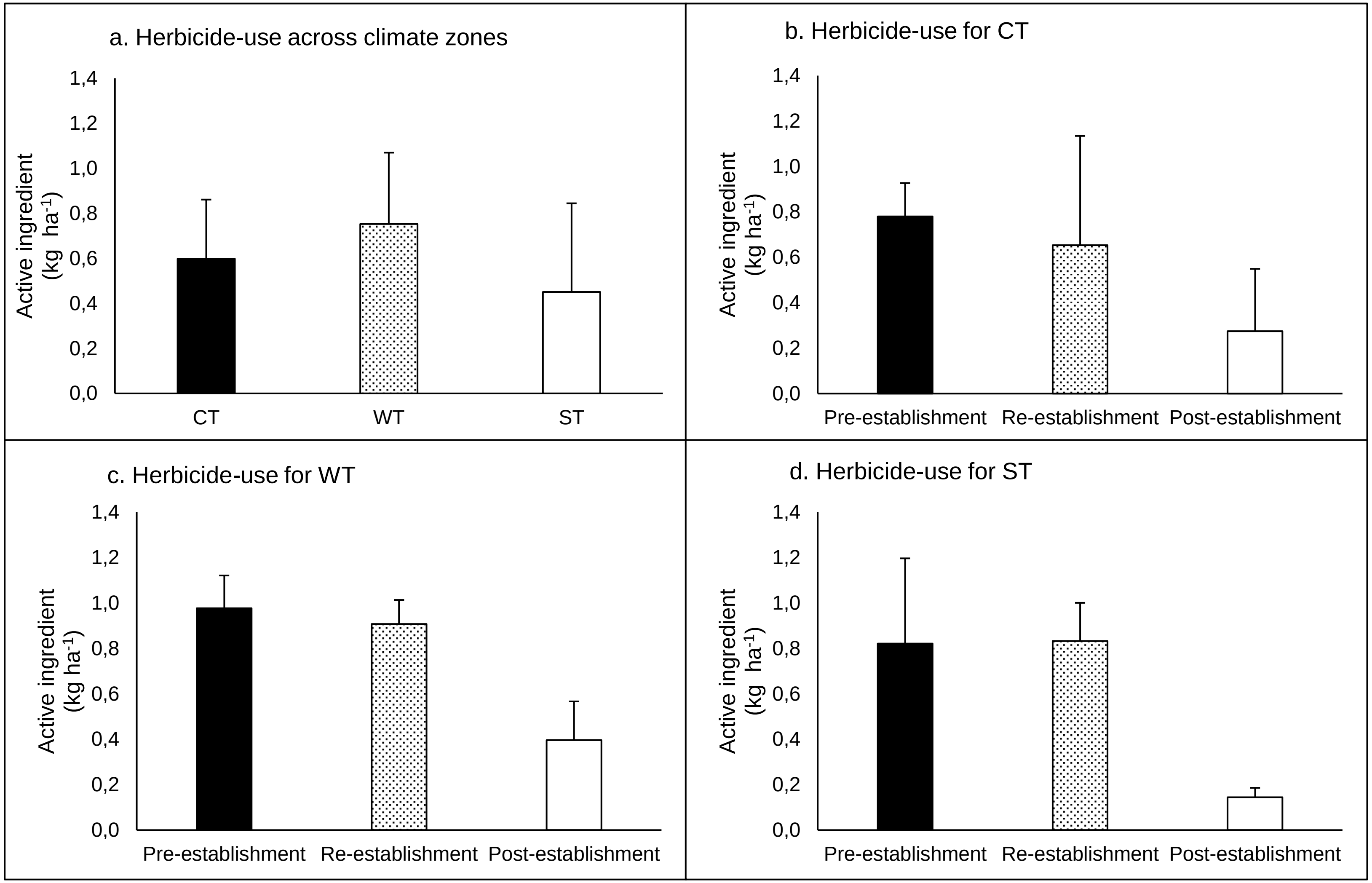
*Excluded scenario 13 from Table 2.2.
ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

The largest quantity of kg herbicide a.i. applied ha^{-1} across the growth phases was within the WT climate zone (0.75 kg a.i. ha^{-1}), followed by the CT climate zone (0.60 kg a.i. ha^{-1}), and the ST climate zone (0.45 kg a.i. ha^{-1}) (**Table 2.4 and Figure 2.2**). Irrespective of climate zone, the general trend was that the pre- and re-establishment phases received more kg a.i. ha^{-1}, followed by the post-establishment phases (pre: $\bar{x}$ = 0.87 kg a.i. ha^{-1} > re: $\bar{x}$ = 0.80 kg a.i. ha^{-1} > post: $\bar{x}$ = 0.27 kg a.i. ha^{-1}). Although more kg of a.i. was applied within the pre-establishment phase across the three climate zones, the total amount was similar to the re-establishment phase (difference of 0.07 kg a.i. across the three climate zones). In contrast the amount of kg a.i. applied during the post-establishment phase was noticeably less across all the climate zones, with ST the least (0.14 kg a.i. ha^{-1}) and WT the highest (0.40 kg a.i. ha^{-1}). This trend was similar for most genera planted across the three climate zones (pre-establishment > re-establishment > post-establishment), except for wattle (scenarios 1 and 6: CT + WT), pine sawn timber (scenarios 5: CT), and eucalypt coppice (scenarios 8 and 12: WT + ST) (**Table 2.5**).



[1]*Eucalyptus* spp. (and coppice) regimes
[2]*Pinus* spp. sawn timber regimes

Figure 2.1. A generic silvicultural regime showing various vegetation management operations where herbicides are used within commercial timber plantations within South Africa (adapted from **Jenkin and Tomkins 2006**).



ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

Figure 2.2. Herbicide use linked to vegetation management phases within three climate zones (CT, WT and ST) during 2017-2018 for commercial timber plantations within South Africa. Bars in figure indicate standard deviation.

Table 2.5. Herbicide use across all scenarios and vegetation management phases, grouped by climatic zone, CT, WT and ST. Also shown is the total active ingredient (a.i.) applied and derived use rate.

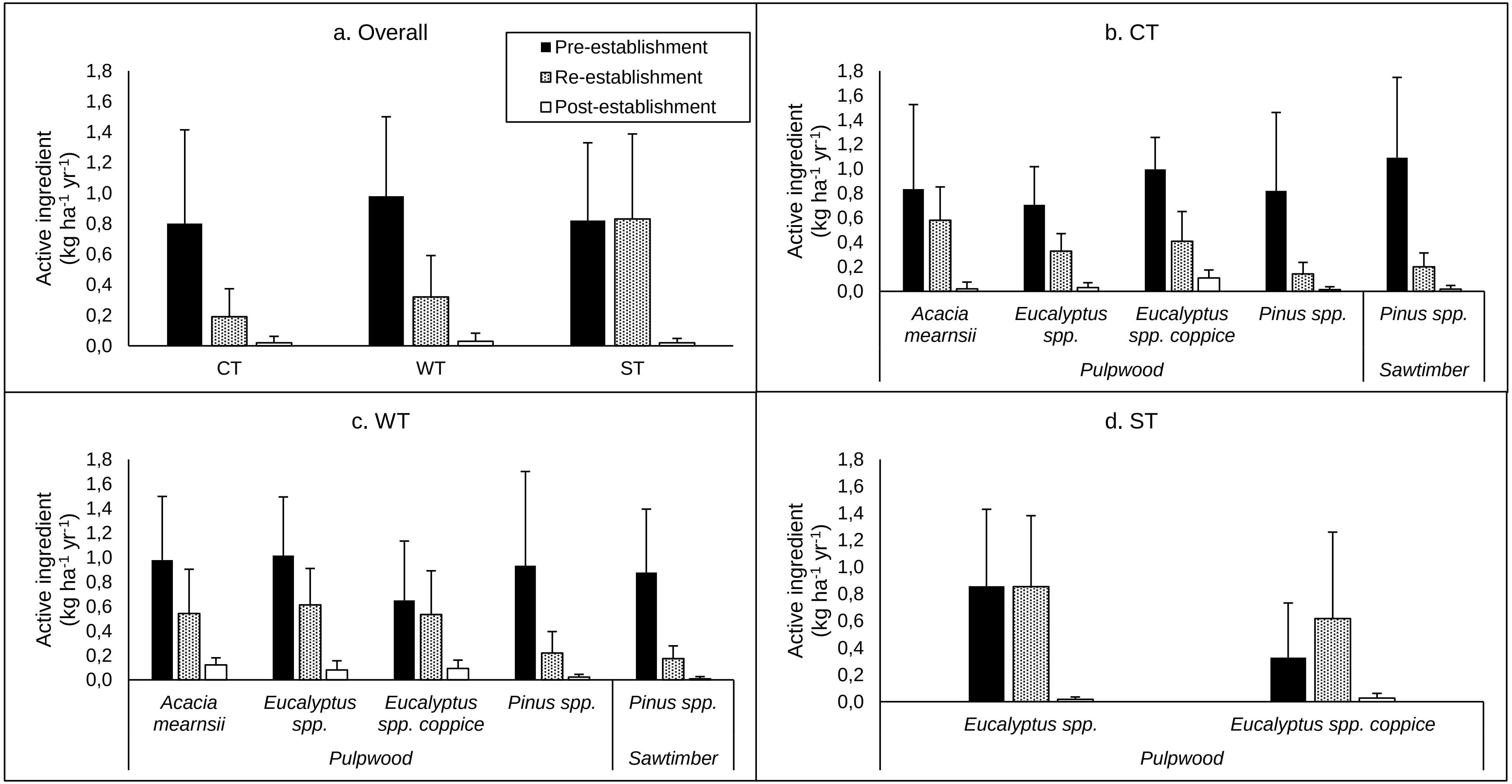
Scenario number	Genera	Product produced	Treatment period					
			Pre-establishment		Re-establishment		Post-establishment	
			a.i. ha^{-1} (kg)	a.i. ha^{-1} yr^{-1} (kg)	a.i. ha^{-1} (kg)	a.i. ha^{-1} yr^{-1} (kg)	a.i. ha^{-1} (kg)	a.i. ha^{-1} yr^{-1} (kg)
Cool temperate								
1	wattle	pulpwood	0.83	0.83	1.74	0.58	0.08	0.02
2	eucalypts	pulpwood	0.73	0.73	0.66	0.33	0.22	0.03
3	eucalypt coppice	pulpwood	1.00	1.00	0.82	0.41	0.77	0.11
4	pines	pulpwood	0.82	0.82	0.57	0.14	0.18	0.01
5	pines	sawn timber	1.09	1.09	1.20	0.20	0.46	0.02
	CT: Average (Total)		**0.80 (4.47)**	**0.80 (4.47)**	**0.65 (4.98)**	**0.19 (1.37)**	**0.27 (1.70)**	**0.02 (0.19)**
Warm temperate								
6	wattle	pulpwood	0.98	0.98	1.08	0.54	0.49	0.12
7	eucalypts	pulpwood	1.01	1.01	0.92	0.61	0.53	0.08
8	eucalypt coppice	pulpwood	0.65	0.65	0.80	0.53	0.61	0.09
9	pines	pulpwood	0.93	0.93	0.87	0.22	0.32	0.02
10	pines	sawn timber	0.88	0.88	0.87	0.17	0.18	0.01
	WT: Average (Total)		**0.98 (4.45)**	**0.98 (4.45)**	**0.91 (4.55)**	**0.32 (1.72)**	**0.40 (2.12)**	**0.03 (0.33)**
Sub-tropical								
11	eucalypts	pulpwood	0.86	0.86	0.85	0.85	0.13	0.02
12	eucalypt coppice	pulpwood	0.33	0.33	0.62	0.62	0.19	0.03
	ST: Average (Total)		**0.82 (1.19)**	**0.82 (1.19)**	**0.83 (1.47)**	**0.83 (1.47)**	**0.14 (0.32)**	**0.02 (0.04)**

ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

2.3.3. *Standardised herbicide use (kg a.i. ha^{-1} yr^{-1})*

Climate zones

Overall the quantity of herbicide applied was highest in the ST climate zone, followed by the WT and CT climate zones (0.56, 0.44, and 0.34 kg a.i. ha^{-1} yr^{-1} respectively). For both CT and WT climate zones, more kg of a.i. was applied ha^{-1} yr^{-1} within the pre-establishment phase (range = 0.73-1.09 kg a.i. ha^{-1} yr^{-1}; $\bar{x}$ = 0.89 kg a.i. ha^{-1} yr^{-1}; sd = 0.14), followed with the re-establishment phase (range = 0.17-0.61 kg a.i. ha^{-1} yr^{-1}; $\bar{x}$ = 0.31 kg a.i. ha^{-1} yr^{-1}; sd = 0.16), with the smallest quantity of a.i. kg applied within the post-establishment phase (range = 0.01-0.12; $\bar{x}$ = 0.05 kg a.i. ha^{-1} yr^{-1}; sd = 0.04) (**Table 2.5 and Figure 2.3**). For the ST climate zone, there was little difference in kg a.i. applied ha^{-1} yr^{-1} between the pre- and re-establishment phases (pre-establishment: $\bar{x}$ = 0.82 kg a.i. ha^{-1} yr^{-1}; re-establishment: $\bar{x}$ = 0.83 kg a.i. ha^{-1} yr^{-1}) with the post-establishment phase being noticeably less ($\bar{x}$ = 0.02 kg a.i. ha^{-1} yr^{-1}). In addition, more kg a.i. ha^{-1} yr^{-1} were applied within the ST climate zone during the re-establishment phase compared to both CT and WT climate zones (0.83 kg a.i. ha^{-1} yr^{-1} in ST as opposed to 0.19 kg a.i. ha^{-1} yr^{-1} in CT and 0.32 kg a.i. ha^{-1} yr^{-1} in WT).



ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

Figure 2.3. Herbicide active ingredient applied over one year according to vegetation management phases within three climate zones (CT, WT and ST) during 2017-2018 for commercial timber plantations within South Africa. Bars in figure indicate standard deviation.

Genera grown

For all genera and end-products excluding eucalypt coppice in the ST climate zone (**Table 2.1: scenario 12**), the same trend was observed with more kg a.i. applied ha^{-1} annually within the pre-establishment phase, followed by the re-establishment phase, with less applied in the post-establishment phase (**Table 2.5 and Figures 2.3b, 2.3c**). Within the ST climate zone, eucalypt coppice received more kg a.i. ha^{-1} yr^{-1} within the re-establishment phase (0.62 kg a.i. ha^{-1} yr^{-1}) than the pre-establishment phase (0.33 kg a.i. ha^{-1} yr^{-1}). Whereas, little difference existed between the pre- and re-establishment phase for planted eucalypts grown in the same climate zone (0.86 kg a.i. ha^{-1} yr^{-1} and 0.85 kg a.i. ha^{-1} yr^{-1} respectively). This trend was similar to eucalypt coppice grown in the WT climate zone (pre-establishment = 0.65 kg a.i. ha^{-1} yr^{-1}; re-establishment = 0.53 kg a.i. ha^{-1} yr^{-1}). The other notable difference was that pines grown for pulpwood and sawn timber within the CT and WT climate zones received the least amount of kg a.i. ha^{-1} yr^{-1} compared to all the other genera grown during the re- and post-establishment phase, due to the extended re-establishment period for this genus relative to eucalypts and wattle (**Table 2.1, Figures 2.3b, 2.3c**).

2.3.4. Method of herbicide application

During the herbicide survey period, herbicides were applied manually using knapsacks sprayers by all of the companies except one, where herbicides were also applied using tractor boom sprayers. All herbicide applications within the pre-establishment phase were applied as a single broadcast spray, irrespective of genera grown or climate zone. For the re-establishment phase, a combination of broadcast and/or inter-tree row spraying were scheduled annually with ca. 2-3 spraying events for CT, ca. 4 spraying events for WT and ca. 5 spraying events for ST. During the post-establishment phase (or once the trees achieve crown closure), most herbicide applications were applied as a spot spray irrespective of climate zone or genera planted.

2.3.5. Herbicides applied within the commercial stands

Glyphosate-based products were the most commonly used herbicide across the various scenarios surveyed, accounting for a total of 183 386 kg of a.i. (or 97% relative to total quantity of 188 288 kg a.i.) applied over 296 819 ha (or 86% relative to total surveyed area of 343 784 ha) (**Table 2.6**). This equates to an overall rate of application of 0.62 kg of glyphosate a.i. ha^{-1}.

Glyphosate isopropylamine salt (360 g a.i. kg^{-1}) was the most frequently used glyphosate formulation, with 152 592 kg of a.i. (or 81% relative to total quantity applied) applied over 263 331 ha (77% of total area surveyed) followed by the glyphosate sodium salt (700 g a.i. kg^{-1}) at 19 820 kg a.i. (11% of total quantity applied) (**Table 2.6**). Both glyphosate ammonium salt (200 g a.i. kg^{-1}) and glyphosate potassium salt (540 g a.i. kg^{-1}) accounted for a combined 6% of the herbicide applied. Metazachlor (500 g a.i. kg^{-1}) and triclopyr butoxy ethyl ester (270 g a.i. kg^{-1}) accounted for 2% of the total amount of herbicide applied. The remaining herbicide products used within the industry accounted for less than 1% and are not discussed further (**Table 2.6**).

Table 2.6. Total active ingredient applied in the area surveyed over 2017-2018 within the commercial forestry industry in South Africa. Also shown is the total active ingredient (a.i.) applied and derived rates per hectare.

Active ingredient	Area (ha)	Quantity a.i. applied (kg)	Actual a.i. ha^{-1} (kg)	Area Relative to total area (%)	Quantity Relative to total quantity applied (%)
clethodim	910	190	0.21	0	0
clopyralid	3 674	714	0.19	1	0
cycloxydim	201	9	0.05	0	0
fluroxypyr meptyl ester	3 520	224	0.06	1	0
glufosinate ammonium	475	147	0.31	0	0
glyphosate ammonium salt	7 706	4 713	0.61	2	3
glyphosate dimethylamine salt	286	328	1.15	0	0
glyphosate isopropylamine salt	263 331	152 592	0.58	77	81
glyphosate potassium salt	7 085	5933	0.84	2	3
glyphosate sodium salt	18 412	19 820	1.08	5	11
Glyphosate: Average (Total)	**296 819**	**183 386**	**0.62 (4.26)**		
imazapyr	44	5	0.11	0	0
imazapyr isopropylamine salt	6 058	166	0.03	2	0
Imazapyr: Average (Total)	**6 102**	**171**	**0.03 (0.14)**		
metazachlor	3 333	1 491	0.45	1	1
metsulfuron-methyl	726	100	0.14	0	0
triclopyr butoxy ethyl ester	18 074	1 426	0.08	5	1
triclopyr triethylamine salt	9 950	432	0.04	3	0
Triclopyr: Average (Total)	**28 024**	**1 858**	**0.07 (0.12)**		
Grand Total	**343 784**	**188 288**	**0.55**	**100**	**100**

2.3.6. *Most used herbicides: glyphosate, metazachlor and triclopyr*

During the pre-establishment phase, 33 640 kg a.i. (or 18% relative to total quantity) of the glyphosate-based products was applied on 35 879 ha (or 10% relative to total area) (**Table 2.7**). This equates to an average herbicide use of 1.10 kg a.i. ha^{-1} annually within the pre-establishment phase. Even though both metazachlor and triclopyr were also used during the re-establishment phase, the overall quantities applied were relatively small (218 and 120 kg a.i. in total) (**Table 2.7**). The re-establishment phase received the highest quantity of herbicides with most of the glyphosate-based and metazachlor products applied during this phase (**Table 2.7**). Within the post-establishment phase, 25 782 kg a.i. (0.07 kg a.i. ha^{-1} yr^{-1}) of glyphosate-based herbicide was applied on 109 539 ha while 1 231 kg of triclopyr a.i. was applied on 21 460 ha (0.01 kg a.i. ha^{-1} yr^{-1}) (**Table 2.7**). Even though metazachlor was also used during this period, the quantity applied was relatively small with only 32 kg a.i. applied on 63 ha equating to a rate of application of 0.01 kg a.i. ha^{-1} yr^{-1}.

2.3.7. *Estimated amount of a.i. glyphosate, metazachlor and triclopyr used within the forestry industry*

Using the areas that were under timber production in 2018 using the most current data available regarding timber growing areas in SA (**FSA 2020**), the herbicide data obtained from the areas surveyed were proportionally adjusted to reflect actual areas under timber production (**Tables 2.2 and 2.8**). This allowed the estimation of annual total herbicide used (**Table 2.9**), which could be used to compare with other primary sectors in SA (e.g. agriculture), as well as other forest growing regions in the world (where data is available). To calculate the estimated total kg of herbicide a.i. applied annually for each of the three most used herbicides identified from the survey (**Table 2.6**), the total area sampled for each of these herbicides was adjusted to reflect their use across the total forestry area (1 191 638 ha) within SA. These adjusted areas for the three most used herbicides were then multiplied by the estimated annual quantity of kg a.i. applied for each herbicide across the three vegetation management phases within commercial forestry.

In total, 374 tonnes of a.i. was estimated to be applied annually, with most of this applied during the re-establishment phase (240 tonnes), followed by the pre-establishment (96 tonnes), and lastly the post-establishment phase (37 tonnes) (**Table**

2.9). Of the three herbicides, 370 tonnes of glyphosate a.i. was applied annually, with 4 tonnes of a.i. applied annually for metazachlor and triclopyr respectively.

2.3.8. Data validation

For validating the outcomes of this study, additional compartmental data from 2008 to 2018 for 5 main scenarios were obtained (namely eucalypt and pine pulpwood for CT, WT, and eucalypts for ST), and compared to the herbicide use data obtained over the survey period. Compartments were selected for each of the 5 key scenarios which had information on herbicide use from 2008 to 2018, with the overall rate of application per hectare calculated on an annual basis and compared to the 2017 to 2018 data set. For these 5 scenarios, there was a mean overall discrepancy of 0.09 kg a.i. ha^{-1}, indicating the data collected from the survey were representative of actual herbicide use (eucalypt: CT = - 0.06 kg a.i. ha^{-1}; WT = - 0.09 kg a.i. ha^{-1}; ST = - 0.03 kg a.i. ha^{-1}; pine: CT = - 0.09 kg a.i. ha^{-1}; WT = - 0.18 kg a.i. ha^{-1}).

Table 2.7. Actual glyphosate, metazachlor and triclopyr applied in the area surveyed over 2017-2018 within the commercial forestry industry in South Africa. Also shown is the total active ingredient (a.i.) applied and derived rate per hectare.

Active ingredient	Area (ha)	Quantity a.i. applied (kg)	Pre-establishment (-1 - 0yrs)			Re-establishment (0 - 6 yrs)			Post-establishment (7 - 35 yrs)		
			Area (ha)	Quantity a.i. applied (kg)	a.i. ha^{-1} yr^{-1} (kg)	Area (ha)	Quantity a.i. applied (kg)	a.i. ha^{-1} yr^{-1} (kg)	Area (ha)	Quantity a.i. applied (kg)	a.i. ha^{-1} yr^{-1} (kg)
glyphosate	296 819	183 386	35 879	33 640	1.10	151 401	123 964	0.53	109 539	25 782	0.07
metazachlor	3 333	1 491	464	120	0.25	2 806	1 339	0.20	63	32	0.07
triclopyr	28 024	1 858	1 008	218	0.20	5 556	409	0.04	21 460	1 231	0.01
Total	328 176	186 735	37 351	33 978		159 763	125 712		131 062	27 045	

Table 2.8. Adjusted areas based on glyphosate, metazachlor and triclopyr applied during 2017-2018 within the surveyed commercial timber plantations in South Africa.

Three distinct phases	FSA areas during 2017/2018	Adjusted areas[1] (ha)		
		glyphosate	metazachlor	triclopyr
Pre-establishment (TUP)	90 767	87 136 (96%)	908 (1%)	2 723 (3%)
Re-establishment (0-6 yrs)	472 306	448 691 (95%)	9 446 (2%)	14 169 (3%)
Post-establishment (7-35 yrs)	628 565	527 995 (84%)	-	100 570 (16%)

[1]Area as a percentage of total land area that received glyphosate, metazachlor and triclopyr

Table 2.9. Estimated glyphosate, metazachlor and triclopyr use across the vegetation management phases within commercial timber plantations in South Africa.

Active ingredient	Pre-establishment (TUP)			Re-establishment (0-6 yrs)			Post-establishment (7-35 yrs)		
	Adjusted areas (ha)	a.i. ha^{-1} yr^{-1} (kg)	Total a.i. applied (kg yr^{-1})	Adjusted areas (ha)	a.i. ha^{-1} yr^{-1} (kg)	Total a.i. applied (kg yr^{-1})	Adjusted areas (ha)	a.i. ha^{-1} yr^{-1} (kg)	Total a.i. applied (kg yr^{-1})
glyphosate	87 136	1.1	95 850	448 691	0.53	237 806	527 995	0.07	36 960
metazachlor	908	0.25	227	9 446	0.2	1 889	-	-	-
triclopyr	2 723	0.2	545	14 169	0.04	567	100 570	0.01	1 006
Total	90 767		96 621	472 306		240 262	628 565		37 965

2.4. Discussion

The amount of herbicide applied (rates and volumes) was largely a function of the interaction of site productivity (linked to climate zone), vegetation management phase and genus planted (pines versus eucalypts) (**Table 2.5 and Figure 2.3**).

As site productivity increases (CT<WT<ST), the need for vegetation management becomes more apparent, in that plant growth (both planted trees and competing vegetation) is greater on more productive sites (**Little et al. 2007; Little and Rolando 2001, 2008)**. Even though the duration of vegetation management in the re-establishment phase is longer for all genera planted within the CT climate zone (**Table 2.1**), fewer vegetation management operations are required due to the reduced rate of growth of competing vegetation (**Jarvel and Pallett 2002; Little and Rolando 2001, 2008; Rolando and Little 2009)**. In addition to this reduced vegetation growth, vegetation management operations tend to include more targeted spot spraying, resulting in a lower dependence on herbicides annually when compared to WT and ST climate zones.

In contrast, competing vegetation growth and hence vegetation management operations in both the WT and ST climate zones were more frequent, with herbicides applied mostly as a directed broadcast or inter-tree row applications. Due to higher mean annual temperatures and all-year-round growing conditions (**Schulze 1997**; **Little and Rolando 2008**), more vigorous competition occurs in the ST than the WT climate zone, which generally requires more kg of herbicide a.i. ha^{-1} yr^{-1} (**Table 2.5**). Even though the vegetation management duration is the shortest within the ST climate zone (ca. 12 months to reach canopy closure), vegetation management operations tend to be more frequent.

The eradication of competing vegetation prior to planting (pre-establishment phase) allows for the cost-effective broadcast application of non-selective herbicides without the need to protect planted trees (**Little and Rolando 2008; Rolando and Little 2009**). Controlling competing vegetation (particularly perennial broadleaves or woody vegetation) becomes more difficult once these vegetation types become established, often exacerbated by a delay in tree planting. As a result, the pre-establishment phase is considered an important phase within forestry, with the highest quantity of kg herbicide a.i. (ca. 0.86 kg a.i. ha^{-1}) applied annually during this phase. Within this phase, most stands would receive a broadcast application of glyphosate, usually at a high rate of application (ca. 3 kg ha^{-1} formulated product or ca. 1.1 kg a.i.

ha^{-1} yr^{-1}), irrespective of site productivity and/or genera grown, to ensure that the trees are planted into sites that are free of competing vegetation (**Richardson 1993; Little and Rolando 2008; Rolando and Little 2009; Weatherford et al. 2015**). Metazachlor was also applied as a pre-emergent herbicide on some sites during this for the control of annual grasses and broadleaves (ca.0.4 kg ha^{-1} formulated product or ca.0.2 kg a.i. ha^{-1} yr^{-1}).

In terms of tree performance, the re-establishment phase is the stage when planted trees can be most impacted by competing vegetation **(Richardson 1993; Wagner et al. 1996, 2006; Little and van Staden 2005; Little et al. 2007, 2018a**). Any competition to the planted trees will result in reduced growth and mortality if competition is severe. Due to most sites receiving some form of pre-plant treatment (pre-plant burning, mulching, ripping or broadcast application of glyphosate, the resulting vegetation would likely re-establish from seeds (and not from existing root stock) (**Little and Rolando 2008; Rolando and Little 2009; du Toit et al. 2010**). Consequently, the quantity of glyphosate applied during this phase is lower than that during the pre-establishment phase (ca.1.5 kg ha^{-1} formulated product or ca.0.53 kg a.i. ha^{-1} yr^{-1}) as most competing vegetation (generally annual or perennial vegetation) are controlled whilst they are still young and establishing (and when conditions allow). In addition, forest companies make use of other means of controlling vegetation such as manual slashing, mechanical discing and/or planting of cover-crops.

Once the planted trees become dominant on the site, competing vegetation have no to little impact on the growth of these trees, with intra-specific competition between trees having more impacts than the inter-specific competition between surrounding vegetation and trees (**Little and Rolando 2002; Little et al. 2018a**). Although the age at which this occurs differs across climate zones and genera grown (**Table 2.1**), the higher planting densities (1 111-1 666 ha^{-1}) used in SA in combination with rapid early growth allows the planted trees to competitively exclude nearly all other vegetation through shading following canopy closure (**Little and Rolando 2002; Wagner et al. 2006; Little et al. 2006, 2007**). Due to the reduced presence of competing vegetation during this phase, vegetation management operations specifically target woody/alien vegetation (which is also shade tolerant), resulting in low quantities of herbicides (triclopyr and glyphosate) used throughout the different climate zones and scenarios. Glyphosate is applied as a broadcast (seldom) or directed spot application (more often) at ca. 0.2 kg ha^{-1} formulated product (or ca. 0.06

kg a.i. ha^{-1} yr^{-1}) depending on vegetation species, with triclopyr used either as a spot, basal bark or cut-surface application (ca. 0.03 kg ha^{-1} formulated product or ca. 0.01 kg a.i. ha^{-1} yr^{-1}) to treat specific difficult-to-kill vegetation such as *Rubus cuneifolius* Pursh (bramble) and/or *Solanum mauritianum* Scopoli (Solanaceae) (bugweed) (**Denny and Golob 1991; Little and Rolando 2002; Little and Moodley 2006; Little 2007, 2008; Willoughby et al. 2013**).

Even though some genera are exposed to vegetation competition for longer (for example pines in CT), it was interesting to note that similar amounts of herbicides were used for most of the genera grown, the exception being planted or coppiced eucalypts within the ST climate zone (**Table 2.5 and Figure 2.3**). For these two scenarios, more kg herbicide a.i. (kg a.i. ha^{-1}) was applied annually during the re-establishment phase than for all the other scenarios (**Figure 2.3d**). For planted eucalypts, the vigorous growth of competing vegetation required more frequent vegetation management operations within the first-year of tree growth, after which canopy closure would reduce the need to control competing vegetation. In contrast, coppice shoots emerge from buds situated within the live bark or cambium at the base of the well-established stumps soon after the trees are felled **(Florence 1996)**. The rapid initial growth of the coppice shoots, combined with deeper existing roots and the limited presence of vegetation following felling all contribute to the lack of weed-coppice competition (**Little and du Toit 2003; Wagner et al. 2006; Little 2007; Roberts et al. 2016; Rolando et al. 2017**). For this reason, coppiced stands seldom received a broadcast application of glyphosate following felling. However, in SA glyphosate is used to manage secondary coppice regrowth following reduction operations (where the stems are selectively thinned leaving 1-2 live coppice shoots per stump), with up to four operations (recommended rate of application glyphosate (360 g a.i. kg^{-1}) at 1.2 % spraying solution) scheduled within the first two years following felling (**Roberts et al. 2016**).

In 2012, the Department of Agricultural Economics, Extension and Rural Development of the University of Pretoria conducted a study to assess the value of glyphosate in the South African agricultural sector with a focus on the 2012/13 agricultural season. During 2012/13, ca. 23 million litres was sold at an estimated value of ZAR641 million, with the main users of glyphosate being maize (46%), wheat (13%) and soybean (6%) farmers, accounting for 65% of all glyphosate use. Forestry use in this study was estimated at 4% (or ca. 1 million litres) of the 23 million litres sold. As there were differences in the units of measure (litres versus kg) and year of data collection (2012/13 versus 2017/18), a direct comparison between the above report and data in the current study is not possible. However, based on the 2017/18 forestry herbicide survey, an estimated 374 tonnes of glyphosate a.i. is applied annually to an area of approximately 1 191 638 ha, with 240 tonnes applied during the re-establishment phase, 96 tonnes during the pre-establishment phase, and the least during the post-establishment phase (37 tonnes) (**Table 2.9**).

Glyphosate is generally the most commonly used herbicide for the control of competing vegetation in planted forests, not only in SA but internationally (**Gouse 2014; Rolando et al. 2017)**. For example, Canada (ca. 275 tonnes yr^{-1}), Australia (ca. 200-250 tonnes yr^{-1}), Chile (ca. 200-295 tonnes yr^{-1}), USA (ca. 185 tonnes yr^{-1}) and New Zealand (ca. 175 tonnes yr^{-1}) all use glyphosate (in addition to other products) for the control of competing vegetation (**NFD 2015; Weatherford et al. 2015; Rolando et al. 2017**). In New Zealand, an estimated 447 tonnes of herbicide a.i. were applied annually within planted forests in 2012, with glyphosate accounting for 39% (or 175 tonnes) of this total (**Rolando et al. 2013**). This equated to a rate of herbicide a.i. application of 0.25 kg ha^{-1} yr^{-1} across the New Zealand forest sector. Even though more glyphosate is applied annually in SA, the rate of application of all herbicides kg a.i. ha^{-1} yr^{-1} was similar. In New Zealand and USA, glyphosate is aerially applied as a pre-plant spray (3.0-3.5 and 1.0-3.0 kg a.i. ha^{-1} respectively) (**Weatherford et al. 2015; Rolando et al. 2017**), whereas in SA and Chile, glyphosate is used throughout the rotation as a ground-based application at 0.66 and 2.0-2.5 kg a.i. ha^{-1} respectively. As glyphosate is a highly effective broad-spectrum herbicide it is used worldwide, at both relatively low frequencies and rates of applications, throughout the growth of commercial forestry trees, to ensure competition from weeds is kept to a minimum.

2.5. Conclusions

This survey was undertaken in 2017/18 to provide up-to-date data on herbicide use in South Africa, specifically within plantation forestry.

Over the survey period, 188 288 kg of herbicide a.i. was applied over 343 784 ha, which equates to an average rate of application of 0.55 kg a.i. ha^{-1}. Overall herbicide use (a.i. kg ha^{-1} yr^{-1}) was highest in the ST climate zone, followed by the WT and CT climate zones. For both the CT and WT climate zones, more kg a.i. was applied ha^{-1} yr^{-1} during the pre-establishment phase, followed by the re-establishment phase, with the smallest quantity of kg a.i. applied during the post-establishment phase. For the ST climate zone, there was little difference in herbicide a.i. use ha^{-1} yr^{-1} between the pre- and re-establishment phases with use during the post-establishment phase being noticeably less. Similar amounts of herbicides were used for most of the genera grown, the exception being in planted or coppiced eucalypt stands within the ST climate zone. For these two scenarios, more kg herbicide a.i. was applied annually during the re-establishment phase than for all the other genera grown.

Glyphosate-based products accounted for 97% of all the herbicides applied during the 2017-2018 data collection period, with metazachlor and triclopyr butoxy ethyl ester accounting for 2%. Of the three vegetation management phases, the re-establishment phase received the highest number of herbicide applications across the three climate zones, with glyphosate-based products the most common herbicide. Both the pre- and post-establishment phase received similar quantities of glyphosate, while triclopyr was applied mostly during the post-establishment phase.

The herbicide information obtained from the survey could be used to benchmark future herbicide use studies within commercial forestry in South Africa, highlight areas where herbicide use can potentially be reduced, to determine appropriate research and management policies, and to help maintain consumer and market confidence. As a result, future research could investigate alternative vegetation management methods, specifically focusing during the pre- and re-establishment phase as these phases receive the most herbicides.

CHAPTER 3. LINKING EUCALYPT ROTATION END DATA TO VEGETATION MANAGEMENT TREATMENTS AND HERBICIDE USE: RESULTS FROM 7 PULPWOOD TRIALS, SOUTH AFRICA

3.1. Introduction

Forest vegetation management, generally directed at reducing competition for site resources (light, soil water and soil nutrients) between desired trees and associated plants (or competing vegetation), is an integral part of successful silviculture (**Wagner et al. 2006**). According to **Ashton and Monaco (1991)**, the three fundamental objectives of any pest (defined as insect, pathogen or weed) management programme include prevention, eradication where feasible, or the management of the pest where prevention or eradication are not possible. As the eradication of weeds (or competitive vegetation) is seldom possible, the competitive vegetation is therefore managed within commercial plantations in SA on a site-specific basis to, or below a predetermined threshold to ensure optimum tree performance (**Little and Rolando 2008; Rolando and Little 2009**).

Vegetation management is practiced throughout the development of a forest stand and provides one of the best opportunities to ensure that stands of the desired species composition and structure develop within an economically feasible period (**Wagner et al. 2006**). Within SA, the management of vegetation is divided into three distinct phases (pre-establishment phase between harvesting and re-planting; re-establishment phase between planting and canopy closure; and post-establishment phase between canopy closure and harvesting), all of which have a direct influence on the type and intensity of vegetation management operations carried out (**Little et al. 2006; Little and Rolando 2008; Rolando and Little 2009; Little et al. 2018b**). The intensity of vegetation management is linked to the three broad climatic zones within which plantations are grown in SA (**Little and Rolando 2008; Rolando and Little 2009; Louw et al. 2011)**. These three climatic zones are: cool temperate (CT): mean annual temperatures (MAT) <16°C with snow and frost risk across the landscape; warm temperate (WT): MAT 16-19°C with frost risk confined to low-lying areas only; and sub-tropical (ST): MAT >19°C which is frost-free. Due to increased vegetation growth on the more productive sub-tropical sites compared to moderately productive WT sites, vegetation management operations are also more frequent, whereas less frequent on cool temperate sites (lower productivity) with the lowest vegetation growth (CT<WT<ST) (**Smith et al. 2005a, 2005b**; **Louw et al. 2011**; **Roberts et al. 2021**).

Various vegetation management methods or approaches, mostly labour intensive, are used within SA and include, but are not limited to, (**Zutter et al. 1987; Little et al. 2006; Wagner et al. 2006; Roberts et al. 2018; Ndlovo et al. 2019**):

(i) physical and/or mechanical removal of non-crop vegetation such as prescribed burning, agricultural hoes, bush-knifes (slashing), or tractor drawn implements such as discing (within the interrow);

(ii) herbicide application using knapsacks (and to a lesser extent tractors with spray booms) to either the foliage of herbaceous weeds, or the basal stem or cambium layer of woody weeds;

(iii) cultural control methods that incorporate practices common to good land management such as manipulation of planting density (planting at higher density to achieve earlier canopy closure to shade out possible weeds), retention of slash to supress weed germination and development;

(iv) maintenance of critical 'weed free' periods (re-establishment phase);

(v) the use of cover cropping (suppressing weeds through planting of a desirable cover crop in areas which are open to invasion).

Even though a combination of appropriate methods for the integrated management of vegetation is always preferred, over the past five decades, the effectiveness and relatively low cost of herbicides (**Little et al. 2006; Wagner et al. 2006**), has led to the dependence on their continued availability to the near exclusion of most non-herbicide methods to ensure optimum tree growth, especially in SA (**Little et al. 2006; Wagner et al. 2006; Willoughby et al. 2009; Baillie 2016; Rolando et al. 2017**).

In SA, the herbicides used and the manner in which they are applied in commercial forests is regulated through a combination of government legislation, third party certification and operational cost-effectiveness, with any pesticide application forming part of a planned operation to achieve a specific management goal (**Little 2014; FSA 2020; FSC 2020**). Based on an industry herbicide survey carried out in 2018, herbicides within commercial plantations are applied at low rates of application (0.55 kg ha^{-1} herbicide active ingredient over the whole rotation) (**Chapter 2**). Regardless, low rates of persistent active ingredients may move either in surface flow, or leach through the soil profile and thereby accumulate within watersheds or catchments (referred to as off-site impacts) (**Tulagi 2014; Baillie and Neary 2015; Baillie 2016**). The potential for off-site movement of herbicides, together with global pressure to reduce or eliminate herbicides and increasing public aversion to herbicide use in forests mean that the continued dependence on herbicides alone is no longer viable (**Little et al. 2006; Baillie 2016; PEFC 2020; FSC 2020**).

Although alternative methods to herbicide weed management practices exist in SA, as well as methods that result in a reduction in herbicide use (without compromising tree growth) (**Little 1999, 2008; Little et al. 2002; Little and Dyer 2002; Fuller and Little 2007**), many of these practices have not always been adopted commercially. This includes practices such as: reducing the area treated (spot or row spraying), reducing frequency of weeding operations (based on stand age and climate class), the targeted control of the more competitive vegetation types, the development of standards for cover-cropping, the adjustment of weed control standards according to site productivity and improving the efficiency of herbicides through use of adjuvants (**Eccles and Little 1995; Little and Schumann 1996; Little and Rolando 2001; Tu et al. 2001; Little et al. 2002; Little et al. 2006; Little 2014**). Although several papers and conference proceedings highlighting these research results have been produced and can be considered successful from a research perspective, not all are applied commercially, or when they are applied, it is by default rather than by design (**Little and Dyer 2002**).

Even though the beneficial impacts of vegetation management are well documented within the SA forestry industry, there is a lack of a systematic and holistic approach in terms of an integrated risk assessment that links quantities of herbicide used with rotation-end financial benefits. An integrated risk assessment is defined as a science-based approach that combines different risk estimation in one assessment (**Bontje et al. 2004**). Integrated risk assessments identify multiple risks at any given time, which improves decision-making efficiency in terms of sustainable forest management (**Girdžiūtėa 2012**).

To meet this need, tree growth data from seven eucalypt vegetation management trials were used to link vegetation management treatments (including quantity and type of herbicide used) with rotation end tree growth responses. The data were also used to develop an herbicide risk assessment (decision support) system for the selection of appropriate vegetation management options when establishing eucalypts in South Africa.

3.2. Materials and methods used for eucalypt trials

Of the vegetation management trials that were implemented in eucalypts in SA since the early 1990's, seven were selected that occurred across diverse sites in the summer rainfall regions of SA (KwaZulu-Natal or Mpumalanga Provinces), with rotation end data ranging from 6-10 years depending on species planted and site productivity (**Table 3.1**). The tree growth data used for this study were based on previously reported studies (**Table 3.2**) implemented and managed by the Institute for Commercial Forestry Research, Pietermaritzburg, South Africa. All seven trials were implemented on regimes designed to produce timber for pulp, with species planted at different densities (ranging from 1 333-2 079 stems per hectare (sph)) and matched to the various sites based on their suitability to climate and susceptibility to abiotic and biotic risk factors (**Swain and Gardner 2003; Smith et al. 2005b**). These trials also covered a range of altitudinal (45-1 469 m above sea level (a.s.l.)), climatic (sub-tropical (ST), warm (WT) and cool temperate (CT)) and productivity gradients.

Table 3.1. Site characteristics for seven vegetation management trials implemented on eucalypts in the summer rainfall region of South Africa.

Site characteristics	Trial names						
	Fairbreeze	**Oaklands**	**KT**	**Mountain Home**	**Enon**	**Tweefontein**	**Draycott**
Magisterial District	Lower Umfolozi	Lower Umfolozi	Lower Umfolozi	Umvoti	Richmond	Umvoti	Estcourt
Latitude **Longitude**	28° 59.973′ S 31° 42.826′ E	28° 35.461′ S 32° 05.243′ E	28° 36.700′ S 32° 07.927′ E	29°33.939′ S 30° 16.994′ E	29° 49.277′ S 30° 14.628′ E	29° 04.524′ S 29° 36.875′ E	29° 04.524′ S 29° 36.875′ E
Altitude (m a.s.l.)	45	87	90	1 130	1 262	1 590	1 469
Mean annual rainfall (mm)	1 144	1 018	1 015	1 062	1 049	816	799
Mean annual temperature (°C)	22.0	21.6	21.5	16.3	16.1	13.4	15.2
[1]**Climate class**	Sub-tropical	Sub-tropical	Sub-tropical	Warm temperate	Warm temperate	Cool temperate	Cool temperate
Species planted	*Eucalyptus grandis* x *E. camaldulensis*	*E. grandis* x *E. camaldulensis*	*Eucalyptus grandis* W. Hill ex Maiden.	*Eucalyptus dunnii* Maiden.	*Eucalyptus smithii* R.T. Baker.	*Eucalyptus macarthurii* H.Deane & Maiden.	*Eucalyptus nitens* Maiden.
Date planted	22/10/1990	06/07/1995	01/08/2003	04/09/1997	24/11/2003	07/01/1999	29/01/1999
Date felled	18/10/1997	14/08/2002	21/05/2009	19/01/2007	23/11/2012	26/04/2007	03/04/2007
Age felled	2 553 d 7 y	2 596 d 7.1 y	2 787 d 7.6 y	3 424 d 9.4 y	3 287 d 9 y	3 031 d 8.3 y	2 986 d 8.2 y
Spacing (planting density)	2.5 x 3 m (1 333 sph)	2.5 x 3 m (1 333 sph)	2.7 x 2 m (1 852 sph) 2.7 x 2.5 m (1481 sph)	3 x 2 m (1 666 sph)	3 x 2 m (1 666 sph)	3.17 x 1.52 m (2 079 sph)	3.11 x 2.06 m (1 563 sph)
Previous crop	sugarcane	*E. grandis* coppice	*E. grandis* coppice	*E. grandis* coppice	*Pinus patula* Schiede ex Schltdl. & Cham.	*E. macarthurii* coppice	*E. nitens*
Land use prior to the planting of trees	sugarcane	sugarcane	grassland	grassland	indigenous bush	grassland	grassland
Management of harvest residues	-	burnt/broadcast	burnt	burnt	broadcast	broadcast	broadcast
Dominate vegetation species within the weedy controls	*Cyperus esculentus* *Panicum maximum* (sedge + grass)	*Panicum maximum* (grass)	*Panicum maximum* (grass)	*Acacia mearnsii* *Solanum maritianum* (woody weeds)	*Cyperus esculentus* (sedge)	*Panicum maximum* (grass)	*Panicum maximum* (grass)
Vegetation biomass in tons ha^{-1} (days after planting biomass samples taken)	4.5 (120 dap)	20.6 (245 dap)	3 (99 dap)	14.6 (935 dap)[2]	2.9 (553 dap)	1.7 (383 dap)	0.9 (369 dap)
[1]**Potential productivity** – Growing conditions	Optimum	Optimum	Optimum	Optimum	Optimum	Optimum (snow risk)	Optimum (drought risk)
[1]**Potential productivity** – Site index (age 5)	21.5	20.0	25.0	22.0	19.5	15.5-16.5	15.0
[1]**Potential productivity** – Mean annual increment (m^3 ha^{-1} $annum^{-1}$) – Potential	43 (7 years)	35 (8 years)	45 (8 years)	36 (9 years)	40 (7 years)	14 (12 years)-18 (11 years)	20 (12 years)
[1]**Potential productivity** – Mean annual increment (m^3 ha^{-1} $annum^{-1}$) – Actual	32 (7 years)	40 (7.1 years)	48 (7.6 years)	28 (9.4 years)	46 (9 years)	26 (8.3 years)	29 (8.2 years)

[1]Data obtained from Smith et al. (2005b) and ICFR Trial research database
[2]Due to the lack of biomass data for this trial, data were obtained for a pine vegetation management trial with similar weeding treatments, planted at the same time and situated in the same compartment and adjacent to the eucalypt trial (Little and Rolando 2001)

Table 3.2. Trial design and trial means, standard errors (s.e.d) and coefficient of variations (CV) for key growth variates for seven vegetation management trials implemented on eucalypts in the summer rainfall region of South Africa.

	Trial Name	Trial design				Tree growth variates: Survival Stocking (sph)			Growth Volume (m^3 ha^{-1})			Uniformity CV Dbh (%)			Research publications based on trial data
		Design	Treatments (n)	Replications (n)	Total number of plots (n)	Grand mean (sph)	s.e.d (units)	CV (%)	Grand mean (m^3 ha^{-1})	s.e.d (units)	CV (%)	Grand mean (%)	s.e.d (units)	CV (%)	
1	Fairbreeze	RCBD	9	4	36	1 238	79.7	-	181.1	24.1	-	26.0	6.7	36.4	Little and van Staden (2003, 2005) and Little et al. (2002, 2003)
2	Oaklands	RCBD	7	4	28	1 004	76.5	10.8	240.6	15.3	9.0	16.3	3.5	30.0	Little (2003)
3	KT	2 x 4 Factorial	8	4	64	1 511	80.8	8.9	326.8	35.8	13.1	31.57	5.2	14.0	Fuller and Little (2007) and Light (2015)
4	Mountain Home	RCBD	8	4	32	1 579	71.3	6.4	220.4	22.3	14.3	30.7	5.7	26.1	Little (2008)
5	Enon	RCBD	5	4	20	1 347	102.3	12.4	374.1	27.8	11.5	29.0	2.5	22.5	Little et al. (2018b)
6	Tweefontein	2 x 2 x 2 Factorial	8	4	32	1 871	118.5	9.0	176.6	37.4	29.9	29.6	4.9	23.8	Little and Rolando (2008) and Little and van den Berg (2009)
7	Draycott	2 x 2 x 2 Factorial	8	4	32	1 414	62.1	6.2	200.7	23.3	23.2	30.0	4.5	21.0	Little and Rolando (2008) and Little and van den Berg (2009)

RCBD: randomized complete blocks design

3.2.1. *Vegetation management treatments implemented across the eucalypt field trials*

Dependent on trial objectives and site type, various vegetation management treatments were tested at each trial that differed in terms of management intensity (high, moderate, low and no vegetation control), area kept free of vegetation (row, inter-row or ring or spot centred on the tree), vegetation type controlled (grasses or broadleaves), and included additional practices to manage vegetation such as the use of cover-crops or increased planting density (**Tables 3.2 and 3.3**). The main post planting vegetation management treatments included:

- <u>Weedfree</u> (high weeding intensity)

The growth of the vegetation was closely monitored, with full vegetation control carried out whenever the vegetation reached ankle height. This type of control would ensure that any vegetation would remain at a sub-competitive level, thus providing an estimate of optimum tree growth for the prevailing conditions for the duration over which the trial was conducted.

- <u>Weedy</u> (no vegetation control)

No further vegetation control was carried out in this treatment following planting. This treatment was used to characterise the vegetation specific to the site, as well as the maximum potential loss of production (in terms of tree growth) in the presence of the competition.

- <u>Moderate weeding intensity</u> (Enon site only)

As for the weedfree, complete vegetation control was carried out but, where possible, there was a delay in the operations resulting in some degree of tree growth suppression.

- <u>Low weeding intensity</u> (Enon site only)

Full vegetation control operations in this treatment were delayed to coincide with every second operation that was carried out in the weedfree treatment. A higher degree of tree growth suppression was expected, together with an associated reduction in vegetation control costs and herbicide use.

Table 3.3. Treatments occurring within seven vegetation management trials implemented on eucalypts in the summer rainfall region of South Africa.

No.	*Trial Name	Weedfree (High weeding intensity)	Weedy	Moderate weeding intensity	Low weeding intensity	Row weeding	Ring weeding	Selective control		Cover crops		
								Grasses	Broadleaves	Sweet potato	Cowpea	Velvet bean
1	Fairbreeze	✓ (Manual) ✓ (Chemical)	✓			✓ (1.2 m) ✓ (Inter-row (1.2 m))	✓ (0.5 m) ✓ (-Ring weeding (0.5 m))				✓	✓
2	[1]Oaklands	✓	✓			✓ (2 m)		✓	✓			
3	[2]KT	✓	✓			✓ (1.8 m) ✓ (0.9 m)						
4	Mountain Home	✓	✓			✓ (2m) ✓ (1.2m) ✓ (Sweet potato (1.2 m))		✓	✓	✓		
5	Enon	✓	✓	✓	✓	✓ (2 m)						
6	[3]Tweefontein	✓	✓									
7	[3]Draycott	✓	✓									

*These trials had additional factorial combinations that could have an indirect influence on vegetation management
[1]Oaklands. Factorial combination of prescribe burning for weedfree and weedy treatments only. All other treatments remained unburnt
[2]KT. Factorial combination with vegetation management and two planting densities (1 852 versus 1 481 sph)
[3]Tweefontein and Draycott. Factorial combination with vegetation management, genetics (improved versus unimproved material) and fertilization

- Area weeded

(i) Row (line) weeding (0.9 m, 1.2 m, 1.8 m or 2 m): A row or line weeding treatment refers to complete control of the vegetation in the row centred on the planted tree line (width of the weeding, centred on the tree row). Different row weeding distance treatments were carried out at each trial (**Table 3.3**) whereby all vegetation within the specified row distance was controlled through the application of herbicides. A 1.2 m inter-row weeding treatment was also included in the Fairbreeze trial whereby competing vegetation was removed within the inter-row between the planted trees and left untreated within the tree row.

(ii) Ring (spot) weeding (0.5 m): Different ring or spot weeding treatments were carried out at the Fairbreeze site to determine the difference between *Ring weeding (0.5 m) and -Ring weeding (0.5 m)* treatments. For the *Ring weeding (0.5 m)* treatment, vegetation was manually removed from a 0.5 m radius around each seedling, whereas the whole area was weeded chemically excepting for a 0.5 m radius around each seedling for the *-Ring weeding (0.5 m)* treatment.

- Selective weeding (Oaklands and Mountain Home sites)

Selective herbicides were used for the selective control of broad vegetation groups (grasses, herbaceous broadleaves or woody broadleaves) to determine their relative competitiveness on the planted crops.

- Additional treatments

Additional treatments were also included in some trials to address specific objectives. In general, these treatments included the use of herbicides, but at reduced rates when compared to other vegetation management treatments.

(i) Cover-crops: Cover-crops (cowpeas (*Vigna unguiculata* (L.) Walp.), velvet beans (*Mucuna pruriens* (L.) DC.) or sweet potatoes (*Ipomoea batatas* (L.) Lam. (Bosbok variety: **Little 2008**)) were grown in the inter-rows for the suppression of undesirable vegetation. The cowpea and velvet bean seeds were sown in double rows, 1 m from the tree rows at Fairbreeze and were fertilized with 10 g 2:3:2 (N:P:K) + 0.5% Zn metre^{-1}, on the same day as the planting of *E. grandis* x *E. camaldulensis* trees. At Mountain Home, sweet potato cuttings were planted between the rows of the trees. All cover-crops were manually weeded on two occasions until a full plant cover had been established, thus reducing the need for further weed management.

(ii) Tree-row planting spacing (KT site only): Planting trees closer within the tree rows should result into earlier canopy closure, thereby reducing the period required to control vegetation in the tree rows.

(iii) Slash (harvest residue) management (Oaklands site only): The retention of post-harvesting slash was compared to the burning of slash to determine the ability of the slash to act as a physical barrier for the prevention (or delay) of the development of competing vegetation. This would potentially reduce the need for vegetation management, and hence herbicide use.

3.2.2. Tree growth measurements used for the eucalypt trial sets

3.2.2.1. Tree growth variates

Tree growth variates of height (Ht in m) and diameter at breast height (Dbh in cm) were measured on a regular basis throughout all seven trials until rotation-end. Stocking (stems ha^1 (sph)) was derived from survival data and, together with Dbh and Ht measurements, was used to determine merchantable volume (underbark volume to a top end diameter of 5 cm) (Merchantable volume in m^3 ha^{-1}). To compare uniformity between different treatments, the coefficient of variation for Dbh (CV Dbh in %) was calculated on a treatment plot basis (Equation 4).

$$\text{Equation 4. Coefficient of variation (CV)} = \left(\frac{Standard\ deviation\ (sd)}{Mean\ (\bar{x})}\right) \times 100$$

3.2.2.2. Relative treatment differences (Stocking, Volume and Dbh CV)

To allow for comparisons within and between eucalypt trials, the performance of treatments was determined relative to the best performing *Weedfree* treatment within each trial. Relative differences were calculated for survival (Stocking_Rel_WF), volume (Volume_Rel_WF) and uniformity (CV Dbh_Rel_WF).

3.2.2.3. Vegetation abundance, management operations and herbicide use

For each site, the vegetation abundance for the weedy treatment were quantified by taking above-ground vegetation biomass samples (3 × 1 m^2 quadrats) from the weedy plots at different dates (**Table 3.1**). All samples were removed from the buffer rows to avoid any impact on the performance of the measured trees. These were oven dried at 80°C to a constant mass and then weighed. This data, together with weed species was used to adjust the quantity of herbicides applied to account for vegetation abundance as well as differences in area weeded (full weed control versus row weeding versus ring weeding). Although the method and timing of vegetation management operations were recorded for each treatment within each trial, the level of detail varied according to field staff responsible for the management of each trial. Where the level of detail was high, the method and number of weeding events per treatment could be used together with the determination of the quantities of herbicide applied. For those trials where detail was lacking, the events recorded were compared to similar weeding treatments implemented in a series of five eucalypt vegetation management trials by **Little and Rolando (2008)**, with any missing information incorporated into the current trial series.

3.2.3. Methods used for vegetation control during the implementation of the vegetation management treatments across the eucalypt and pine trials

All vegetation control operations were carried out using methods reflecting current practices used within the South African forest industry when the trials were implemented. These included manual or chemical weed control in the form of a:

- Pre-plant spray: Complete cover spray with Roundup® (isopropylamine salt of glyphosate 360 g a.i. kg^{-1}) @ 4 kg ha^{-1} formulated product on all vegetation within site prior to the planting of the seedlings. All trials, and hence all treatments received a pre-plant spray.
- Coning operation: Inverted plastic cones were placed over each seedling as protection from spray drift, with the rest of the area receiving a full cover spray. Roundup® (isopropylamine salt of glyphosate 360 g a.i. kg^{-1}) @ 4 kg ha^{-1} was applied in all treatments except for the selective weeding treatments, where either Fusilade® (fluasifop-p-butyl 150 g a.i. kg^{-1}) @ 3 kg ha^{-1}, MCPA® (4-chloro-2-methylphenoxyacetic acid 400 g a.i. kg^{-1}) @ 2.5 kg ha^{-1}, or Garlon® 480 EC (triclopyr (pyridyloxy compound as butoxy ethyl ester) 480 g a.i. kg^{-1}) @ 2.5 kg ha^{-1} was applied to control either grasses, herbaceous broadleaves (HBL) or perennial broadleaves (PBL) respectively.
- Chemical hoe: Directed, but broadcast application of herbicides (as for the coning operation) onto the vegetation once the trees were too large for a coning

operation. Care was taken to prevent any herbicide coming into contact with the tree stem or foliage.

- Spot spray: A directed spray was carried out (using the same herbicides as the coning operation) onto individual plants or clusters of vegetation where there was not a full cover of vegetation. This type of spraying operation also occurred post-canopy closure.
- Slash: Vegetation (mainly large woody perennial weeds) were manually cut at ankle height with either a machete or bushknife, with Garlon® 480 EC (triclopyr (pyridyloxy compound) (as butoxy ethyl ester) 480 g a.i. kg^{-1}) @ 2.5 kg ha^{-1} applied to the cut surface.
- Ring weeding: Manual removal of vegetation, either by hand or with a mattock, from a predetermined area surrounding the seedling. A 0.5 m ring weeding was carried out prior to all coning operations to remove those weeds that would have been covered by the cones.

3.2.4. Data analysis used for all eucalypt trial data sets

Analysis of variance (ANOVA) was used to test for treatment effects within the chosen eucalypt and pine trials. Only if the F value was significant ($p < 0.05$) were treatment differences further investigated using Student's t-test least significant difference (lsd) statistic. Prior to all analyses, the assumptions underlying a valid analysis of variance were tested (Shapiro-Wilk test for normality and Levene's test for homogeneity of variances). All comparisons between the tree variates were performed on plot means using Genstat® for Windows™ 16th Edition (**VSN International, Hemel Hempstead, UK, 2018**). Descriptive statistics were also used in the form of tables and figures to assist with the description of the vegetation management and herbicide-data obtained (means and standard deviation).

3.3. Tree performance risk associated with reduced levels of vegetation management for eucalypt trial data sets

To determine the risk associated with reduced levels of vegetation management in terms of decreased stocking, volume and increased variability, the treatments within each trial were partitioned into three risk classes (Low, Moderate or High) relative to that of the *Weedfree* treatment (**Table 3.4**). Herbicide use rating for total quantities of herbicides applied ha^{-1} was also partitioned into three risk classes (Low, Moderate or High). Vegetation management treatments with less than 5 kg herbicides applied ha^{-1}, were considered Low risk, whereas herbicide quantities applied between 5-10 kg ha^{-1} considered Moderate risk and High risk where more than 10 kg ha^{-1} was applied. Although these criteria used to partition the risk classes were selected to illustrate principles, they can be adjusted to correspond with company-specific tree performance criteria.

(i) Stocking_Rel_WF: This risk class was based on tree survival targeted by the forest industry (≥90%) to be achieved at canopy closure (**Vireo et al. 2002; Ndlovu et al. 2019a, 2019b, 2019c**), with treatment survival between 90-100% relative to the *Weedfree* treatment considered a Low risk, 80-89% a Moderate risk, and <79% a High risk.

(ii) Vol_Rel_WF: For the partitioning of volume into risk classes, data from the research trials within which significant treatment differences occurred were used. The mean values for each level of significance were combined, with treatment volume differences relative to the *Weedfree* treatment compared. Treatment values between 90-100% relative to the *Weedfree* treatment were considered Low risk, 80-89% a Moderate risk, and <79% a high risk.

(iii) CV Dbh_Rel_WF: The impacts of vegetation management on eucalypt variability by **Little et al. (2003)** were used for the partitioning of these risk classes. Results from this research indicated a Dbh coefficient of variation of between 0-20% for the *Weedfree* treatments, and >30% for the weedy treatment. Subsequently, treatment variability between 0-20% relative to the *Weedfree* treatment were considered Low risk, 21-30% a Moderate risk and >31% a high risk.

Depending on the allocation of risk for Stocking_Rel_WF, Volume_Rel_WF and CV Dbh_Rel_WF, the overall growth risk could be partitioned into one of the three risk classes (Low, Moderate, or High) for each vegetation management treatment. For example, if all three growth responses were classified as Low risk, overall growth risk would be considered Low risk (**Table 3.4**). Whereas, if any of the three growth responses were classified as high, overall risk would also be considered high risk.

Table 3.4. Risk categorization for rotation-end growth responses relating to vegetation management within seven vegetation management trials implemented on eucalypts in the summer rainfall region of South Africa. (adapted from **Kliejunas et al. 2006**).

Risk rating	Survival (Stocking_Rel_WF (%))	Volume (Vol_Rel_WF (%))	Uniformity (CV Dbh_Rel_WF (%))
Low (L)	90-100	90-100	0-20
Moderate (M)	80-89	80-89	21-30
High (H)	< 79	< 79	>31

Rotation-end growth responses			Overall risk
Survival	Yield	Uniformity	
H	H	H	H
M or L	M or L	H	H
M or L	H	M or L	H
H	M or L	M or L	H
M	M	M	M
L	M	M	M
M	L	M	M
M	L	L	M
L	M	L	M
L	L	M	M
L	L	L	L

3.3.1. Linking of vegetation management treatments to reduce herbicide use

A two way-contingency table was used to link the quantity of herbicide applied ha^{-1} for each vegetation management treatment within each eucalypt trial with the tree growth risk rating obtained for that specific treatment (**Table 3.4**). This would allow the partitioning of the different vegetation management treatments in terms of quantity of herbicide applied (lower more desirable), with the tree growth responses obtained at final measurement (higher more desirable).

3.4. Results and Discussion

3.4.1. Site related tree performance

Conditions for tree growth were considered optimum for all tree species planted across the different sites, with estimated potential productivities in terms of mean annual increment (MAI) ranging from 14-20 m^3 ha^{-1} annum^{-1} for the CT sites, 36-40 m^3 ha^{-1} annum^{-1} for WT sites, and 35-45 m^3 ha^{-1} annum^{-1} for the ST sites (**Smith et al. 2005**) (**Table 3.1**). Generally, the trials situated within the ST and WT climate zones had better tree growth (MAI between 28-48 m^3 ha^{-1} annum^{-1}) compared to the CT climate zone (MAI of 26-28 m^3 ha^{-1} annum^{-1}), which can be attributed to the higher mean annual rainfall, temperatures and increased number of growth days associated with these climatic zones (**Smith et al. 2005; Louw et al. 2011; Louw and Smith 2012**). As for tree performance, weed abundance and growth was higher on the WT and ST sites, which resulted in higher levels of weeding required, and a decrease in tree volume (m^3 ha) and uniformity if left uncontrolled (**Tables 3.5 and 3.6**). Excepting for Oaklands and Enon, where survival (stocking) was 76% and 88%, mean survival of trees in the *Weedfree* treatments for the five other trials was ≥90%, a value considered to be commercially acceptable (**Figure 3.1**) (**Vireo et al. 2002; Ndlovu et al. 2019**). Mortality was not treatment-related at both Enon and Oaklands. Higher mortality for *E. smithii* (Enon) during establishment is recognised as a problem, often resulting in >10-15% mortality, two to three years after planting (**Viero and Little 2006**). The generally high survival of trees planted in the other five trials may in part be attributed to the trees being planted into sites that were free of competing vegetation (a pre-plant spray was carried out in all trials), which allowed for initial growth (above- and below-ground) to a level where the development of any competition (from three months onwards at the weediest sites) did not cause mortality.

Table 3.5. Summary data showing selected rotation-end tree growth variates within seven vegetation management trials implemented on eucalypts in the summer rainfall region of South Africa. Words in parentheses represent climate zone and species grown.

1. Fairbreeze (ST: *E. grandis x E. camaldulensis*)	**Tree growth variates**		
Vegetation management treatments	Survival Stocking (sph)	Growth Volume (m^3 ha^{-1})	Uniformity CV Dbh (%)
Weedfree (manual)	1 139^{ns}	223.9^{a}	18.8^{a}
Weedfree (chemical)	1 278^{ns}	191.4^{ab}	21.0^{ab}
-Ring weeding (0.5 m)	1 333^{ns}	207.5^{ab}	25.7^{abc}
Row weeding (1.2 m)	1 222^{ns}	185.6^{ab}	23.8^{abc}
Ring weeding (0.5 m)	1 305^{ns}	196.1^{ab}	29.0^{abc}
Cowpea	1 139^{ns}	158.1^{bc}	22.6^{ab}
Velvet bean	1 194^{ns}	160.6^{bc}	22.1^{ab}
Inter-row weeding (1.2 m)	1 278^{ns}	169.4^{bc}	37.1^{c}
Weedy	1 250^{ns}	137.8^{c}	33.8^{bc}
LSD ($p < 0.05$)	79.8	24.1	13.8

2. Oaklands (ST: *E. grandis x E. camaldulensis*)	**Tree growth variates**		
Vegetation management treatments	Survival Stocking (sph)	Growth Volume (m^3 ha^{-1})	Uniformity CV Dbh (%)
Unburnt x Weedfree	1 019^{ns}	287.9^{a}	11.5^{a}
Burnt x Weedfree	995^{ns}	266.9^{ab}	10.6^{a}
Unburnt x Row weeding (2 m)	995^{ns}	265.6^{ab}	11.1^{a}
Unburnt x Broadleaves remaining	1 042^{ns}	229.7^{cd}	21.8^{bc}
Unburnt x Grass remaining	1 042^{ns}	217.5^{d}	17.1^{ab}
Unburnt x Weedy	972^{ns}	208.1^{d}	20.6^{bc}
Burnt x Weedy	972^{ns}	199.5^{d}	27.4^{c}
LSD ($p < 0.05$)	159.1	31.9	7.2

3. KT (ST: *E. grandis*)	**Tree growth variates**		
Vegetation management treatments	Survival Stocking (sph)	Growth Volume (m^3 ha^{-1})	Uniformity CV Dbh (%)
Factor A. Spacing			
1 852 sph (2.7 x 2.0 m)	1 627^{a}	315.4^{ns}	32.9^{ns}
1 481 sph (2.7 x 2.5 m)	1 352^{b}	338.2^{ns}	30.3^{ns}
LSD ($p < 0.001$)	43.6	68.4	9.0
Factor B. Vegetation management			
Weedfree	1 531^{a}	365^{a}	24.8^{a}
Row weeding (1.8 m)	1 557^{a}	335^{ab}	28.7^{ab}
Row weeding (0.9 m)	1 535^{a}	310^{bc}	31.7^{bc}
Weedy	1 422^{b}	297^{c}	41.0^{c}
LSD ($p < 0.001$)	63.5	33.9	6.4
Factorial combination: Vegetation management x Spacing			
1 852 sph (2.7 x 2.0 m)			
Weedfree	1 707^{ns}	342.3^{ns}	25.0^{ns}
Row weeding (1.8 m)	1 736^{ns}	322.6^{ns}	27.3^{ns}
Row weeding (0.9 m)	1 692^{ns}	305.1^{ns}	33.9^{ns}
Weedy	1 547^{ns}	291.6^{ns}	45.4^{ns}
1 481 sph (2.7 x 2.5 m)			
Weedfree	1 354^{ns}	387.8^{ns}	26.2^{ns}
Row weeding (1.8 m)	1 377^{ns}	348.4^{ns}	30.2^{ns}
Row weeding (0.9 m)	1 377^{ns}	314.9^{ns}	32.1^{ns}
Weedy	1 296^{ns}	301.6^{ns}	36.6^{ns}
Factorial LSD ($p < 0.05$)	179.1	76.5	10.3

ns = non-significance at $p < 0.05$. Different letters within each column indicate significant difference at $p < 0.05$ or $p < 0.001$ as indicated by the Students *t*-test.
ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

Continues from Table 3.5.

4. Mountain Home (WT: *E. dunnii*)	Tree growth variates		
	Survival	Growth	Uniformity
Vegetation management treatments	Stocking (sph)	Volume (m^3 ha^{-1})	CV Dbh (%)
Weedfree	1 615^{ns}	258.0^{a}	23.0^{a}
Sweet potato (1.2 m)	1 641^{ns}	270.5^{a}	23.9^{a}
Grasses remaining	1 562^{ns}	251.3^{a}	30.0^{a}
Sweet potato	1 589^{ns}	243.3^{a}	28.2^{a}
Row weeding (2 m)	1 589^{ns}	239.5^{a}	29.1^{a}
Row weeding (1.2 m)	1615^{ns}	230.9^{a}	21.4^{a}
Broadleaves remaining	1510^{ns}	152.3^{b}	45.3^{b}
Weedy	1510^{ns}	117.5^{b}	44.9^{b}
LSD ($p < 0.05$)	159.1	31.9	7.2

5. Enon (WT: *E. smithii*)	Tree growth variates		
	Survival	Growth	Uniformity
Vegetation management treatments	Stocking (sph)	Volume (m^3 ha^{-1})	CV Dbh (%)
Weedfree	1 467^{ns}	414.0^{a}	28.0^{ns}
Moderate weeding	1 296^{ns}	373.5^{ab}	28.3^{ns}
Low weeding	1 346^{ns}	370.8^{ab}	28.1^{ns}
Row weeding (2 m)	1 389^{ns}	393.8^{a}	27.9^{ns}
Weedy	1 238^{ns}	318.5^{b}	32.7^{ns}
LSD ($p < 0.05$)	148.2	46.28	11.8

6. Tweefontein (CT: *E. macarthurii*)	Tree growth variates		
	Survival	Growth	Uniformity
Vegetation management treatments	Stocking (sph)	Volume (m^3 ha^{-1})	CV Dbh (%)
Improved x Fertilization x Weedfree	2 001^{ns}	212.8^{ns}	27.8^{ns}
Improved x NoFertilization x Weedfree	1 915^{ns}	212.5^{ns}	32.3^{ns}
Unimproved x Fertilization x Weedfree	1 723^{ns}	167.5^{ns}	31.1^{ns}
Unimproved x NoFertilization x Weedfree	1 769^{ns}	164.9^{ns}	29.0^{ns}
Improved x Fertilization x Weedy	1 980^{ns}	200.1^{ns}	27.6^{ns}
Improved x NoFertilization x Weedy	1 910^{ns}	164.1^{ns}	29.7^{ns}
Unimproved x Fertilization x Weedy	1 934^{ns}	156.6^{ns}	31.0^{ns}
Unimproved x NoFertilization x Weedy	1 739^{ns}	134.1^{ns}	28.1^{ns}
Factorial LSD ($p < 0.05$)	246.4	77.7	10.3

7. Draycott (CT: *E. nitens*)	Tree growth variates		
	Survival	Growth	Uniformity
Vegetation management treatments	Stocking (sph)	Volume (m^3 ha^{-1})	CV Dbh (%)
Improved x Fertilization x Weedfree	1 464^{ns}	233.5^{ns}	27.8^{ns}
Improved x NoFertilization x Weedfree	1 438^{ns}	188.9^{ns}	26.1^{ns}
Unimproved x Fertilization x Weedfree	1 348^{ns}	173.2^{ns}	29.1^{ns}
Unimproved x NoFertilization x Weedfree	1 334^{ns}	169.9^{ns}	30.4^{ns}
Improved x Fertilization x Weedy	1 464^{ns}	238.3^{ns}	30.6^{ns}
Improved x NoFertilization x Weedy	1 488^{ns}	232.2^{ns}	32.9^{ns}
Unimproved x Fertilization x Weedy	1 441^{ns}	199.0^{ns}	31.0^{ns}
Unimproved x NoFertilization x Weedy	1 344^{ns}	156.7^{ns}	32.4^{ns}
Factorial LSD ($p < 0.05$)	129.1	9.3	67.7

ns = non-significance at $p < 0.05$. Different letters within each column indicate significant difference at $p < 0.05$ as indicated by the Students *t*-test.
ST: Sub tropical; WT: Warm temperate; CT: Cool temperate.

Table 3.6. Vegetation control operations and total herbicide use (formulated product) over the full rotation within seven vegetation management trials implemented on eucalypts in the summer rainfall region of South Africa. For each weeding treatment the values in parentheses represent the rates of herbicide application adjusted to account for weeding distances and vegetation loads associated within each trial.

Trial name	Vegetation management treatments	Type and number of weeding operations used at each trial									
		Pre-plant spray[1] ($kg\ ha^{-1}$)	Ring (1 m)	[1]Coning ($kg\ ha^{-1}$)	[1]Chemical Hoe ($kg\ ha^{-1}$)	[1]Spot spray ($kg\ ha^{-1}$)	Manual operations (n)	Herbicide operations (n)	Total number weeding operations (n)	Total quantity herbicide applied ($kg\ ha^{-1}$)	Quantity herbicide applied annually ($kg\ ha^{-1}\ yr^{-1}$)
1. Fairbreeze	Weedfree (manual)	1 (4.0)	7	-	-	2 (0.6)	7	3	10	5.2	0.7
	Weedfree (chemical)	1 (4.0)	2	2 (2.1)	3 (2.1)	2 (0.6)	2	8	10	15.6	2.2
	-Ring weeding (0.5 m)	1 (4.0)	-	1 (2.2)	3 (2.2)	2 (0.6)	-	7	7	14.2	2.0
	Row weeding (1.2 m)	1 (4.0)	2	1 (0.9)	3 (0.9)	2 (0.6)	2	7	9	8.8	1.3
	Ring weeding (0.5 m)	1 (4.0)	-	1 (2.2)	3 (2.2)	2 (0.6)	-	7	7	14.2	2.0
	Cowpea	1 (4.0)	2	-	-	2 (0.6)	2	3	4	5.2	0.7
	Velvet bean	1 (4.0)	2	-	-	2 (0.6)	2	3	4	5.2	0.7
	Inter-row weeding (1.2 m)	1 (4.0)	2	1 (0.9)	3 (0.9)	2 (0.6)	2	6	8	8.8	1.3
	Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.6
2. Oaklands	Unburnt x Weedfree	1 (4.0)	2	2 (2.1)	3 (1.4)	2 (0.6)	2	8	10	13.5	1.9
	Burnt x Weedfree	1 (4.0)	2	2 (2.1)	3 (1.4)	2 (0.6)	2	8	10	13.5	1.9
	Unburnt x Row weeding (2 m)	1 (4.0)	2	1 (0.9)	3 (0.9)	2 (0.6)	2	7	9	8.8	1.2
	[2]Unburnt x Broadleaves remaining	1 (4.0)	3	1 ([2]1.3)	3 ([2]1.3)	2 (1.0)	3	7	10	11.2	1.6
	[3]Unburnt x Grasses remaining	1 (4.0)	3	1 ([3]1.6)	3 ([3]1.6)	2 (1.2)	3	7	10	12.6	1.8
	Unburnt x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.6
	Burnt x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.6
3. KT	1 852 sph (2.7 x 2 m)										
	Weedfree	1 (4.0)	2	2 (2.0)	3 (1.3)	2 (0.6)	2	8	10	13.2	1.7
	Row weeding (1.8 m)	1 (4.0)	2	1 (1.3)	3 (0.9)	2 (0.6)	2	7	9	9.2	1.2
	Row weeding (0.9 m)	1 (4.0)	2	1 (0.5)	3 (0.3)	2 (0.6)	2	7	9	6.8	0.9
	Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.5
	1 481 sph (2.7 x 2.5 m)										
	Weedfree	1 (4.0)	2	2 (2.0)	3 (1.4)	2 (0.6)	2	8	10	13.5	1.8
	Row weeding (1.8 m)	1 (4.0)	2	1 (1.3)	3 (0.9)	2 (0.6)	2	7	9	9.3	1.2
	Row weeding (0.9 m)	1 (4.0)	2	1 (0.5)	3 (0.4)	2 (0.6)	2	7	9	6.9	0.9
	Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.5

[1]Roundup® (isopropylamine salt of glyphosate 360 g a.i. kg^{-1}) (non-selective herbicide) was used for all weeding operations. expecting for the following treatments: [2]Unburnt x Grasses remaining and [3]Unburnt x Broadleaves remaining where Fusilade® (fluasifop-p-butyl 150 g a.i. kg^{-1}) (grass selective herbicide) and MCPA® (potassium salt phenoxy compound 400 g a.i. kg^{-1}) (broadleaf selective herbicide) were applied.

Continues from Table 3.6.

Trial name	Vegetation management treatments	Type and number of weeding operations used at each trial									
		Pre-plant spray[1] (kg ha^{-1})	Ring (1 m)	[1]Coning (kg ha^{-1})	[1]Chemical Hoe (kg ha^{-1})	[1]Spot spray (kg ha^{-1})	Manual operations (n)	Herbicide operations (n)	Total number weeding operations (n)	Total quantity herbicide applied (kg ha^{-1})	Quantity herbicide applied annually (kg ha^{-1} yr^{-1})
4. Mountain Home	Weedfree	1 (4.0)	3	1 (3.3)	3 (2.0)	2 (0.6)	3	7	10	14.5	1.5
	Sweet potato (1.2 m)	1 (4.0)	3	1 (0.6)	3 (0.6)	2 (0.6)	3	7	10	7.8	0.8
	[3]Grasses remaining	1 (4.0)	2	1 ([3]1.5)	2 (0.4)	2 (1.2)	2	6	8	8.8	0.9
	Sweet potato	1 (4.0)	2	1 (2.0)	2 (1.3)	2 (0.6)	2	6	8	9.9	1.1
	Row weeding (2 m)	1 (4.0)	3	1 (1.3)	3 (1.3)	2 (0.6)	3	7	10	10.3	1.1
	Row weeding (1.2 m)	1 (4.0)	3	1 (0.6)	3 (0.6)	2 (0.6)	3	7	10	7.8	0.8
	[2]Broadleaves remaining	1 (4.0)	2	1 ([2]1.3)	2 (0.8)	2 (1.0)	2	6	8	8.9	1.0
	Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
5. Enon	Weedfree	1 (4.0)	3	1 (2.0)	3 (1.3)	2 (0.6)	3	7	10	11.2	1.2
	Moderate weeding	1 (4.0)	2	1 (2.0)	2 (2.0)	2 (0.6)	2	6	8	11.2	1.2
	Low weeding	1 (4.0)	-	-	1 (2.4)	3 (0.9)	2 (slash)	5	7	9.1	1.0
	Row weeding (2 m)	1 (4.0)	3	1 (0.9)	3 (0.9)	2 (0.6)	3	7	10	8.6	1.0
	Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
6. Tweefontein	Improved x Fertilization x Weedfree	1 (4.0)	1	1 (1.3)	-	3 (0.6)	1	5	6	7.1	0.9
	Improved x NoFertilization x Weedfree	1 (4.0)	1	1 (1.3)	-	3 (0.6)	1	5	6	7.1	0.9
	Unimproved x Fertilization x Weedfree	1 (4.0)	1	1 (1.3)	-	3 (0.6)	1	5	6	7.1	0.9
	Unimproved x NoFertilization x Weedfree	1 (4.0)	1	1 (1.3)	-	3 (0.6)	1	5	6	7.1	0.9
	Improved x Fertilization x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.5
	Improved x NoFertilization x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.5
	Unimproved x Fertilization x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.5
	Unimproved x NoFertilization x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.5
7. Draycott	Improved x Fertilization x Weedfree	1 (4.0)	1	-	-	3 (0.6)	1	4	5	5.8	0.7
	Improved x NoFertilization x Weedfree	1 (4.0)	1	-	-	3 (0.6)	1	4	5	5.8	0.7
	Unimproved x Fertilization x Weedfree	1 (4.0)	1	-	-	3 (0.6)	1	4	5	5.8	0.7
	Unimproved x NoFertilization x Weedfree	1 (4.0)	1	-	-	3 (0.6)	1	4	5	5.8	0.7
	Improved x Fertilization x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.5
	Improved x NoFertilization x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.5
	Unimproved x Fertilization x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.5
	Unimproved x NoFertilization x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.5

[1]Roundup® (isopropylamine salt of glyphosate 360 g a.i. kg^{-1}) (non-selective herbicide) was used for all weeding operations. expecting for the following treatments: [2]Unburnt x Grass remaining and [3]Unburnt x Broadleaves remaining where Fusilade® (fluasifop-p-butyl 150 g a.i. kg^{-1}) (grass selective herbicide) and MCPA® (potassium salt phenoxy compound 400 g a.i. kg^{-1}) (broadleaf selective herbicide) were applied.

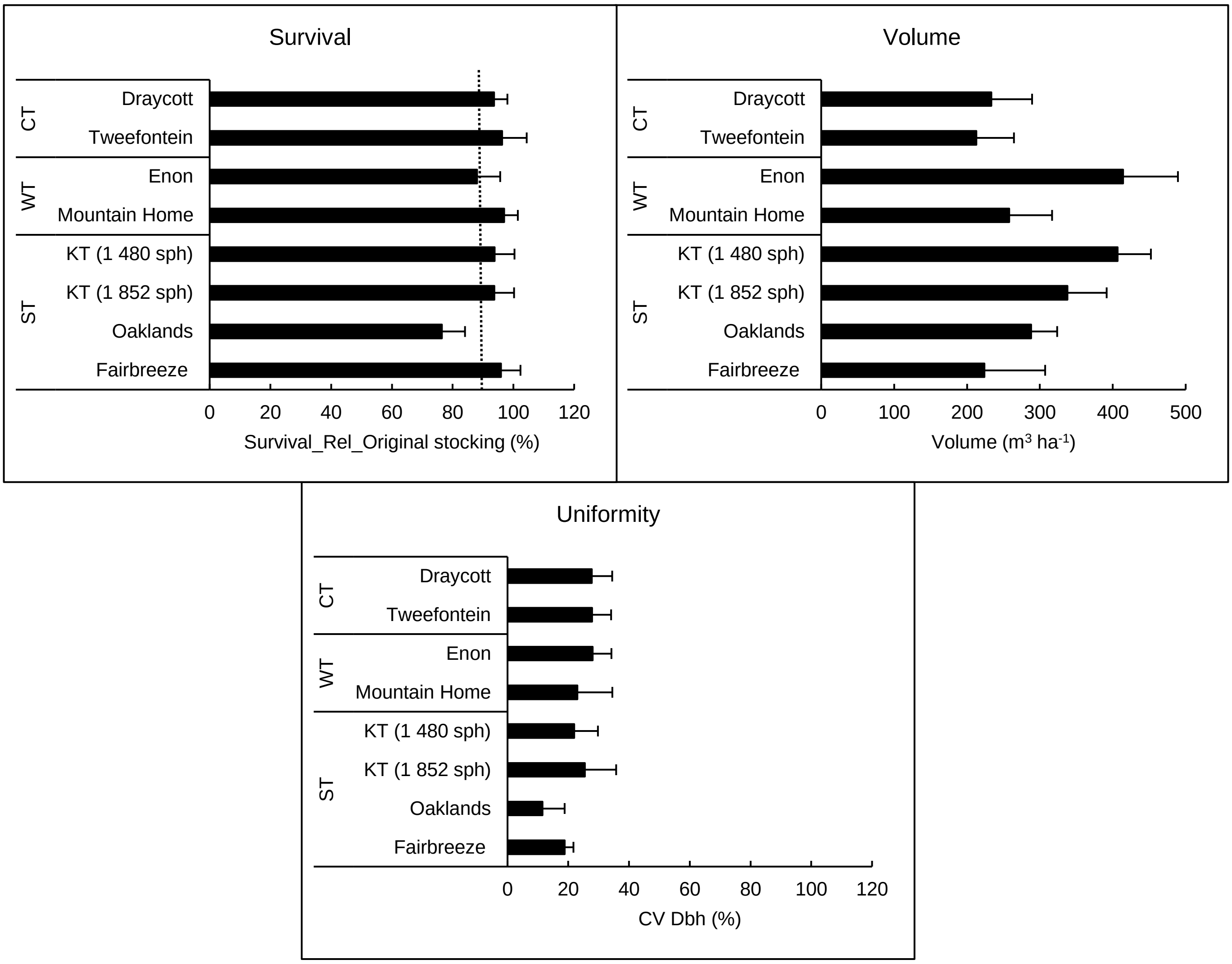


Figure 3.1. Rotation-end survival, volume and uniformity measurements for weedfree treatments within the seven eucalypt vegetation management trials in KwaZulu-Natal, South Africa. Vertical dotted line indicates desired industry tree survival (>90 percentage). Weedfree survival is relative to original stocking for each respective trial. Bars in figure indicate standard deviation.

The reason for higher mortality at Oaklands is unclear, especially as planting took place within the optimum planting window for Zululand (winter), and the cuttings were planted with water (**Viero and Little 2006; Viero and du Toit 2012**) (**Figure 3.1**). Although survival at Enon was lower, *E. smithii* had the highest rotation end volume in the weedfree plots, which could be attributed to the longer rotation length (9 years compared to $\bar{x}$ = 7.9 years for the other trials), and that *E. smithii,* when correctly matched to site, produces high volume (**Viero and Little 2006**).

In general, rotation-end tree volume (m^3 ha^{-1}) was mainly influenced by climate zone, site productivity, eucalypt species planted, previous land use and clearfelling age (**Table 3.1**). Within the ST climate zone, the overall volume obtained at KT was higher than at both Oaklands and Fairbreeze. *Eucalyptus grandis*, bred for disease resistance was planted at KT, which will generally outperform *E. grandis* x *E. camaldulensis* when grown on similar sites and in the absence of disease (**Smith et al. 2005**). The previous land-use at Fairbreeze (nutrient depleted ex-agricultural land - sugarcane) prior to conversion to forestry contributed to the lower yield obtained at this site in comparison to Oaklands and KT, despite this site having the highest rainfall (**Little 2003; Little and van Staden 2003; Little et al. 2003, 2005, 2007; Little and Rolando 2012**) (**Table 3.1**). This is attributed to the dominant weed on the site being *Cyperus esculentus* (yellow nutsedge), characteristic of ex-agricultural lands. This species is able to propagate itself by seed, with the main form of reproduction being underground vegetative structures (corms and tubers) (**Schippers et al. 1993; Little 1999; Little and van Staden 2003; Little et al. 2003**). These vegetative structures allow yellow nutsedge to rapidly develop when conditions for growth become suitable, resulting in high levels of competition to the young, planted seedlings, the stage at which they are most vulnerable to competition from weeds. Within the WT climate zone, both Enon and Mountain Home had similar site productivities (**Table 3.1**), with the final yield influenced by species planted (*E. smithii* better than *E. dunnii*) (**Table 3.5**) rather than on site productivity alone (**Viero and Little 2006**). Although site productivity was also similar for the two trials occurring within the CT climate zone (Tweefontein with potential mean annual increment of 18 m^3 ha^{-1} $annum^{-1}$ and Draycott with potential mean annual increment of 20 m^3 ha^{-1} $annum^{-1}$) (**Table 3.1**), lower volume was obtained at Tweefontein, possibly due to the lower MAT (13.4°C) compared to Draycott (15.2°C) (**Table 3.2**). Similar to tree growth, vegetation species and growth was also influenced by climate zone, site productivity and previous land use (**Table 3.1**). This is reflected in both the quantity of vegetation biomass (CT climate zone trials ($\bar{x}$ = 1.3 tons ha^{-1}); WT climate zone trials ($\bar{x}$ = 8.8 tons ha^{-1}) and ST climate zone trials ($\bar{x}$ = 9.4 tons ha^{-1})) (**Table 3.1**) and reduction in growth of the *Weedy* relative to the *Weedfree* treatments across the sites (**Table 3.1**). For example, greater reductions occurring in the ST and WT ($\bar{x}$ = 33%) compared to the CT climate zones ($\bar{x}$ = 7%). Similar trends in terms of competition and climate zones have been obtained in vegetation management studies in SA by **Jarvel and Pallett (2002), Little et al. (2007) and Little and Rolando (2008)**.

Of the various vegetation types, grass (*Panicum maximum* Jacq) was the dominant species in four of the seven trials (Fairbreeze, KT, Tweefontein and Draycott) (**Table 3.1**). This is possibly a function of historical land use as these sites were ex-agricultural land prior to conversion to forestry (**Little and van Staden 2003; Fuller and Little 2007; Little and Rolando 2008; Little and van den Berg 2009**). For Mountain Home, black wattle (*Acacia mearnsii* De Wild) was the dominant species (**Little 2008**), due to the site previously planted to black wattle prior to conversion to eucalypts. The longevity of black wattle seed, combined with the burning of the post-harvest plantation residues (which provided conditions ideal for germination and growth), meant that this was the dominant and most competitive of the weed species on this site (**Little et al. 2000; Little 2008**).

3.4.2. Treatment related growth responses

Except for Tweefontein and Draycott (CT sites), significant treatment differences occurred in the rest of the trials in terms of the rotation-end growth variates (survival, volume and uniformity). This was expected as the cool-temperate climate associated with the higher-altitude sites at Tweefontein and Draycott resulted in the reduced growth of competing vegetation (**Little and Rolando 2008; Little and van den Berg 2009**). For the other trials, tree and vegetation growth were more affected by increased site productivity associated with higher mean annual temperatures and rainfall, resulting in the development of higher levels of competition-induced tree growth suppression where the vegetation was not controlled.

3.4.2.1. Survival

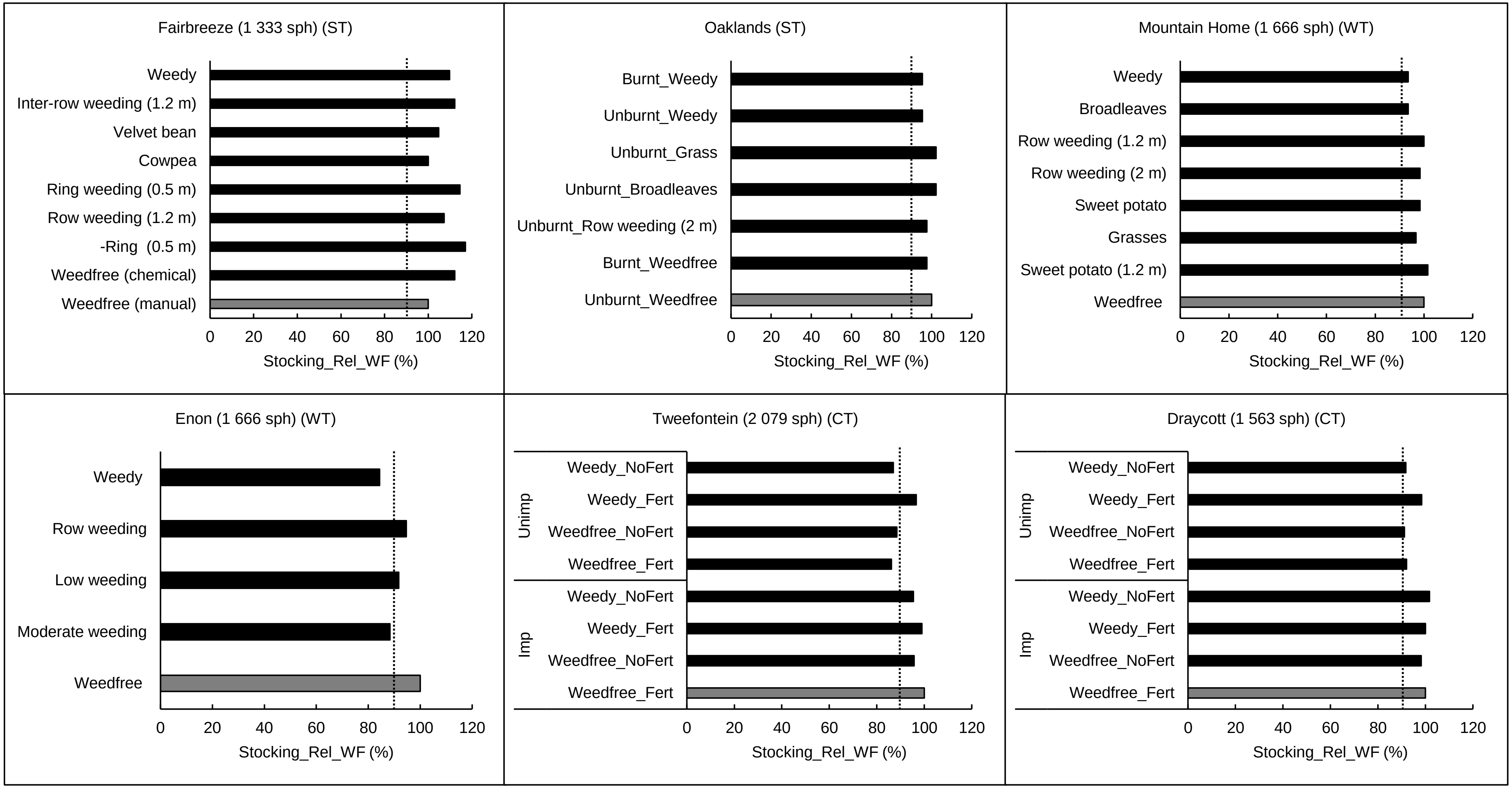
Differences in terms of survival occurred at KT, with both the main factors of Planting density (*F* prob = <0.001) and Vegetation management (*F* prob = <0.004) being significant (**Table 3.5**). For KT, the significant differences within the Planting density factor are not treatment related, but because of the two different planting densities planted. Regardless of Planting density, all treatments that included the clearing of competing vegetation from trees ($\bar{x}$ = 1 541 sph) had significantly better survival than the *Weedy* treatments ($\bar{x}$ = 1 422 sph). Survival was not significantly impacted by competing vegetation in the other six trials within this series (**Figure 3.2**). These results are comparable to those obtained in similar vegetation management trials conducted on eucalypts in SA, where the planting of trees on sites free of competing vegetation allows for the initial establishment of seedlings, such that when weed competition does occur, survival is not negatively impacted (**Little 1999; Little and Rolando 2008; Little et al. 2018b**).

3.4.2.2. Volume (yield)

Tree volume (m^3 ha^{-1}) was significantly impacted by the vegetation management treatments in five of the seven trials, all occurring in the WT or ST climate zones (**Table 3.5**). In general, the *Weedfree* and *Weedy* treatments had the highest and lowest volumes respectively ($\bar{x}$ = 310.2 and 240.9 m^3 ha^{-1} respectively), with these results similar to those obtained for other vegetation management trials conducted within SA and globally (**Richardson 1993; Little 1999; Wagner et al. 2006; Willoughby et al. 2009; Little et al. 2006, 2018**).

Draycott and Tweefontein: Limited weed growth at these two sites meant that although there was a reduction in growth between the *Weedfree* and *Weedy* treatments, competition was never at a level which resulted in significant differences ($\bar{x}$ = 194.5 and 181.1 m^3 ha^{-1} respectively) (**Table 3.5 and Figure 3.3**).

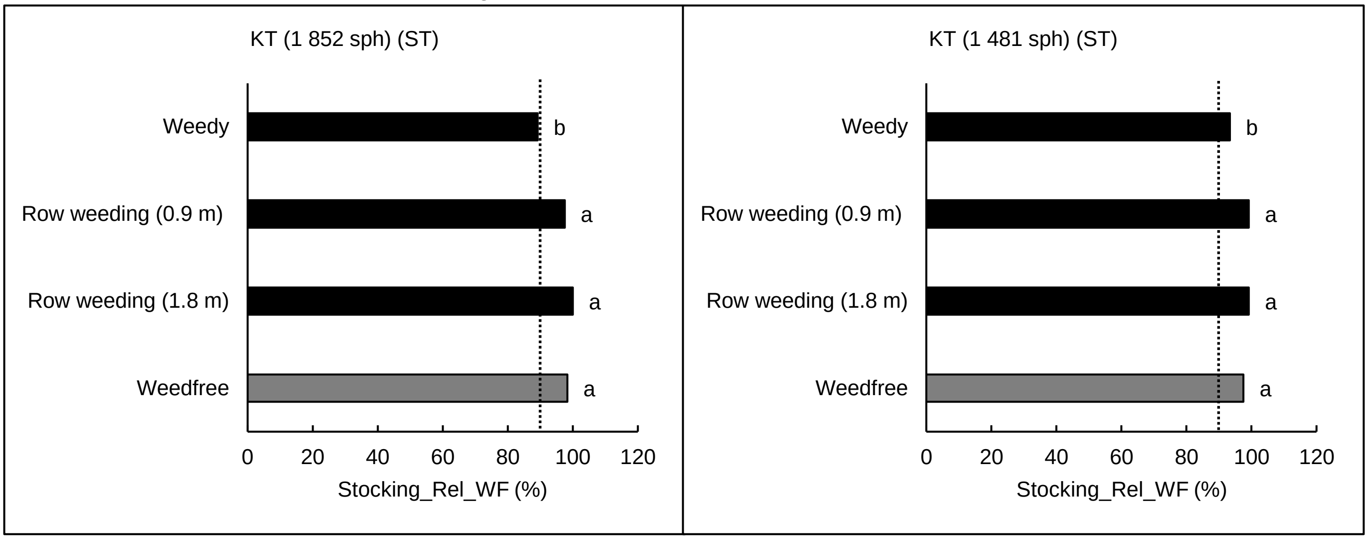
Fairbreeze: The *-Ring weeding (0.5 m)*, *Row weeding (1.2 m)* and *Ring weeding (0.5 m)* treatments ($\bar{x}$ = 196.4 m^3 ha^{-1}) were not significantly different from the *Weedfree* treatments (manual or chemical) ($\bar{x}$ = 207.6 m^3 ha^{-1}), whereas the use of *Cover-crops* (cowpea or velvet bean) ($\bar{x}$ = 158.1 m^3 ha^{-1}) and the *Interrow weeding* treatments (160.6 m^3 ha^{-1}) were not significant different to the *Weedy* treatment (137.8 m^3 ha^{-1}). The *Weedfree (chemical)* (191.4 m^3 ha^{-1}) treatment was not significantly different to all other treatments (including the *Cover-crops* treatments) ($\bar{x}$ = 185.9 m^3 ha^{-1}), except for the *Weedy* treatment.



ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

Figure 3.2. Rotation-end survival relative to the overall best performing treatment (weedfree) in seven eucalypt vegetation management trials in KwaZulu-Natal, South Africa. Values in parentheses are original planting density. Vertical dotted line indicates desired industry tree survival (>90 percentage). Within each trial, bars with different letters indicate significant differences, while bars with no letters or the same letters indicates non-significance differences (both at $p < 0.05$) as indicated by the Students *t*-test.

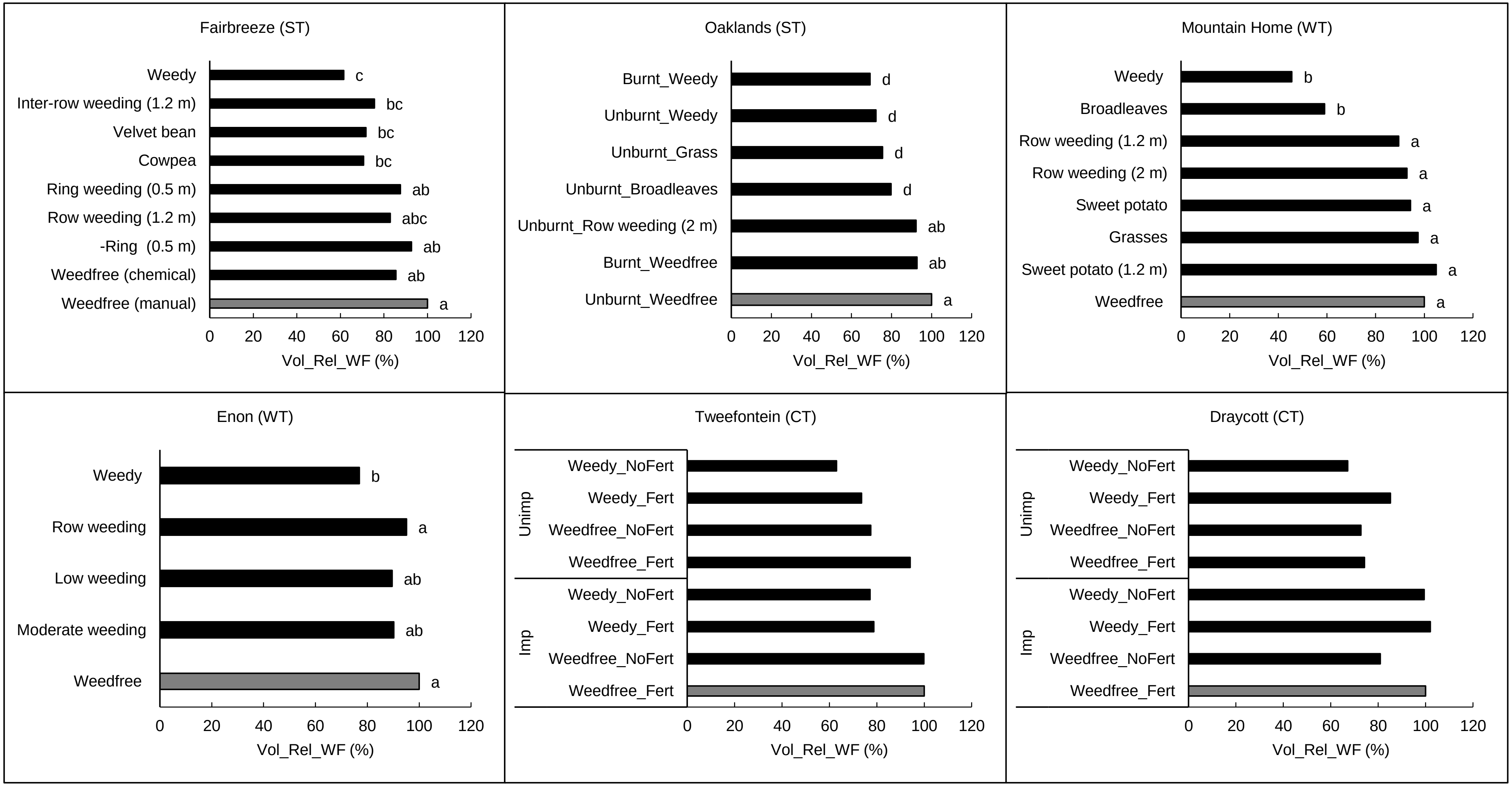
Continues from Figure 3.2.



ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

Oaklands: The *Unburnt x Weedfree* treatment (287.9 m^3 ha^{-1}) was significantly better than all the other treatments excepting for the *Burnt x Weedfree* and *Unburnt x Row weeding (2 m)* treatments ($\bar{x}$ = 266.3 m^3 ha^{-1}), with the latter two not significantly different from the *Unburnt x Minipit* (249.7 m^3 ha^{-1}). The two *Weedy* treatments (*Unburnt* and *Burnt*) (199.5 and 203.8 m^3 ha^{-1} respectively) were not significantly different to each other, nor to the *Unburnt x Broadleaves remaining* or *Grass remaining* treatments (229.7 and 217.5 m^3 ha^{-1} respectively), indicating that neither the retention of slash or the selective removal of vegetation provided any benefit in terms of tree volume over the *Weedfree* treatment.

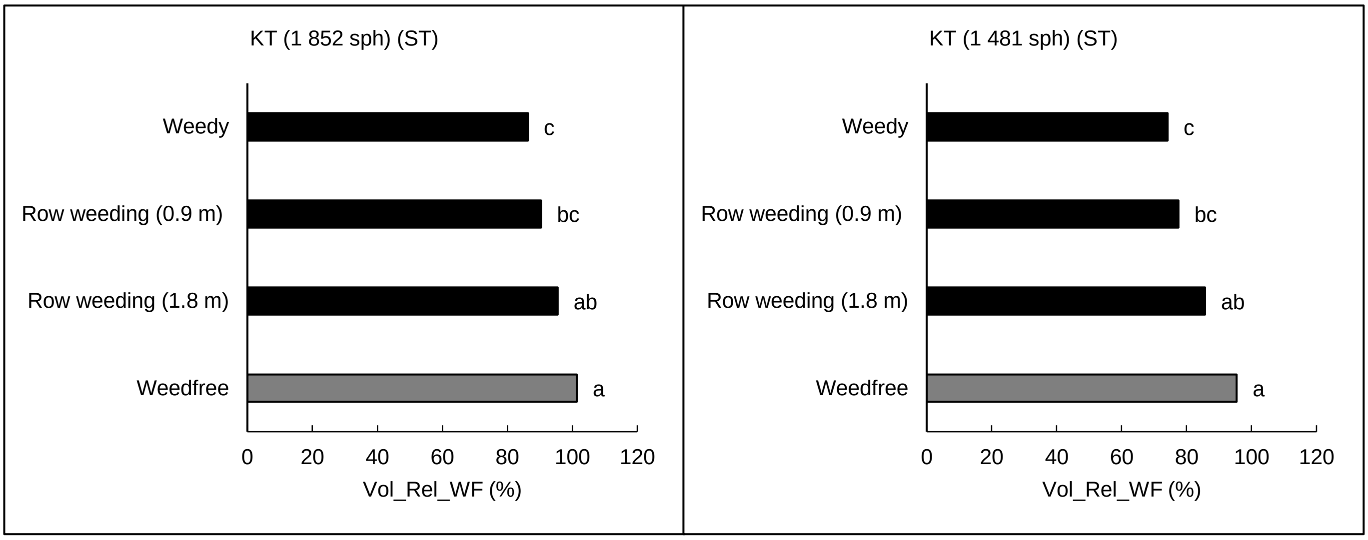
KT: The main effect of Vegetation management was significant, with an increase in tree volume in relation to an increase in weeding distance (**Figure 3.3**). The *Weedfree* and *Row weeding (1.8 m)* treatments (365.0 and 335.5 m^3 ha^{-1} respectively) were significantly better than the *Weedy* treatment (296.6 m^3 ha^{-1}), while the *Row weeding (0.9 m)* (310.0 m^3 ha^{-1}) was not significantly different to the *Row weeding (1.8 m)* or *Weedy* treatment.



ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

Figure 3.3. Rotation-end volume relative to overall best performing treatment (weedfree) within each of the seven eucalypt vegetation management trials in KwaZulu-Natal, South Africa. Within each trial, bars with different letters indicates significant differences, while bars with no letters or same letters indicates non significance differences (both at $p < 0.05$) as indicated by the Students *t*-test.

Continues from Figure 3.3.



ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

Mountain Home: As Mountain Home was an ex-black wattle site with the slash burned, the dominant competitor was that of wattle regeneration, and to a lesser extent *Solanum mauritianum* (both perennial woody weeds). For this reason, the *Weedy* and *Broadleaves remaining* treatments (117.5 and 152.3 m^3 ha^{-1} respectively) produced significantly lower volume than the rest of the vegetation management treatments (which were not significantly different from each other) ($\bar{x}$ = 248.9 m^3 ha^{-1}).

Enon: Treatment performance was a function of area kept free of competing vegetation and weeding intensity (**Figure 3.3**). The *Weedfree* and *Row weeding (2 m)* treatments (414 and 393.8 m^3 ha^{-1} respectively) were significantly different from the *Weedy* treatment (318 m^3 ha^{-1}), with the lowered frequency of weeding (*Moderate* (373.5 m^3 ha^{-1}) and *Low weeding* (370.8 m^3 ha^{-1})) not being significantly different to the *Weedfree* or *Weedy* treatments.

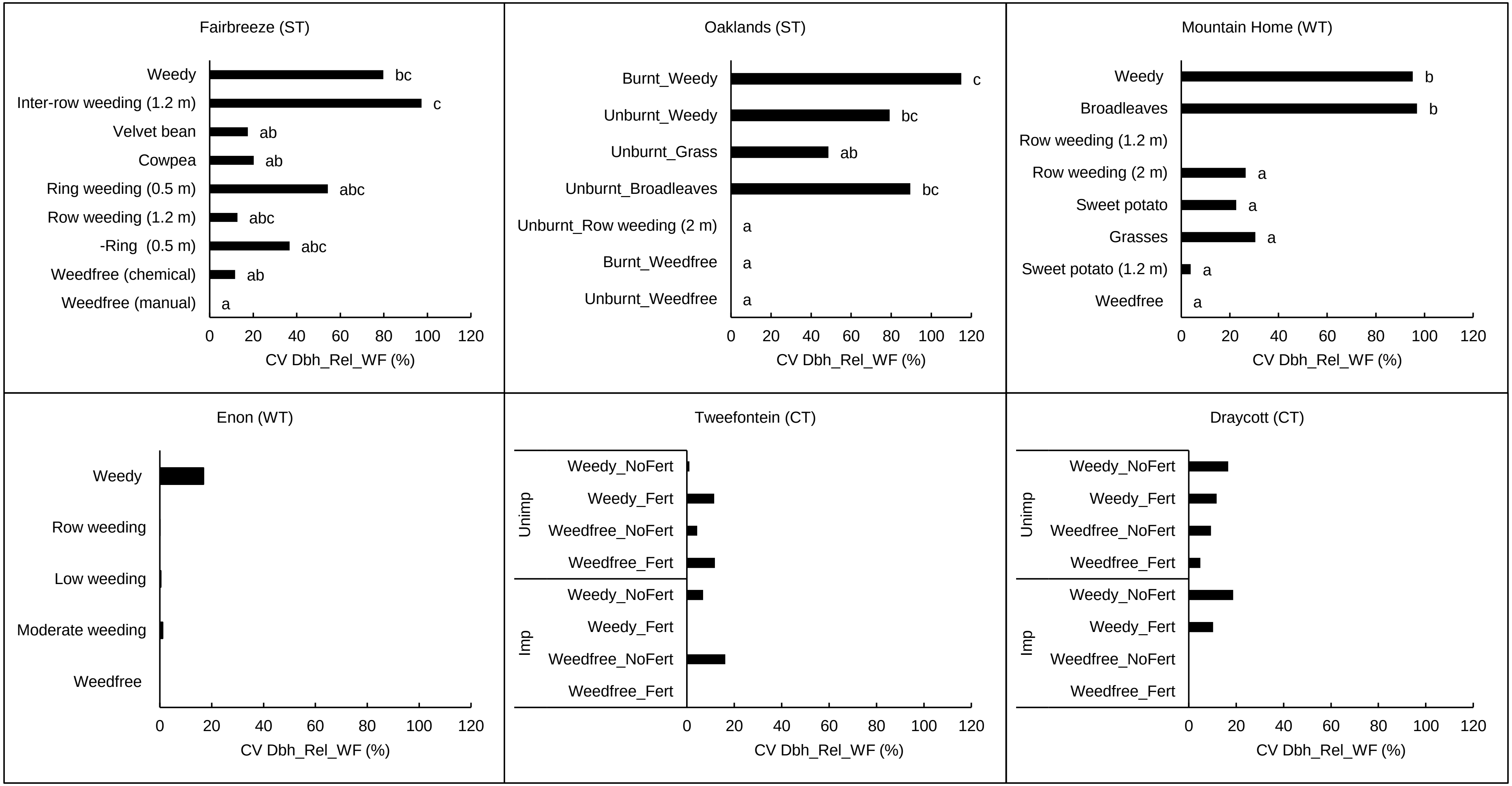
3.4.2.3. Uniformity

Amongst other factors, variability in tree growth may be influenced by site, level of genetic improvement, planting stock type (seedlings versus cuttings), and silvicultural treatments (fertilizer and/or vegetation management) (**Morris 1994; Little et al. 2003**). In general, and for all the trials, interspecific competition from competing vegetation resulted in greater variability in the *Weedy* treatments ($\bar{x}$ = 37.6%), and for those treatments where the weeds grew in close proximity to the trees ($\bar{x}$ = 31.6%), compared to the *Weedfree* treatments ($\bar{x}$ = 19.2%), resulting in significant differences in four trials (Fairbreeze, Oaklands, KT and Mountain Home) (**Figure 3.4**). The lack of interspecific competition during the establishment phase for those treatments where weeds were kept away from the trees, is likely to have resulted in symmetric intra-genotypic competition post-establishment (**Little et al. 2003**). Whereas interspecific competition during establishment is likely to have resulted in asymmetric intra-genotypic competition post-establishment.

Tweefontein, Draycott and Enon: The delayed development of vegetation, which remained sub-competitive at Tweefontein and Draycott meant that the range in variability between the various treatments was small ($\bar{x}$ = 5% at both trials), and not significant. Although the *Weedy* treatment at Enon showed the highest variability (32.7%), it was not significantly different from the other treatments ($\bar{x}$ = 28.1%). Reasons for this are unclear, but from visual observations it may be due to the high, but uniform spread of the main competitive species (*Solanum mauritianum*) within the weedy plots resulting in a similar level of symmetric interspecific competition for all measured trees.

Fairbreeze: The *Weedfree (manual)* treatment (18.8%) had the lowest variability and was significantly lower than both the *Inter-row (1.2 m)* and *Weedy* treatments (37.1 and 33.8% respectively). The *-Ring* and *Ring weeding (0.5 m)*, treatments (25.7 and 29.0% respectively) had competitive vegetation in close proximity to the trees and recorded higher variability than the *Weedfree* treatments ($\bar{x}$ = 19.9%), albeit not significantly different to the *Row weeding (1.2 m)* (an increase in the area kept free from vegetation) (21.2%), and the two *Cover-crops* (delayed development of competition due to delayed sowing of seed) ($\bar{x}$ = 22.4%).

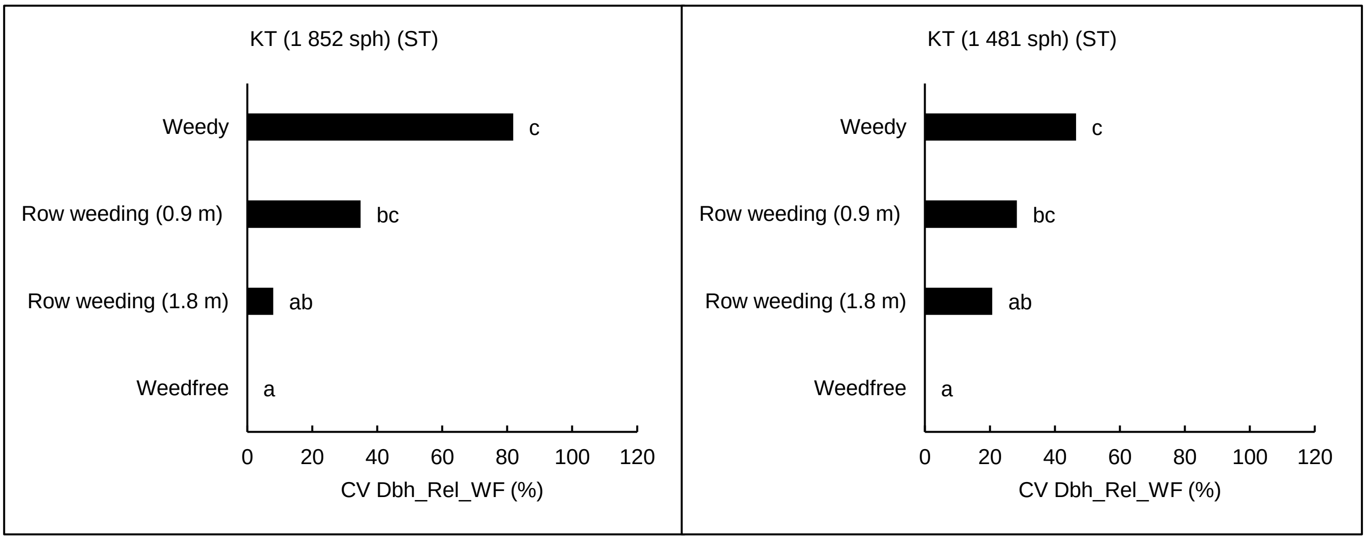
Oaklands: The treatments with the highest variability were those where the vegetation was uncontrolled and in close proximity to the tree (*Burnt x Weedy* (27.4%); *Unburnt x Weedy* (20.6%); *Unburnt x Grass remaining* (17.1%) and *Unburnt x Broadleaves remaining* (21.8%)), with low variability occurring in the rest of the treatments (*Unburnt* x *Weedfree* (11.5%), *Burnt x Weedfree* (10.6%), *Unburnt x Row weeding (2 m)* (11.1%) and *Unburnt x Minipit* (10.3%)). The *Unburnt x Grass remaining* treatment had the lowest variability of the weedy treatments, possibly due to the presence of a uniform grass cover which provided a similar level of competition across all measured trees.



ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

Figure 3.4. Coefficient of variation for Dbh relative to overall best performing treatment (weedfree) at rotation-end for seven eucalypt vegetation management trials in KwaZulu-Natal, South Africa. Within each trial, bars with different letters indicates significant differences, while bars with no letters or same letters indicates non-significance differences (both at $p < 0.05$) as indicated by the Students *t*-test.

Continues from Figure 3.4.



ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

KT: Vegetation management as a main factor was significant (*F* prob = < 0.002) in terms of variability, with no significant interaction occurring for Planting density. There was a decrease in variability with increasing row weeding distance: *Weedy* (41.0%) ≥ *Row weeding (0.9 m)* (33.0%) ≥ *Row weeding (1.8 m)* (28.7%) ≥ *Weedfree* (25.6%).

Mountain Home: Both the *Broadleaves remaining* and *Weedy* treatments (45.3 and 44.9%, respectively) had significantly higher variability than all the other treatments ($\bar{x}$ = 26.5%), which were not significantly different from each other, nor from the *Weedfree* treatment (23.0%).

3.4.3. Categorization of treatment-related risk (relative to the Weedfree treatment)

To allow for the categorization of treatment-related risk in terms tree growth responses (survival, volume and uniformity), treatment differences relative to the respective *Weedfree* treatment were calculated (**Figures 3.2, 3.3 and 3.4**). Generic criteria were then used to partition the relative differences of the treatments for each trial into three risk classes: Low; Moderate; or High (**Table 3.4**).

3.4.3.1. Survival (Stocking_Rel_WF)

Only five treatments in two trials had survival classified as a Moderate risk relative to the *Weedfree* treatment (80-89%) (**Figure 3.2 and Table 3.7**), with the rest of the treatments classified as Low risk (90-100%). These treatments included the *Moderate* *weeding* and *Weedy* treatments (88 and 84% respectively) at Enon, and the *Unimproved x NoFertilization x Weedy* (87%), *Unimproved x NoFertilization x Weedfree* (88%) and *Unimproved x Fertilization x Weedfree* (86%) treatments at Tweefontein (**Figure 3.2**).

3.4.3.2. Volume (Vol_Rel_WF)

The assigning of treatments to the three risk categories was varied, both within and between trials. In general, a Low risk (90-100%) was assigned to those treatments where the vegetation was kept at a sub-competitive level (for example *Grasses remaining* and *Sweet potato* at Mountain Home; *Moderate weeding* at Enon), or where it was kept away from the trees in the form of a ≥1.2 m row weeding (for example *Row weeding* treatments at Oaklands, KT, Mountain Home and Enon) (**Figure 3.3 and Table 3.7**). Treatments that were considered high risk (<79%) included all the *Weedy* treatments at all the trials, with the exception of the *Unimproved x Fertilization x Weedy* treatment at Draycott (85%), and the *Weedy* (1 852 sph) (86%) treatment at KT (both categorized as Moderate risk). Selective weeding (*Grass* and *Broadleaves remaining*), *Low weeding* intensity, the use of *Cover-crops* or where the size of the *Ring/Row weeding* distance was not large enough (<1.2 m) for the removal of competitive vegetation, were also considered high risk treatments. The remaining treatments were considered Moderate risk (80-89%) (**Table 3.7**).

Table 3.7. Overall risk to productivity categorization for rotation-end growth response for vegetation management treatments within seven eucalypt vegetation management trials. South Africa (adapted from **Kliejunas et al. 2006**).

Trial name	Vegetation management treatments	Rotation end tree growth responses			Overall growth risk
		Survival	Yield	Uniformity	
1. Fairbreeze	Weedfree (manual)	L	L	L	L
	Weedfree (chemical)	L	M	L	M
	-Ring weeding (0.5 m)	L	L	H	H
	Row weeding (1.2 m)	L	M	L	M
	Ring weeding (0.5 m)	L	M	H	H
	Cowpea	L	H	M	H
	Velvet bean	L	H	L	H
	Inter-row weeding (1.2 m)	L	H	H	H
	Weedy	L	H	H	H
2. Oaklands	Unburnt x Weedfree	L	L	L	L
	Burnt x Weedfree	L	L	L	L
	Unburnt x Row weeding (2 m)	L	L	L	L
	Unburnt x Broadleaves remaining	L	H	H	H
	Unburnt x Grass remaining	L	H	H	H
	Unburnt x Weedy	L	H	H	H
	Burnt x Weedy	L	H	H	H
3. KT	<u>1 852 sph (2.7 x 2.0 m)</u>				
	Weedfree	L	L	L	L
	Row weeding (1.8 m)	L	L	L	L
	Row weeding (0.9 m)	L	M	H	H
	Weedy	L	M	H	H
	<u>1 481 sph (2.7 x 2.5 m)</u>				
	Weedfree	L	L	L	L
	Row weeding (1.8 m)	L	L	L	L
	Row weeding (0.9 m)	L	H	M	H
	Weedy	L	H	H	H
4. Mountain Home	Weedfree	L	L	L	L
	Sweet potato (1.2 m)	L	L	L	L
	Grasses remaining	L	L	H	H
	Sweet potato	L	L	M	M
	Row weeding (2 m)	L	L	M	M
	Row weeding (1.2 m)	L	M	L	M
	Broadleaves remaining	L	H	H	H
	Weedy	L	H	H	H
5. Enon	Weedfree	L	L	L	L
	Moderate weeding	M	L	L	M
	Low weeding	L	M	L	M
	Row weeding (2 m)	L	L	L	L
	Weedy	M	H	L	H
6. Tweefontein	Improved x Fertilization x Weedfree	L	L	L	L
	Improved x NoFertilization x Weedfree	L	L	L	L
	Unimproved x Fertilization x Weedfree	M	L	L	M
	Unimproved x NoFertilization x Weedfree	M	H	L	H
	Improved x Fertilization x Weedy	L	H	L	H
	Improved x NoFertilization x Weedy	L	H	L	H
	Unimproved x Fertilization x Weedy	L	H	L	H
	Unimproved x NoFertilization x Weedy	M	H	L	H
7. Draycott	Improved x Fertilization x Weedfree	L	L	L	L
	Improved x NoFertilization x Weedfree	L	M	L	M
	Unimproved x Fertilization x Weedfree	L	L	L	L
	Unimproved x NoFertilization x Weedfree	L	L	L	L
	Improved x Fertilization x Weedy	L	H	L	H
	Improved x NoFertilization x Weedy	L	H	L	H
	Unimproved x Fertilization x Weedy	L	M	L	M
	Unimproved x NoFertilization x Weedy	L	H	L	H

L: Low risk; M: Moderate risk and H: High risk

3.4.3.3. Uniformity (Dbh CV_Rel_WF)

Relative to the *Weedfree* treatments, variability ranged between 0-115%, with all treatments classified as Low risk (0-20%) at Tweefontien, Draycott and Enon. With the exception of the *Row weeding (2 m)* treatment at Mountain Home (classified as a Moderate risk) (27%), all the treatments where the vegetation was kept ≥1.2 m away from the trees were also classified as a Low risk. All other treatments were considered high risk (relative variability >31%), with the exception of the *Cowpea* treatment (21%) at Fairbreeze, *Row weeding (0.9 m)* (1 481 sph) treatment (28%) at KT, and the *Sweet potato* treatment (23%) at Mountain Home, which were all regarded as Moderate risk (21-30%) (**Figure 3.4 and Table 3.7**).

3.4.3.4. Overall growth response risk rating

The overall risk rating for each vegetation management treatment was based on the combined risk related to survival, volume and uniformity (**Table 3.7**). Regardless of trial, species planted, and associated site and climatic conditions, all *Weedy* treatments in all trials were regarded as high risk. Although the *Weedy* treatments within both CT climate zone sites (Tweefontein and Draycott) where not significantly different to the *Weedfree* treatments, due to the risk classification, these treatments were also classified as high risk. In addition, all the treatments that had selective weeding (*Grasses* or *Broadleaves remaining*), where the vegetation was in close proximity to the tree (*Cover-crops*, *Inter-row weeding* and *-Ring weeding*), or where the ring/row weeding was not far enough away from the trees (*Ring weeding (0.5 m)* or *Row weeding (0.9 m)*) were also regarded as high risk. Row weeding distances of ≥1.2 m produced variable results, possibly due to site-related competing vegetation type and abundance. A 1.2 m row weeding at Mountain Home (with sweet potatoes), 1.8 m at KT and 2 m at Enon and Oaklands were classified as Low risk, whereas a 1.2 m at Mountain Home and Fairbreeze, and 2 m at Mountain Home were classified as a Moderate risk. Compared to the *Weedfree (manual)* treatment which received a Low risk rating, the use of herbicides in the *Weedfree (chemical)* treatments at Fairbreeze resulted in an overall Moderate risk rating (with reduced yield being the deciding factor). **Little (1999)** attributing the improved growth of the manually weeded treatments to increased nutrient mineralisation on the highly leached soils that were present in this trial following manual weeding.

3.4.4. Vegetation management operations

The number of vegetation management operations and quantity of herbicide applied throughout the rotation was directly related to site productivity, with more operations and herbicide used for the *Weedfree* treatments in the ST ($\bar{x}$ = 10 weeding operations; $\bar{x}$ = 14.1 kg of herbicides applied ha^{-1} or 1.9 kg ha^{-1} yr^{-1}) and WT ($\bar{x}$ = 10 weeding operations; $\bar{x}$ = 12.9 kg of herbicides applied ha^{-1} or 1.4 kg ha^{-1} yr^{-1}) climate zones compared to the CT ($\bar{x}$ = 6 weeding operations; $\bar{x}$ = 6.4 kg of herbicides applied ha^{-1} or 0.8 kg ha^{-1} yr^{-1}) climate zone (**Table 3.6**). These data are similar to that obtained from the herbicide survey from **Chapter 2** on the use of herbicides within the forestry industry in South Africa, with more herbicides used as site productivity increased (CT<WT<ST). Although all sites (treatments) received a pre-plant herbicide application, the subsequent use of herbicides was lower for those treatments that were manually weeded, or where there was a reduction in either intensity of weeding operations, selective control of the vegetation, or where there was a reduced area that was weeded (**Table 3.6**).

The *Weedfree* and *Row weeding* treatments received the highest number of vegetation operations ($\bar{x}$ = 9 and $\bar{x}$ = 10 respectively), with the *Weedy* treatments the least (1). Even though the various *Row weeding* treatments received the same number operations as the *Weedfree* treatments (trial specific), due to the reduced area weeded, the quantity of herbicides applied was less ($\bar{x}$ = 8.4 kg ha^{-1} versus $\bar{x}$ = 12.9 kg ha^{-1} herbicide used respectively). Compared to the *Weedfree* treatments, the use of cover-crops (sweet potatoes, cowpeas or velvet beans) suppressed weed growth once established, resulting in reduced vegetation management operations and quantities of herbicides applied ($\bar{x}$ = 10 versus 6 weeding operations; $\bar{x}$ = 15.1 kg ha^{-1} versus 6.8 kg ha^{-1} herbicide used). At Oaklands and Mountain Home the selective control of vegetation (*Grasses* or *Broadleaves remaining*) resulted in a lowered quantity or herbicide used and/or number of weeding operations compared to the *Weedfree* treatments ($\bar{x}$ = 9 versus 10 operations; $\bar{x}$ = 10.4 kg ha^{-1} versus 13.9 kg ha^{-1} herbicide used respectively). Although this may in part be attributed to rates of application of the selective herbicides used (fluazifop-p-butyl @ 3 kg ha^{-1} and methylphenoxyacetic acid @ 2.5 kg ha^{-1} compared to glyphosate @ 4 kg ha^{-1}), once the desired species becomes dominant on the site through selective weeding, the suppression of new emergent resulted in reduced follow-up control. At KT, the altering of planting density did not have a notable effect on the number of weeding operations scheduled (x = 10), however, the herbicide quantity did differ slightly, with the higher planting density of 1 852 sph receiving less herbicides compared to the lower planting density of 1 481 sph (ca. 0.5 kg ha^{-1} less).

3.4.5. Linking weeding intensity (number of weeding operations and herbicide use) to tree growth (survival, volume and uniformity) risk

Within forestry, the ideal vegetation management treatment would be one where tree growth is not impacted by competing vegetation with the lowest input in terms of weeding operations and herbicide use (or lowest cost). Regardless of the trials, there was a direct link between improved tree growth with an increase in weeding operations and herbicide use (**Table 3.8**). However, irrespective of vegetation management treatment, cognisance needs to be taken of any negative environmental and/or social impacts associated for any specific treatment. For example, there is the potential for active ingredients to move off-site and accumulate within watersheds or catchments for those treatments that rely on the use of herbicides (even if low quantities are applied) (**Baillie 2016**). Likewise, those treatments that make use of manual weeding require increased labour units, are not considered ergonomically favourable, and they are generally more costly than where herbicides are used (**Little et al. 2002; Wagner et al. 2006; Steenkamp 2007; Willoughby et al. 2009; McEwan and Steenkamp 2014**). Taking the above into consideration, the treatments within each trial were partitioned into three broad scenarios based on tree growth (survival, volume and uniformity) and herbicide-use.

Table 3.8. Two-way table linking rotation-end tree growth responses to herbicide use for various vegetation management treatments within seven eucalypt vegetation management trials in KwaZulu-Natal. South Africa. Darker shading indicates more desirable treatment options in terms of optimum tree performance (survival. growth and uniformity) together with reduced herbicide-use.

Trials	*Herbicide use rating	Tree growth risk response rating Low	Moderate	High
1. Fairbreeze	Low	-	-	Weedy
	Moderate	Weedfree (manual)	Row weeding (1.2 m)	Cowpea Velvet bean Inter-row weeding (1.2 m)
	High	-	Weedfree (chemical)	-Ring weeding (0.5 m) Ring weeding (0.5 m)
2. Oaklands	Low	-	-	Unburnt x Weedy Burnt x Weedy
	Moderate	Unburnt x Row weeding (2 m)	-	-
	High	Unburnt x Weedfree Burnt x Weedfree	-	Unburnt x Broadleaves remaining Unburnt x Grasses remaining
3. KT 1 852 sph (2.7 x 2.0 m)	Low	-	-	Weedy
	Moderate	Row weeding (1.8 m)	-	Row weeding (0.9 m)
	High	Weedfree	-	-
3. KT 1 481 sph (2.7 x 2.5 m)	Low	-	-	Weedy
	Moderate	Row weeding (1.8 m)	-	Row weeding (0.9 m)
	High	Weedfree	-	-
4. Mountain Home	Low	-	-	-
	Moderate	Sweet potato (1.2 m)	Sweet potato Row weeding (1.2 m)	Grasses remaining Broadleaves remaining Weedy
	High	Weedfree	Row weeding (2 m)	-
5. Enon	Low	-	-	Weedy
	Moderate	Row weeding (2 m)	Low weeding	-
	High	Weedfree	Moderate weeding	-
6. Tweefontein	Low	-	-	Imp_Fert_Weedy Imp_NoFert_Weedy Unimp_Fert_Weedy Unimp_NoFert_Weedy
	Moderate	Imp_Fert_Weedfree Imp_NoFert_Weedfree	Unimp_Fert_Weedfree	Unimp_NoFert_Weedfree
	High	-	-	-
7. Draycott	Low	-	Unimp_Fert_Weedy	Imp_Fert_Weedy Imp_NoFert_Weedy Unimp_NoFert_Weedy
	Moderate	Imp_Fert_Weedfree Unimp_Fert_Weedfree Unimp_NoFert_Weedfree	Imp_NoFert_Weedfree	-
	High	-	-	-

*Herbicide use rating for total quantities of herbicides applied ha^{-1}
Low: <5 kg ha^{-1}
Moderate: 5-10 kg ha^{-1}
High: >10 kg ha^{-1}

3.2.5.1. Maximisation of timber production

This approach is favoured by most forest companies within SA, whereby silvicultural inputs are structured to ensure optimum volume is obtained in a sustainable cost-effective manner (taking both environmental and/or social impacts into consideration) (**Little and Dyer 2002; Little et al. 2018b**). For example, in a study on the financial performance of vegetation management on *E. smithii*, **Little et al. (2018b)** found that even though the weedfree treatment was labour-intensive and used the most herbicides of all treatments (it was also the most expensive to implement), it had the highest volume as well as highest return on investment compared to the other treatments. Similar trends were obtained when comparing the treatments that formed part of this trial series, where the *Weedfree* treatments had the lowest tree growth risk ratings at rotation-end, albeit it with an associated high herbicide use rating at rotation end (>10 kg ha^{-1} herbicides applied) (**Table 3.8**). The exception to this was at Fairbreeze where the *Weedfree* (chemical) had a Moderate tree growth risk rating and high herbicide use rating compared to the *Weedfree* (manual) treatment, and one of the four *Weedfree* treatments at each of the two CT trials (Tweefontein and Draycott). However, compared to the other trials, all the *Weedfree* treatments at Tweefontein and Draycott had fewer weeding operations together with lowered herbicide use (**Table 3.6**), resulting in a Moderate herbicide use rating for these two trials (**Table 3.8**).

3.2.5.2. Compromise between timber production and herbicide use

This approach focusses on the selection of treatments whereby optimum tree growth is balanced against reduced herbicide use. Since the number of weeding operations and herbicide use are linked to vegetation management operations (regardless of whether a selective spray, ring or row weeding is used), the treatments classified as Low to Moderate risk for tree growth responses, and Moderate risk for herbicide use rating (5-10 kg ha^{-1} herbicides applied) would be preferred. A total of 11 treatments across all trials fulfilled these criteria and included the following treatments: *Weedfree (manual)* at Fairbreeze; *Sweet potato (1.2 m)* at Mountain Home; and the *Row weeding (≥1.2 m)* treatments at Oaklands, KT and Enon (**Table 3.8**). Even though the *Weedfree (manual)* treatment at Fairbreeze was included within these treatments, the high costs associated with manual weeding (**Little et al. 2002**), coupled with decreasing labour availability (urban migration), high labour turnover and absenteeism related to health (HIV, Aids and the continued impact of COVID-19), and reduced ergonomic acceptability all contribute to the move away from the intensive use of manual labour for silvicultural operations within SA (**Little et al. 2002; Steenkamp 2007; McEwan and Steenkamp 2014; Zabel 2020**). Limited weed growth in the CT region resulted in fewer weeding operations (and reduced herbicide use), with two and three of the *Weedfree* treatments at Tweefontein and Draycott (respectively) being included within this group of treatments.

3.2.5.3. Focus on reduced herbicide-use

If the focus were on a reduction in herbicide use and labour so as to reduce any environmental and/or social impacts, then all the treatments not included in the above two scenarios would be included, together with a resulting accepted loss of timber production. The treatments within this scenario could be partitioned into three broad groups:

- less than 5 kg ha^{-1} herbicide applied + high tree growth risk rating: all the *Weedy* treatments;
- between 5-10 kg ha^{-1} herbicide applied + high tree growth risk rating: all the *Ring/Row weeding* treatments that were <1.2 m, all the *Selective weeding* treatments, and the velvet bean and cowpea *Cover-crop* treatments; and
- between 5-10 kg ha^{-1} herbicide applied + Moderate tree growth risk rating: the 1.2 m *Row weeding* at Fairbreeze and Mountain Home, the *Low intensity weeding* at Enon, and the *Sweet potato* treatment at Mountain Home.

3.5. Conclusions

Tree growth responses (survival, volume and uniformity) obtained at rotation end for the seven trials were a function of inherent site conditions, previous land use, species planted and the manner in which the competing vegetation was managed. Generally, the trials situated within the ST and WT climate zones (MAI between 28-48 m^3 ha^{-1} $annum^{-1}$) had better tree growth compared to the CT climate zone (MAI of 26-28 m^3 ha^{-1} $annum^{-1}$), which can be attributed to the higher mean annual rainfall, temperatures and increased number of growth days associated with these climatic zones. As for tree growth, weed abundance and growth was higher on these sites (CT: $\bar{x}$ = 1.3 tons ha^{-1}; WT: $\bar{x}$ = 8.8 tons ha^{-1}; ST: $\bar{x}$ = 9.4 tons ha^{-1}), which resulted in higher levels of weeding required (6 weeding operations for CT and 10 weeding operations for both

WT and ST). Similarly, within any specific trial, the more intensive the weeding (number, area treated and/or herbicide use), the better the growth obtained (*Weedfree* treatments always optimum).

A range of vegetation management treatments were tested (for example selective control of vegetation types, different row/ring weeding distances, planting of cover-crops within the interrow of planted trees, different weeding intensities treatments etc.), with each treatment having different number of weeding operations scheduled and quantity of herbicides applied. Generally, an increase in herbicide use was linked to an increase in the number of weeding operations scheduled (including method of control). For example, if the pre-plant weeding operations (with Roundup® @ 4 kg ha^{-1} formulated product) are excluded from each treatment, with herbicide use from planting to rotation end only considered (from establishment phase onwards), herbicide quantities applied ranged from 0-11.6 kg ha^{-1} (over $\bar{x}$ = 8.1 yrs) formulated product applied across ca. 0-9 weeding operations (*Weedy*>*Weedfree*).

Since tree growth responses were linked to weeding intensity (and hence herbicide use), and if the aim of the grower is to maximise volume, then complete vegetation management is required (*Weedfree* treatments). However, herbicide use can be reduced while obtaining similar tree growth responses to that of full vegetation management. Competing vegetation within ST and WT climate zones can be managed through manual removal with bush knifes (or slashers), clearing any vegetation within a ≥1.2m row width, or the planting of sweet potatoes within the interrow (no alternative weeding treatments tested in CT climate zones). If reduced herbicide use is the main focus, leaving all competing vegetation untreated would be the preferred treatment, albeit with negative impacts on tree growth, specifically on the more productive ST and WT climate zones.

The combined results from the seven trials indicates the importance of vegetation management in terms of ensuring eucalypt production, with a higher intensity of weeding favoured, albeit with an increase in herbicide use. Although the economic viability of the various treatments needs to be determined, this chapter was focussed on linking the level of weed control to tree growth and herbicide use. By doing this, the information from this trial series can also be used for the determination of social and environmental risk factors associated with each vegetation management treatment tested (which is currently lacking in SA).

CHAPTER 4. LINKING PINE PERFORMANCE TO VEGETATION MANAGEMENT TREATMENTS AND HERBICIDE USE: RESULTS FROM 12 PULPWOOD TRIALS, SOUTH AFRICA

4.1. Introduction

Since the introduction is the same as the one in **Chapter 3** (with the same theme about vegetation management within commercial forestry), for brevity it has not been repeated. Similar to Chapter 3, the objective of this research was to enable a more holistic approach to assessment of risk as determined by the quantities of herbicides during pine establishment. Tree growth data up to 10 years from twelve pine vegetation management trials with different vegetation management treatments (including type and quantity of herbicide) was used to develop an herbicide risk assessment (decision support) system for the selection of appropriate vegetation management options when establishing pines in South Africa.

4.2. Materials and methods used for pine trials

Twelve vegetation management trials implemented on pines in the early 1990's was selected for inclusion in the analysis (**Table 4.1**). The trials occurred across diverse sites within the summer rainfall region of SA (in KwaZulu-Natal and Mpumalanga) and had a minimum age of 9.5 years. All the trials were implemented and managed by the Institute for Commercial Forestry Research, in Pietermaritzburg South Africa. Dependent on site and end-product, species were matched to the various sites based on their suitability to climate and susceptibility to site-specific abiotic and biotic risk factors and planted at appropriate densities (from 816 - 1 372 sph) (**Swain and Gardner 2003; Smith et al. 2005b**). These trials also covered a range of altitudinal (45 - 1 469 m a.s.l.), climatic (sub-tropical (ST), warm (WT) and cool temperate (CT)) and productivity gradients.

Table 4.1. Site characteristics for 12 vegetation management trials implemented on pines in the summer rainfall region of South Africa.

Site characteristics		Trial names						
		Kwambonambi	Bergvliet_A	Bergvliet_B	Hlabeni	Mountain Home	Longridge	Spitzkop
Magisterial District		Lower Umfolozi	Pilgrims Rest	Pilgrims Rest	Ixopo	Pietermaritzburg	Pilgrims Rest	Pilgrims Rest
Latitude **Longitude**		28º 36.854′ S 32º 11.515′ E	25º 04.509′ S 30º 54.000′ E	25º 04.761′ S 30º 52.950′ E	29º 59.795′ S 29º 48.510′ E	29º 33.958′ S 30º 17.010′ E	25º 07.725′ S 30º 44.268′ E	25º 09.344′ S 30º 48.301′ E
Altitude (m a.s.l.)		55	880	980	1 055	1 181	1 219	1 400
Mean annual rainfall (mm)		1 085	1 321	1 271	842	1 062	1 348	1 155
Mean annual temperature (°C)		21.6	18.7	18.5	16.7	16.3	17.5	16.6
[1]**Climate class**		Sub-tropical	Warm temperate	Warm temperate	Warm temperate	Warm temperate	Warm temperate	Warm temperate
Species planted		*P. elliottii x P. caribaea*	*P. elliottii*	*P. elliottii*	*P. greggii*	*P. greggii*	*P. elliottii*	*P. elliottii* *P. patula* *P. taeda*
Date planted		23/08/1996	15/01/1997	09/12/1998	19/11/1998	03/09/1997	15/09/1997	02/11/1995
Date felled		14/07/2010	12/03/2009	24/11/2015	28/06/2010	17/05/2007	14/05/2007	23/04/2007
Age felled		5 073 d 13.9 y	4 439 d 12.2 y	6 194 d 16.9 y	4 239 d 11.6 y	3 543 d 9.7 y	3 528 d 9.7 y	4 190 d 11.5 y
Spacing (planting density)		3.5 x 3.5 m (816 sph)	3.5 x 3.5 m (816 sph)	3.5 x 3.5 m (816 sph)	3 x 3 m (1 111 sph)	3 x 3 m (1 111 sph)	3 x 3 m (1 111 sph)	1.75 x 1.75 m and thinned to 3.5 x 3.5 m (816 sph)
Previous crop		*Pinus elliottii* sawtimber	*P. elliottii sawtimber*	*Pinus patula* sawtimber	Ex-agricultural (maize)	*Eucalyptus grandis* pulpwood	*P. elliottii* sawtimber	*Pinus patula* sawtimber
Management of harvest residues		burnt	broadcast	broadcast/removed	-	burnt	broadcast	burnt
Potential productivity	Growing conditions	Optimum	Optimum	Optimum	Optimum – drought risk	Optimum	Optimum	All species = Optimum
	Mean annual increment (m^3 ha^{-1} $annum^{-1}$)	27.4 (9.7 y)	12.4 (9.2 y)	10.2 (9.3 y)	34.2 (9.5 y)	19.3 (10.4 y)	13.4 (9.7 y)	*P. elliottii* 10.9 (9.5 y) *P. patula* 11.5 (9.5 y) *P. taeda* 7.0 (9.5 y)

[1]Data obtained from Smith et al. (2005) and ICFR Trial research database

Continues from Table 4.1.

Site characteristics		Trial names				
		Langgewacht	Mt Gilboa	Blyde	Mossbank	Ceylon
Magisterial District		Umzimkulu	Lions River	Pilgrims Rest	Polela	Pilgrims Rest
Latitude		30° 30.585′ S	29º 15.749′ S	24º 49.906′ S	29º 49.234′ S	25º 06.008′ S
Longitude		29° 38.337 E	30º 18.786′ E	30º 51.502′ E	29º 42.177′ E	30º 39.378′ E
Altitude (m a.s.l.)		1 385	1 500	1 538	1 826	1 935
Mean annual rainfall (mm)		743	1 118	1 247	970	1 211
Mean annual temperature (°C)		15.7	13.7	15.5	13.4	13.8
[1]Climate class		Cool temperate	Cool temperate	Cool temperate	Cool temperate	Cool temperate
Species planted		*P. elliottii*	*P. patula*	*P. patula*	*P. patula*	*P. elliottii* *P. patula* *P. taeda*
Date planted		15/01/2008	01/08/2000	29/10/1998	26/10/1995	07/11/1995
Date felled		03/07/2017	18/07/2016	23/11/2015	13/04/2010	16/05/2007
Age felled		3 457d 9.5 y	5 830d 15.9 y	6 234d 17.1 y	5 283d 14.5 y	4 208d 11.5 y
Spacing (planting density)		2.7 x 2.7 m (1 372 sph) 3 x 3 m (1 111 sph) 3.5 x 3.5 m (816 sph)	3 x 3 m (1 111 sph)	3.5 x 3.5 m (816 sph)	3 x 3 m (1 111 sph)	1.75 x 1.75 m and thinned to 3.5 x 3.5 m (816 sph)
Previous crop		*P. taeda* sawtimber	*Pinus patula* pulpwood	*Pinus taeda* sawtimber	*Pinus patula* pulpwood	*Pinus patula* sawtimber
Management of harvest residues		broadcast	broadcast	burnt/broadcast/chopper-rolled	broadcast	burnt
Actual productivity	Growing conditions	Optimum	Optimum	Optimum	Risk of snow damage	All species = Risk of snow damage
	Mean annual increment (m^3 ha^{-1} $annum^{-1}$)	9.5 (9.5 y)	15.9 (9.8 y)	17.7 (9.4 y)	19.0 (10.4 y)	*P. elliottii* 6.0 (9.5 y) *P. patula* 9.7 (9.5 y) *P. taeda* 5.5 (9.5 y)

[1]Data obtained from Smith et al. (2005) and ICFR Trial research database

4.2.1. Vegetation management treatments implemented across the pine field trials

Dependent on trial objectives and site type, various vegetation management treatments were tested that differed in terms of weeding intensity (high, moderate, low intensity and no vegetation control), area weeded (ring weeding distances), selective control of vegetation types (grasses and herbaceous or woody broadleaves), and additional practices (such as slash management, soil preparation, fertilization and varying planting densities) (**Table 4.2 and 4.3**). The main vegetation management treatments included:

- Weedfree (high intensity weeding – all trials)

The growth of the vegetation was closely monitored, with full vegetation control carried out whenever the vegetation reached ankle height. This type of control would ensure that any vegetation would remain at a sub-competitive level, thus providing an estimate of optimum tree growth for the prevailing conditions for the duration over which the trial was conducted.

- Weedy (no vegetation control – all trials excepting for Spitzkop)

Following a pre-plant weed control operation to remove all on site vegetation, no further vegetation control was carried out in this treatment following planting. This treatment was used to characterise the vegetation specific to the site, as well as the maximum potential loss of production (in terms of tree growth) in the presence of the inter-specific competition. Unfortunately, contractors working in an adjacent compartment inadvertently slashed the woody weeds in the weedy plots at the Spitzkop trial on two occasions (at 5 and 8 yrs). As such, there was no weedy treatment at this trial, with the weedy treatment for Spitzkop subsequently referred to as a “Low intensity weeding” treatment.

- Moderate (or operational) intensity weeding (Kwambonambi, Bergvliet_A, Mountain Home and Mossbank)

As for the weedfree treatment, complete vegetation control was carried out but, where possible, there was a delay in the operations resulting in some degree of tree growth suppression.

Table 4.2. Trial design and trial means, standard errors (s.e.d) and coefficient of variations (CV) up to 10.4 years in 12 vegetation management trials implemented on pines in the summer rainfall region of South Africa.

	Trial Name	Trial design					Tree growth variates: Survival Stocking (sph)			Growth Volume (m^3 ha^{-1})			Uniformity CV Dbh (%)			Trial data based on research publications
		Treatments (n)	Replications (n)	Design	Total number of plots (n)	Age of data analysed (y)	Grand mean (sph)	s.e.d (units)	CV (%)	Grand mean (m^3 ha^{-1})	s.e.d (units)	CV (%)	Grand mean (%)	s.e.d (units)	CV (%)	
1	Kwambonambi	7	4	RCBD	28	9.7	671	60.2	18.0	184.9	19.3	20.9	20.0	1.9	19.0	Little and Rolando (2001)
2	Bergvliet_A	6	5	RCBD	30	9.2	642	80.5	28.0	99.8	5.5	12.4	23.2	6.1	52.8	Little and Rolando (2001)
3	Bergvliet_B	6	3	3 x 2 Factorial	18	9.3	703	29.1	10.1	61.1	5.6	16.0	19.4	5.3	44.9	Ndlovu et al. (2019c)
4	Hlabeni	16	3	4 x 4 Factorial	48	9.5	953	102.9	18.7	314.6	25.9	14.3	19.8	2.8	24.5	Ndlovu et al. (2019a)
5	Mountain Home	6	5	RCBD	30	10.4	993	46.1	10.4	182.4	12.3	15.0	22.5	2.7	28.0	Little and Rolando (2001)
6	Longridge	10	3	2 x 5 Factorial	30	9.7	1 028	38.5	6.5	125.7	12.9	17.8	15.0	3.0	34.5	Little and Rolando (2006)
7	Spitzkop	6	4	3 x 2 Factorial	24	9.5	752	39.1	10.4	93.4	11.5	24.6	14.7	2.7	37.0	Little (2012)
8	Langgewacht	9	3	3 x 3 Factorial	27	9.5	629	29.4	5.5	84.5	6.5	9.3	14.9	1.9	20.0	-
9	Mt Gilboa	6	4	RCBD	24	9.8	870	45.9	10.5	155.7	6.5	8.3	16.9	1.2	13.9	-
10	Blyde	16	3	2 x 4 x 2 Factorial in Strip-Split Plots	48	9.4	668	42.6	14.8	166.0	10.4	16.8	18.6	1.4	11.6	Ndlovu et al. (2019b)
11	Mossbank	7	4	RCBD	28	10.4	1 048	38.6	7.4	197.8	7.3	7.4	15.8	2.7	34.7	Little and Rolando (2001)
12	Ceylon	6	4	3 x 2 Factorial	24	9.5	748	34.4	9.2	67.1	10.6	31.5	17.8	3.0	34.0	Little (2012)

RCBD: randomized complete blocks design

Table 4.3. Treatments occurring within 12 vegetation management trials implemented on pines in the summer rainfall region of South Africa.

No.	*Trial Name	Slash Management	Soil Preparation	Fertilization	Vegetation management: Weedfree (High intensity)	Weedy	Moderate/ Low intensity	Ring	Selective control (Vegetation remaining): Grass	Herbaceous broadleaves (HBL)	Perennial broadleaves (PBL)
1	Kwambonambi				✓	✓	✓	(2 m Ferns remaining)	✓	✓	✓
2	Bergvliet_A				✓	✓	✓	(1.5 m)		✓	✓
3	Bergvliet_B	Clear Single Double			✓	✓					
4	Hlabeni			No Fertilization NPK Maxiphos Agriphos	✓	✓		(1 m) (2 m)			
5	Mountain Home				✓	✓	✓	(2 m)	✓	✓	
6	Longridge			✓	✓	✓			✓	✓	✓
7	[1]Spitzkop				✓		✓ (Low intensity weeding)				
8	[2]Langgewacht				✓	✓	✓ (Low intensity weeding)				
9	[3]Mt Gilboa				✓	✓					
10	Blyde	Burn	Pit Rip Chopper roll Chopper roll and rip		✓	✓					
11	Mossbank			Weedfree and Weedy only	✓	✓	✓		✓	✓	✓
12	[1]Ceylon				✓	✓					

*These trials had additional factorial combinations that could have an indirect influence on vegetation management.
[1]Spitzkop and Ceylon: Three pine species (*Pinus elliottii*, *P. patula* and *P. taeda*) with and without vegetation management
[2]Langgewacht: Factorial combination with vegetation management and three planting densities (1 372 versus 1 111 versus 816 sph)
[3]Mt Gilboa: Four different mulches (kraft paper. biomac. plantex and sludge) with and without vegetation management

- Low intensity weeding (Langgewacht and Spitzkop)

Vegetation control operations in this treatment were delayed to coincide with every second operation that was carried out in the weedfree treatment. A higher degree of tree growth suppression was expected, together with an associated reduction in vegetation control costs and herbicide use.

- Ring weeding (1 m, 1.5 m or 2 m) (Kwambonambi, Bergvliet_A, Hlabeni and Mountain Home)

Ring weeding treatments were implemented whereby all vegetation within the specified diameter was controlled manually. Depending on the trial, the vegetation outside of the ring was allowed to grow uncontrolled, or it was selectively weeded. For example, all competing vegetation was removed except for ferns at Kwambonambi (2 m ring with ferns remaining), grasses or grasses and broadleaves at Bergvliet_A (1.5 m ring with either grasses or grasses and broadleaves remaining) and grasses at Mountain Home (2 m ring with grasses remaining). Although the timing of vegetation control within this treatment would be similar to that of the weedfree treatment, the reduction in the area kept free of vegetation would lead to a reduction in herbicides used.

- Selective weeding (Kwambonambi, Bergvliet, Mountain home, Longridge and Mossbank)

Selective herbicides were used for the control of broad vegetation groups (grasses, herbaceous broadleaves (HBL) or perennial broadleaves (PBL)) to determine their relative competitiveness with the planted trees.

- Additional treatments (Bergvliet_B, Hlabeni, Longridge, Mt Gilboa, Blyde and Mossbank)

Additional vegetation management treatments were included in seven trials to answer specific trial objectives, and although all included the use of herbicides, these were at reduced rates when compared to other vegetation management treatments.

(i) Slash management: At Bergvliet_B, post-harvesting slash was either completely removed from treatment plots (clear), retained but evenly broadcasted (single), or extra slash (obtained from clear treatment) added and evenly broadcasted (double). At Blyde, the retention of post-harvesting slash was compared to the burning of the slash to determine if slash would prevent (or delay) the development of competing vegetation.

(ii) Soil preparation (Blyde): Different soil preparation (pitting, ripping, chopper roll and chopper roll + ripping) treatments were carried out to determine if the planted seedling would be able to out-grow competing vegetation due to the added benefit of improved root-to-soil contact which according to **Light (2015)** and **Dovey (2016)** enhances early seedling survival and growth. The pitting treatment consisted of manual pitting (standard pit dimensions: 20 cm deep and 20 x 20 cm wide) using a mattock with the slash first removed around the area to be pitted. This treatment was the standard against which the other treatments in this trial were compared. Ripping was carried out to a depth of 40 cm with a Caterpillar D7 to prepare a planting position, and not for the amelioration of any soil physical limitations. The chopper roller consisted of a large cylindrical drum with cutting blades, drawn by a skidder. Chopper rolling was carried out to break down the slash, facilitating the preparation of quality pits in slash. The Chopper roll + ripping treatment consisted of a combination of chopper rolling, followed by ripping to a depth of 40 cm.

(iii) Fertilization (Hlabeni, Longridge and Mossbank): As for soil preparation, fertilizer was added to determine if the rapid early seedling growth could reduce the establishment phase and hence duration of vegetation management.

(iv) Tree-row planting spacing (Langgewacht site only): Planting trees closer within the tree rows should result into earlier canopy closure, thereby reducing the period required to control vegetation in the tree rows.

(v) Mulches: At Mt Gilboa, four different mulches (kraft paper broad, plantex (polyester), biomac (hessian) and sludge (wet formulation of 7.5 kg pulp mill waste mixed with 10 litres water)) were applied to a 1 m^2 square around the trees to determine their ability to supress weed germination and growth.

4.2.2. Tree growth measurements used for the pine trial sets

4.2.2.1. Tree growth variates

Tree growth variates of height (Ht in m) and diameter at breast height at 1.3m (Dbh in cm) were measured on a regular basis throughout all 12 trials. Stocking (stems ha^1 (sph)) was derived from survival data and, together with Dbh and Ht measurements, merchantable volume in m^3 ha^{-1} (underbark volume to a top end diameter of 7.5 cm) was calculated. To compare uniformity between different treatments, the coefficient of variation for Dbh (CV Dbh in %) was calculated on a treatment plot basis (Equation 4).

Although five of the 12 trials had rotation-end data (Kwambonambi, Bergvliet_B, Hlabeni, Mt Gilboa and Blyde), the remaining trials were terminated early as a result of accidental felling, or loss due to abiotic/biotic factors (for example wildfire or baboon damage etc.). Using existing pine growth models, attempts were made to extrapolate data for those 7 trials with shorter-term data through to 17 years. This, however, was not successful due to the narrow range of species and tree class sizes that were used for the generation of these models, in contrast to the range of pine species and volumes represented by these trials/treatments. Subsequently, a 9.2 to 10.4 year cut-off was selected for comparison, as this was a common measurement date for all trials. This chosen period is also representative of the duration within which intensive vegetation control practices are carried out commercially in pine plantations in SA (**Rolando and Little 2009**).

4.2.2.2. Relative treatment differences (Stocking, Volume and Dbh CV)

To allow for comparisons within and between pine trials, the performance of the treatments was determined relative to the best performing *Weedfree* treatment within each trial. Relative differences were calculated for survival (Stocking_Rel_WF), volume (Volume_Rel_WF) and uniformity (CV Dbh_Rel_WF).

4.2.2.3. Vegetation abundance, management operations and herbicide use

For each site, predominant species type was identified, and vegetation abundance quantified by taking above-ground vegetation biomass samples (3 × 1 m^2 quadrats) from the weedy plots. All samples were removed from the buffer rows to avoid any impact on the performance of the measured trees. These were oven dried at 80°C to a constant mass and then weighed. Although the method and timing of vegetation management operations were recorded for each treatment within each trial, the level of detail varied according to field staff responsible for the management of each trial. Where the level of detail was high, the method and number of weeding events per treatment could be used together with the determination of the quantities of herbicide applied. For those trials where detail was lacking, the events recorded were compared to similar weeding treatments implemented in a series of four pine vegetation management trials by **Little and Rolando (2001)** and **Rolando and Little (2009)**, with any missing information incorporated into the current trial series.

4.2.3. *Methods used for vegetation control during the implementation of the vegetation management treatments across the eucalypt and pine trials*

All vegetation control operations were carried out using methods reflecting current practices used within the South African forest industry when the trials were implemented. These included manual or chemical weed control in the form of a:

- Pre-plant spray: Complete cover spray with Roundup® (isopropylamine salt of glyphosate 360 g a.i. kg^{-1}) @ 4 kg ha^{-1} formulated product on all vegetation within site prior to the planting of the seedlings. All trials, and hence all treatments received a pre-plant spray.
- Coning operation: Inverted plastic cones were placed over each seedling as protection from spray drift, with the rest of the area receiving a full cover spray. Roundup® (isopropylamine salt of glyphosate 360 g a.i. kg^{-1}) @ 4 kg ha^{-1} was applied in all treatments except for the selective weeding treatments, where either Fusilade® (fluazifop-p-butyl 150 g a.i. kg^{-1}) @ 3 kg ha^{-1}, MCPA® (4-chloro-2-methylphenoxyacetic acid 400 g a.i. kg^{-1}) @ 2.5 kg ha^{-1}, or Garlon® 480 EC (triclopyr (pyridyloxy compound) (as butoxy ethyl ester) 480 g a.i. kg^{-1}) @ 2.5 kg ha^{-1} was applied to control either grasses, HBL or PBL respectively.
- Chemical hoe: Directed, but broadcast application of herbicides (as for the coning operation) onto the vegetation once the trees were too large for a coning operation. Care was taken to prevent any herbicide coming into contact with the tree stem or foliage.
- Spot spray: A directed spray was carried out (using the same herbicides as the coning operation) onto individual plants or clusters of vegetation where there was not a full cover of vegetation. This type of spraying operation also occurred post-canopy closure.
- Slash: Vegetation (mainly large woody perennial weeds) were manually cut at ankle height with either a machete or bushknife, with Garlon® 480 EC (triclopyr (pyridyloxy compound) (as butoxy ethyl ester) 480 g a.i. kg^{-1}) @ 2.5 kg ha^{-1} applied to the cut surface.
- Ring weeding: Manual removal of vegetation, either by hand or with a mattock, from a predetermined area surrounding the seedling. A 0.5 m ring weeding was carried out prior to all coning operations to remove those weeds covered by the cones.

4.2.4. Data analysis used for all pine trial data sets

Analysis of variance (ANOVA) was used to test for all treatment effects across the selected pine trials. Only if the *F* value was significant ($p < 0.05$) were treatment differences further investigated using Student's t-test least significant difference (lsd) statistic. Prior to all analyses, the assumptions underlying a valid analysis of variance were tested (Shapiro-Wilk test for normality and Levene's test for homogeneity of variances). All comparisons between the tree variates were performed on plot means using Genstat® for Windows™ 16th Edition (**VSN International, Hemel Hempstead, UK, 2018**). Descriptive statistics was also used in the form of tables and figures to assist with the description of the vegetation management and herbicide-data obtained (means and standard deviation).

4.3. Tree performance risk associated with reduced levels of vegetation management for pine trial data sets

To determine the risk associated with reduced levels of vegetation management in terms of decreased stocking and volume and increased variability, the treatments within each trial were partitioned into three risk classes (Low, Moderate or High) relative to that trials *Weedfree t*reatment (**Table 4.4**). Herbicide use rating for total quantities of herbicides applied ha^{-1} was also partitioned into three risk classes (Low, Moderate or High). Vegetation management treatments with less than 5 kg herbicides applied ha^{-1}, were considered Low risk, whereas herbicide quantities applied between 5-10 kg ha^{-1} considered Moderate risk and High risk where more than 10 kg ha^{-1} was applied. Although the criteria used to partition the risk classes were selected to illustrate principles, they can be adjusted to correspond with company-specific tree performance criteria.

(i) Stocking_Rel_WF: This risk class was based on tree survival targeted by the forest industry (≥90%) to be achieved at canopy closure (**Vireo et al. 2002; Ndlovu et al. 2019a, 2019b, 2019c**), with treatment survival between 90-100% relative to the *Weedfree* treatment considered a Low risk, 80-89% a Moderate risk, <79% a High risk.

(ii) Vol_Rel_WF: For the partitioning of volume into risk classes, data from the research trials within which significant treatment differences occurred were used. The mean values for each level of significance were combined, with treatment volume differences relative to the *Weedfree* treatment compared. Treatment values between

90-100% relative to the *Weedfree* treatment were considered Low risk, 80-89% a Moderate risk, and <79% a High risk.

(iii) CV Dbh_Rel_WF: The impacts of vegetation management on eucalypt variability by **Little et al. (2003)** were used for the partitioning of these risk classes. Results from this research indicated a Dbh coefficient of variation of between 0-20% for the *Weedfree* treatments, and >30% for the weedy treatment. Subsequently, treatment variability between 0-20% relative to the *Weedfree* treatment were considered Low risk, 21-30% a Moderate risk and >31% a High risk.

Depending on the allocation of risk for Stocking_Rel_WF, Volume_Rel_WF and CV Dbh_Rel_WF, the overall growth risk could be partitioned into one of the three risk classes (Low, Moderate, or High) for each vegetation management treatment. For example, if all three growth responses were classified as Low risk, overall growth risk would be considered Low risk (**Table 4.4**). Whereas, if any of the three growth responses were classified as high, overall risk would also be considered high risk.

Table 4.4. Risk categorization for rotation-end growth responses relating to vegetation management within seven vegetation management trials implemented on eucalypts in the summer rainfall region of South Africa. (adapted from **Kliejunas et al. 2006**).

Risk rating	Survival (Stocking_Rel_WF (%))	Volume (Vol_Rel_WF (%))	Uniformity (CV Dbh_Rel_WF (%))
Low (L)	90-100	90-100	0-20
Moderate (M)	80-89	80-89	21-30
High (H)	< 79	< 79	>31

Rotation-end growth responses			Overall risk
Survival	Yield	Uniformity	
H	H	H	H
M or L	M or L	H	H
M or L	H	M or L	H
H	M or L	M or L	H
M	M	M	M
L	M	M	M
M	L	M	M
M	L	L	M
L	M	L	M
L	L	M	M
L	L	L	L

4.3.1. Linking of vegetation management treatments to reduce herbicide use

A two way-contingency table was used to link the quantity of herbicide applied ha^{-1} for each vegetation management treatment within each eucalypt and pine trial with the tree growth risk rating obtained for that specific treatment (**Table 4.4**). This would allow the partitioning of the different vegetation management treatments in terms of quantity of herbicide applied (lower more desirable), with the tree growth responses obtained at final measurement (higher more desirable).

4.4. Results and Discussion

4.4.1. Vegetation type and biomass across sites

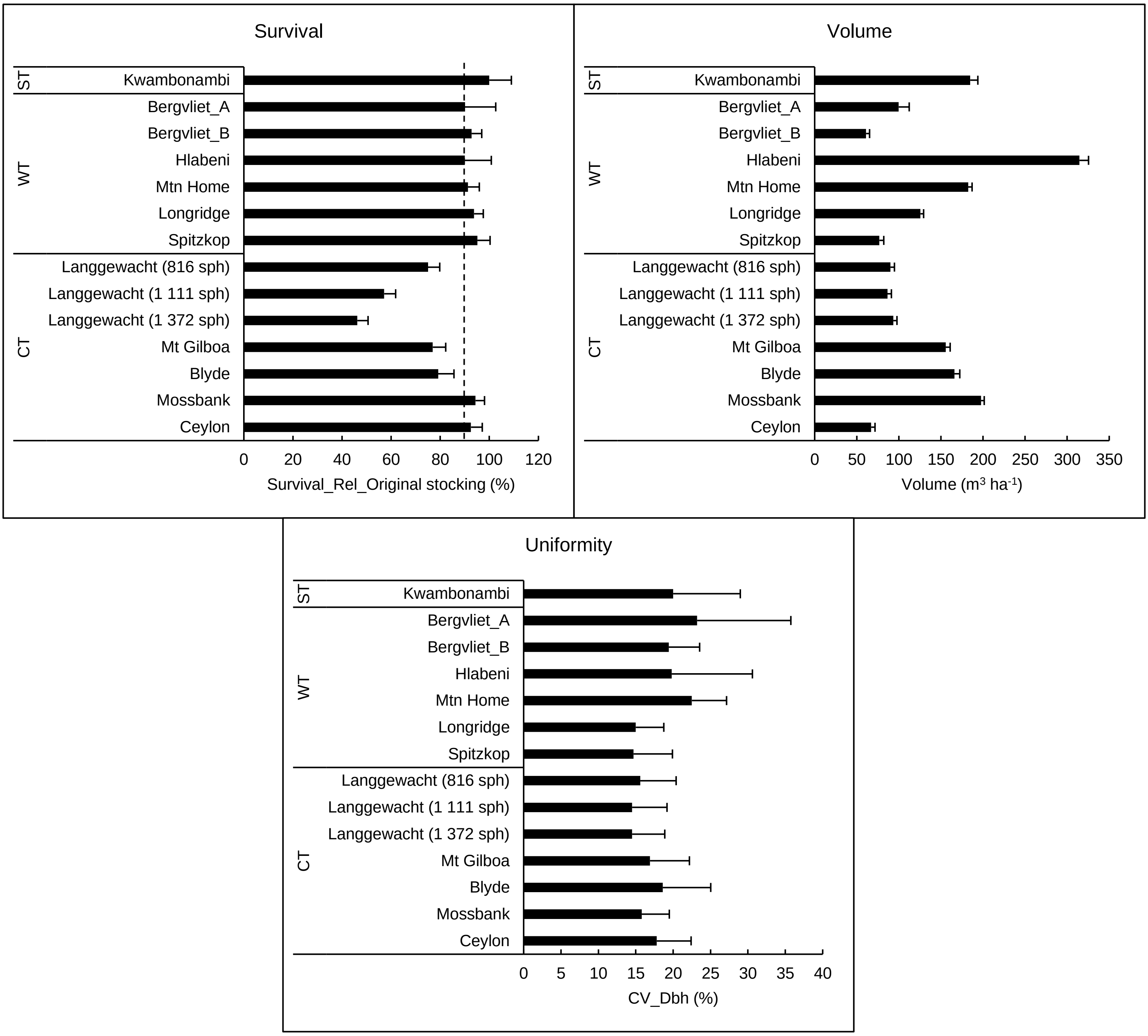
The vegetation type and abundance that occurred within this trial series was similar to that recorded for previous vegetation management studies conducted for pine establishment in southern Africa (**Jarvel and Pallett 2002; Rolando and Little 2009**). These previous studies established a correlation between increasing species occurrence, abundance and diversity and decreasing altitude (associated with increased temperature and rainfall). At most of the higher altitude sites (1 500 to 1 935 m a.s.l.) in this trial series (CT climate zone: Mt Gilboa, Ceylon, Mossbank), *Phytolacca octandra* L. (inkberry) and natural regen of *P. patula* were the dominant species, together with some grasses and HBL species (such as *Bidens pilosa* L. (blackjack)). Vegetation was considered sub-competitive at the Mossbank site where 0.5 tons ha^{-1} of above ground biomass was measured at 1 610 days after planting. In contrast, 9.0 tons ha^{-1} (at 913 days) above ground vegetation biomass was measured at Blyde, which was also considered a high altitude, CT site (**Ndlovu et al. 2019b**). The high biomass on this site was due to a dominance of woody vegetation (*Solanum maritianum* Scopoli (bugweed) and *Buddleja salviifolia* (L.) Lam (sagewood)). **Jarvel and Pallett (2002)** also reported woody species within the CT climate zone of Mpumalanga. Although the most important factor affecting vegetation cover abundance and species composition was altitude, other factors which were also important were the length of time since clearfelling and the proximity of the stand to indigenous woody vegetation in ravines (**Jarvel and Pallett 2002**), which was the case for Blyde which was located next to an indigenous forest.

At the lower- and mid-altitude sites (55-1 155 m a.s.l.) (ST and WT climate zones), the dominant vegetation type tended to be perennial broadleaves (**Little and Rolando 2001**). *Lantana camara* L. (sensu lato) (common lantana) and bugweed were dominant at the Kwambonambi site on the east coast of KwaZulu-Natal (7.8 tons ha^{-1} at 1 333 days); *Setaria megaphylla* (Steud.) Dur and Schinz (setaria)), bugweed, *Acacia mearnsii* De Wild (black wattle) and eucalypt regeneration dominated at the Bergvliet_A site (7.5 tons ha^{-1} at 1 182 days) with a similar mix recorded for

Bergvliet_B (6.3 tons ha^{-1} at 840 days); black wattle, grasses and HBL were dominant at the Mountain Home site (9.8 tons ha^{-1} at 953 days) with annual HBL (mainly blackjack), bugweed and grasses (mainly setaria) dominating at Spitzkop and Langgewacht (biomass not measured). At the Longridge site (4.3 tons ha^{-1} at 949 days), vegetation cover and biomass were low (dominated by bugweed and setaria), whereas at Hlabeni (6.9 tons ha^{-1} at 949 days), the site predominantly featured short-term (3 to 5 years) competitors, namely *Panicum maximum* Jacq. (grass) and various HBL such as blackjack.

4.4.2. Site and treatment related tree performance

As the tree species were matched to each site, conditions for tree growth were considered optimum, although there was the risk of drought at Hlabeni and snow at Mossbank and Ceylon. Actual productivities in terms of mean annual increment (MAI) for the *Weedfree* treatments, ranged from 5.5 - 19.0 m^3 ha^{-1} annum^{-1} for the CT sites, 7.0 - 34.2 m^3 ha^{-1} annum^{-1} for WT sites, and 27.4 m^3 ha^{-1} annum^{-1} for the ST site (**Table 4.1**). Generally, the trials situated within the ST and WT climate zones had better tree growth (MAI of $\bar{x}$ = 16.3 m^3 ha^{-1} annum^{-1} or volume of $\bar{x}$ = 166.65 m^3 ha^{-1}) compared to the CT climate zone (MAI of 11.7 m^3 ha^{-1} annum^{-1} or volume of 122.4 m^3 ha^{-1}), which can be attributed to the higher mean annual rainfall, temperatures and increased number of growth days associated with these climatic zones (**Smith et al. 2005a; Louw et al. 2011; Louw and Smith 2012**) (**Figure 4.1**). As such, volume was mainly influenced by climate zone (CT<WT<ST), past/current site management and pine species planted (**Table 4.5**).



ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

Figure 4.1. Survival, volume and uniformity measurements for the weedfree treatment within 12 pine vegetation management trials in the summer rainfall region of South Africa. Vertical dotted line indicates desired industry tree survival (>90 percentage). Weedfree survival is relative to original stocking for each respective trial. Bars on means indicate standard deviation.

Table 4.5. Summary data showing selected tree growth variates up to 10.4 years in 12 vegetation management trials implemented on pines in the summer rainfall region of South Africa.

1. Kwambonambi (ST: *P. elliottii x P. caribaea*)	**Tree growth variates**		
	Survival	Growth	Uniformity
Vegetation management treatments	Stocking (sph)	Volume ($m^3\ ha^{-1}$)	CV Dbh (%)
Weedfree	816^{a}	266.1^{a}	15.6^{ns}
Moderate	804^{a}	220.6^{a}	16.6^{ns}
Ring weeding (2 m) (Ferns remaining)	765^{ab}	219.8^{ab}	18.4^{ns}
Grass remaining	587^{b}	139.1^{c}	21.1^{ns}
HBL remaining	778^{a}	196.8^{b}	21.8^{ns}
PBL remaining	536^{b}	136.6^{c}	19.9^{ns}
Weedy	408^{b}	115.0^{c}	23.2^{ns}
LSD ($p < 0.05$)	179.0	57.4	5.7

2. Bergvliet_A (WT: *P. elliottii*)	**Tree growth variates**		
	Survival	Growth	Uniformity
Vegetation management treatments	Stocking (sph)	Volume ($m^3\ ha^{-1}$)	CV Dbh (%)
Weedfree	724^{ns}	113.7^{a}	25.9^{ns}
Ring weeding (1.5 m)	650^{ns}	104.5^{ab}	28.2^{ns}
Moderate weeding	633^{ns}	121.2^{a}	26.7^{ns}
HBL remaining	575^{ns}	112.6^{a}	27.4^{ns}
PBL remaining	570^{ns}	90.8^{b}	23.0^{ns}
Weedy	551^{ns}	64.8^{c}	24.2^{ns}
LSD ($p < 0.05$)	238.3	17.0	18.1

3. Bergvliet_B (WT: *P. elliottii*)	**Tree growth variates**		
	Survival	Growth	Uniformity
Vegetation management treatments	Stocking (sph)	Volume ($m^3\ ha^{-1}$)	CV Dbh (%)
Factor A: Slash management			
Clear	753^{a}	61.5^{ns}	23.3^{ns}
Single	680^{ab}	59.2^{ns}	18.4^{ns}
Double	676^{b}	62.5^{ns}	19.3^{ns}
LSD ($p < 0.05$)	60.4	8.26	7.7
Factor B. Vegetation management			
Weedfree	737^{a}	94.7^{a}	15.8^{a}
Weedy	669^{b}	27.5^{b}	24.9^{b}
LSD ($p < 0.05$)	49.3	6.8	6.3
Factorial combination: Slash management x Vegetation management			
Clear x Weedfree	723^{a}	84.2^{a}	20.0^{ab}
Clear x Weedy	782^{a}	31.6^{b}	26.6^{b}
Single x Weedfree	757^{a}	92.2^{a}	14.2^{a}
Single x Weedy	604^{b}	26.5^{b}	22.6^{ab}
Double x Weedfree	731^{a}	95.5^{a}	13.0^{a}
Double x Weedy	621^{b}	38.0^{b}	25.6^{b}
LSD ($p < 0.05$)	85.4	11.6	10.9

ns = non-significance at $p < 0.05$. Different letters within each column indicate significant difference at $p < 0.05$ as indicated by the Students *t*-test.
ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate

Continues from Table 4.5

4. Hlabeni **(WT: *P. greggii*)** **Vegetation management treatments**	**Tree growth variates** Survival Stocking (sph)	Growth Volume (m^3 ha^{-1})	Uniformity CV Dbh (%)
Factor A: Fertilization			
NoFert	985^{ns}	326.7^{ns}	18.6^{ns}
Agri	922^{ns}	307.9^{ns}	19.0^{ns}
Max	979^{ns}	321.0^{ns}	19.1^{ns}
NPK	937^{ns}	302.6^{ns}	22.1^{ns}
LSD ($p < 0.05$)	149.9	37.9	4.0
Factor B: Vegetation management			
Weedfree	972^{ns}	324.8^{ns}	17.8^{a}
Ring weeding (2 m)	947^{ns}	329.8^{ns}	17.7^{a}
Ring weeding (1 m)	966^{ns}	310.9^{ns}	19.8^{a}
Weedy	937^{ns}	292.7^{ns}	24.0^{b}
LSD ($p < 0.05$)	149.9	18.4	4.0

5. Mountain Home **(WT: *P. greggii*)** **Vegetation management treatments**	**Tree growth variates** Survival Stocking (sph)	Growth Volume (m^3 ha^{-1})	Uniformity CV Dbh (%)
Weedfree	1 014^{ns}	200.9^{a}	18.7^{ns}
Moderate weeding	931^{ns}	188.3^{a}	19.5^{ns}
Ring weeding (2 m)	1 097^{ns}	235.6^{a}	20.7^{ns}
HBL and Grass remaining	1 042^{ns}	210.7^{a}	25.3^{ns}
PBL remaining	972^{ns}	131.5^{b}	26.3^{ns}
Weedy	903^{ns}	127.2^{b}	24.8^{ns}
LSD ($p < 0.05$)	136.0	36.2	8.0

6. Longridge **(WT: *P. elliottii*)** **Vegetation management treatments**	**Tree growth variates** Survival Stocking (sph)	Growth Volume (m^3 ha^{-1})	Uniformity CV Dbh (%)
Factor A: Fertilization			
Fertilization	1 023^{ns}	125.2^{ns}	14.3^{ns}
NoFertilization	1 032^{ns}	126.2^{ns}	15.7^{ns}
LSD ($p < 0.05$)	51.2	17.2	3.9
Factor B: Vegetation management			
Weedfree	1 030^{ns}	129.6^{ns}	16.7^{ns}
Grass remaining	961^{ns}	125.4^{ns}	13.3^{ns}
HBL remaining	1 053^{ns}	135.5^{ns}	10.3^{ns}
PBL remaining	1 065^{ns}	125.4^{ns}	19.7^{ns}
Weedy	1 030^{ns}	112.6^{ns}	14.9^{ns}
LSD ($p < 0.05$)	80.9	27.19	6.3

7. Spitzkop **(WT: *P. elliottii, P. patula, P. taeda*)** **Vegetation management treatments**	**Tree growth variates** Survival Stocking (sph)	Growth Volume (m^3 ha^{-1})	Uniformity CV Dbh (%)
Factor A: Species			
P. elliottii	745^{ns}	104.0^{a}	10.8^{ns}
P. patula	755^{ns}	109.2^{a}	16.8^{ns}
P. taeda	755^{ns}	66.8^{b}	16.6^{ns}
LSD ($p < 0.05$)	83.4	24.5	5.7
Factor B: Vegetation management			
Weedfree	755^{ns}	102.9^{ns}	14.1^{ns}
Low intensity weeding	748^{ns}	83.8^{ns}	15.3^{ns}
LSD ($p < 0.05$)	67.1	20.0	4.8

8. Langgewacht **(CT: *P. elliottii*)** **Vegetation management treatments**	**Tree growth variates** Survival Stocking (sph)	Growth Volume (m^3 ha^{-1})	Uniformity CV Dbh (%)
Factor A: Spacing			
1 371 sph (2.7 x 2.7 m)	663^{ns}	86.5^{ns}	14.2^{ns}
816 sph (3.5 x 3.5 m)	605^{ns}	76.9^{ns}	15.3^{ns}
1 111 sph (3 x 3 m)	620^{ns}	90.0^{ns}	12.7^{ns}
LSD ($p < 0.05$)	95.9	23.4	5.5
Factor B. Vegetation management			
Weedfree	628^{ns}	92.1^{a}	13.1^{ns}
Low intensity weeding	634^{ns}	86.1^{a}	14.3^{ns}
Weedy	626^{ns}	75.1^{b}	14.7^{ns}
LSD ($p < 0.05$)	35.5	8.1	2.9

9. Mt Gilboa **(CT: *P. patula*)** **Vegetation management treatments**	**Tree growth variates** Survival Stocking (sph)	Growth Volume (m^3 ha^{-1})	Uniformity CV Dbh (%)
Weedfree	856^{ns}	143.3^{ns}	16.0^{ns}
Biomac	800^{ns}	155.2^{ns}	17.7^{ns}
Kraft	844^{ns}	153.8^{ns}	18.4^{ns}
Plantex	911^{ns}	158.1^{ns}	16.3^{ns}
Sludge	867^{ns}	161.4^{ns}	16.5^{ns}
Weedy	944^{ns}	162.3^{ns}	16.2^{ns}
LSD ($p < 0.05$)	138.4	19.4	3.5

ns = non-significance at $p < 0.05$. Different letters within each column indicate significant difference at $p < 0.05$ as indicated by the Students *t*-test.
ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

Continues from Table 4.5

10. Blyde (CT: *P. patula*)	**Tree growth variates**		
Vegetation management treatments	Survival Stocking (sph)	Growth Volume (m^3 ha^{-1})	Survival Stocking (sph)
<u>Factor A: Slash management</u>			
Burn	661^{ns}	165.0^{ns}	18.4^{ns}
No Burn	674^{ns}	166.9^{ns}	16.6^{ns}
LSD (p < 0.05)	103.9	42.0	2.5
<u>Factor B: Site preparation</u>			
ChopPit	663^{ns}	153.1^{b}	17.1^{ns}
ChopRip	646^{ns}	158.4^{b}	18.0^{ns}
Pit	608^{ns}	166.8^{b}	16.5^{ns}
Rip	753^{ns}	185.7^{a}	18.6^{ns}
LSD (p < 0.05)	130.8	14.9	4.1
<u>Factor C: Vegetation management</u>			
Weedfree	687^{ns}	183.3^{a}	18.0^{ns}
Weedy	648^{ns}	148.7^{b}	17.1^{ns}
LSD (p < 0.05)	60.6	17.0	2.0
<u>Factorial combination: Site preparation x Vegetation management</u>			
ChopPit x Weedfree	612^{ns}	162.5^{a}	18.5^{ns}
ChopPit x Weedy	612^{ns}	149.6^{a}	17.6^{ns}
ChopRip x Weedfree	646^{ns}	163.5^{a}	19.0^{ns}
ChopRip x Weedy	680^{ns}	153.3^{a}	21.2^{ns}
Pit x Weedfree	714^{ns}	211.0^{a}	14.0^{ns}
Pit x Weedy	510^{ns}	122.5^{b}	18.6^{ns}
Rip x Weedfree	765^{ns}	196.1^{a}	20.0^{ns}
Rip x Weedy	748^{ns}	175.3^{a}	21.0^{ns}
Factorial LSD (p < 0.05)	139.0	26.8	4.3

11. Mossbank (CT: *P. patula*)	**Tree growth variates**		
Vegetation management treatments	Survival Stocking (sph)	Growth Volume (m^3 ha^{-1})	Uniformity CV Dbh (%)
Weedfree	1 042^{ns}	200.8^{ns}	14.0^{ns}
Weedfree x Fertilization	972^{ns}	208.5^{ns}	16.8^{ns}
Moderate weeding	1 088^{ns}	208.1^{ns}	14.5^{ns}
HBL remaining	1 042^{ns}	192.7^{ns}	16.9^{ns}
Grass remaining	1 065^{ns}	194.6^{ns}	13.1^{ns}
Weedy	1 088^{ns}	195.2^{ns}	17.7^{ns}
Weedy x Fertilization	1 042^{ns}	184.5^{ns}	19.1^{ns}
LSD (p < 0.05)	114.6	21.7	8.1

12. Ceylon (CT: *P. elliottii, P. patula, P. taeda*)	**Tree growth variates**		
Vegetation management treatments	Survival Stocking (sph)	Growth Volume (m^3 ha^{-1})	Uniformity CV Dbh (%)
<u>Factor A: Species</u>			
P. elliottii	694^{b}	57.3^{b}	16.6^{ns}
P. patula	755^{ab}	91.7^{a}	18.1^{ns}
P. taeda	796^{a}	52.2^{b}	18.7^{ns}
LSD (p < 0.05)	73.4	22.5	6.5
<u>Factor B: Vegetation management</u>			
Weedfree	748^{ns}	74.0^{ns}	17.9^{ns}
Weedy	748^{ns}	60.1^{ns}	17.8^{ns}
LSD (p < 0.05)	59.9	18.4	5.3

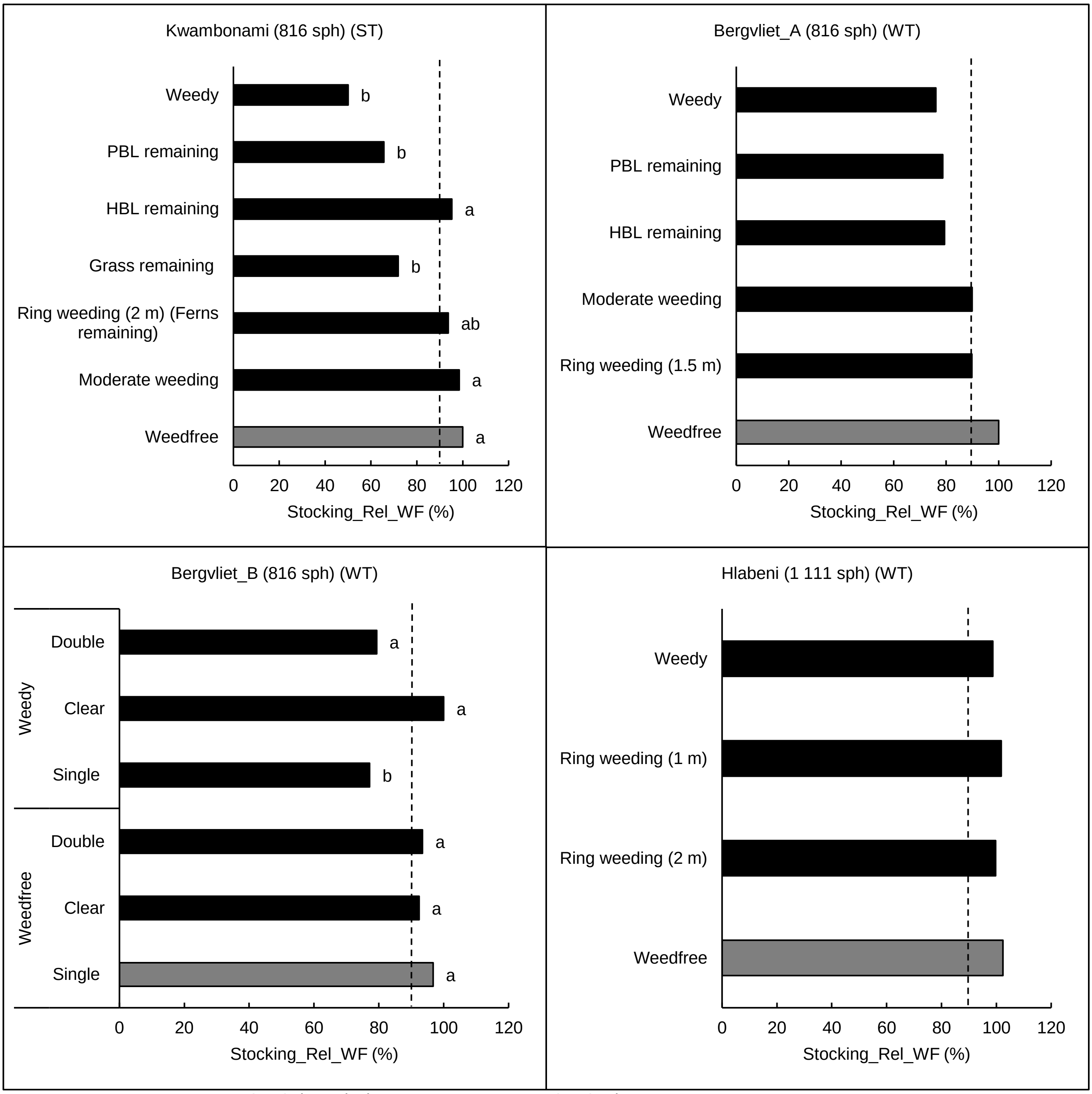
ns = non-significance at p < 0.05. Different letters within each column indicate significant difference at p < 0.05 as indicated by the Students *t*-test.
ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

4.4.3. *Treatment-related growth responses*

Significant differences in terms of the growth variates (survival, volume and uniformity) occurred in nine of the 12 trials (ST: 1 of 1 trial; WT: 5 out 6 trials; CT: 3 out 5 trials) (**Table 4.5**). Survival was significantly impacted in three of the 12 trials (Kwambonambi: *F* prob = < 0.001; Bergvliet_B and Ceylon *F* prob = < 0.05) (**Table 4.5 and Figure 4.2**), and Volume in eight of the 12 trials (all trials excepting for Hlabeni, Longridge, Mt Gilboa and Mossbank) (**Table 4.5 and Figures 4.3 and 4.4**). In contrast, only two of the 12 trials (Bergvliet_B and Hlabeni) recorded significant differences (*F* prob = < 0.05) for uniformity (**Table 4.5** and **Figure 4.4**).

4.4.3.1. Influence of weeding treatments on tree performance (all trials)

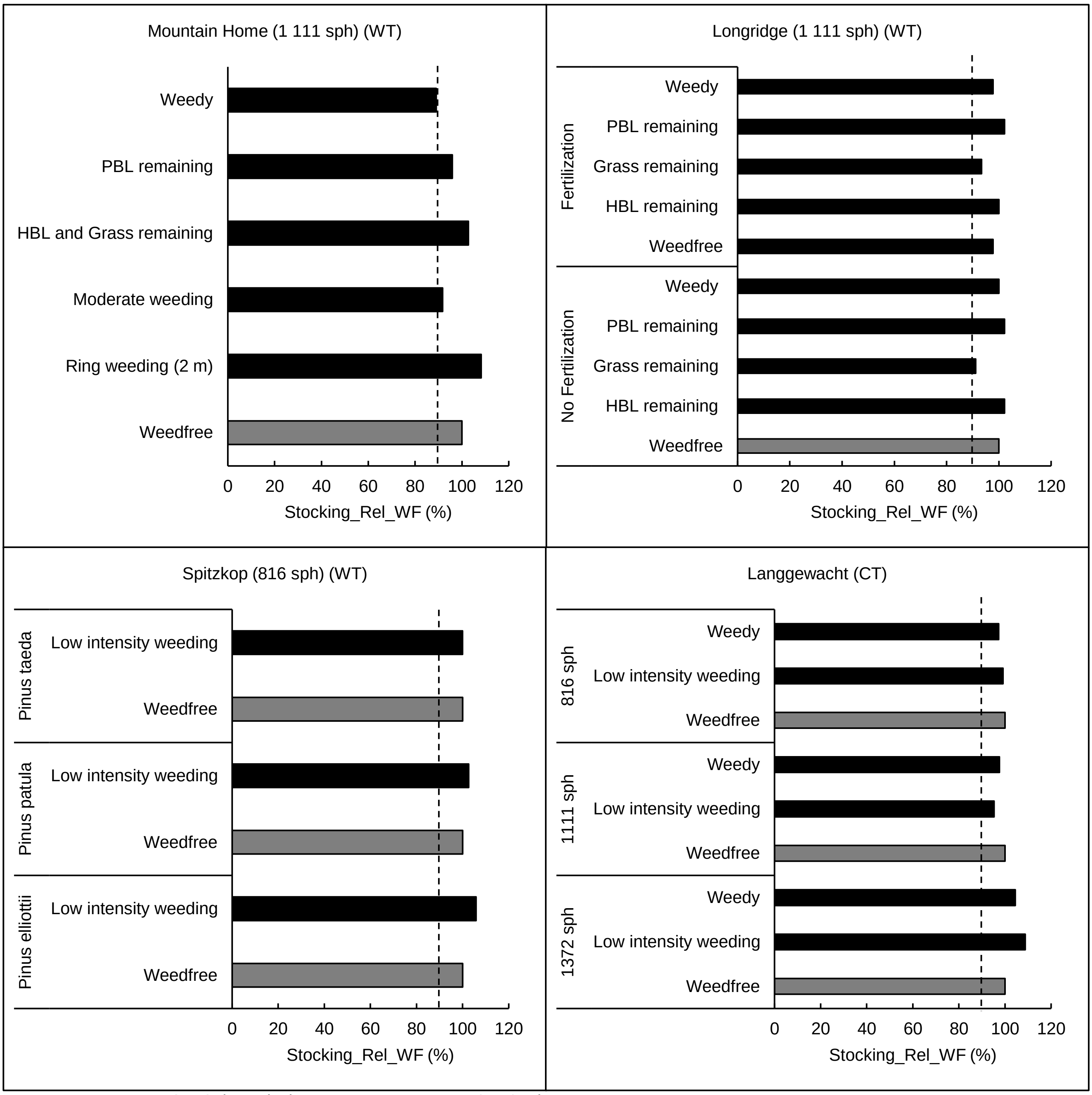
The lower abundance of vegetation in the CT climate zone meant that tree performance was not negatively impacted by on-site vegetation in three of the five trials within that zone. The two exceptions were the Langgewacht and Blyde trials where the presence of PBL resulted in significant differences between the *Weedfree* and *Weedy* volumes. In five out of seven trials in both the WT and ST climate zones, the *Weedfree* treatments outperformed the *Weedy* treatments (**Table 4.5**). The two exceptions were Longridge which had low vegetation abundance, and Spitzkop where the *Weedy* treatment received two unscheduled weeding operations. Within these two climate zones, the various *Ring weeding* (*1*, *1.5* and *2 m*) and *Moderate/Low intensity* weeding treatments resulted in significantly improved tree performance that was similar to that of the *Weedfree* treatments. In contrast the *Selective control* of vegetation (*Grass remaining*, *HBL remaining*, *Grass and HBL remaining,* and *PBL remaining*) produced variable results in terms of survival and volume. The magnitude of response, and hence level of significance was linked to the abundance of the vegetation type for that site. For example, the retention of grasses, HBL or PBL resulted in a significant loss of volume at the Kwambonambi site, but not at the Bergvliet_A and Mountain Home sites, where only the retention of PBL was significant.



ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

Figure 4.2. Survival (%) relative to overall best performing treatment (weedfree) in 12 pine vegetation management trials in the summer rainfall region of South Africa. Values in parentheses are the original planting density. Vertical dotted line indicates desired industry tree survival (>90 percentage). Within each trial, bars with different letters indicate significant treatment differences at $p < 0.05$). No letters indicate non-significance.

Continues from Figure 4.2.



ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

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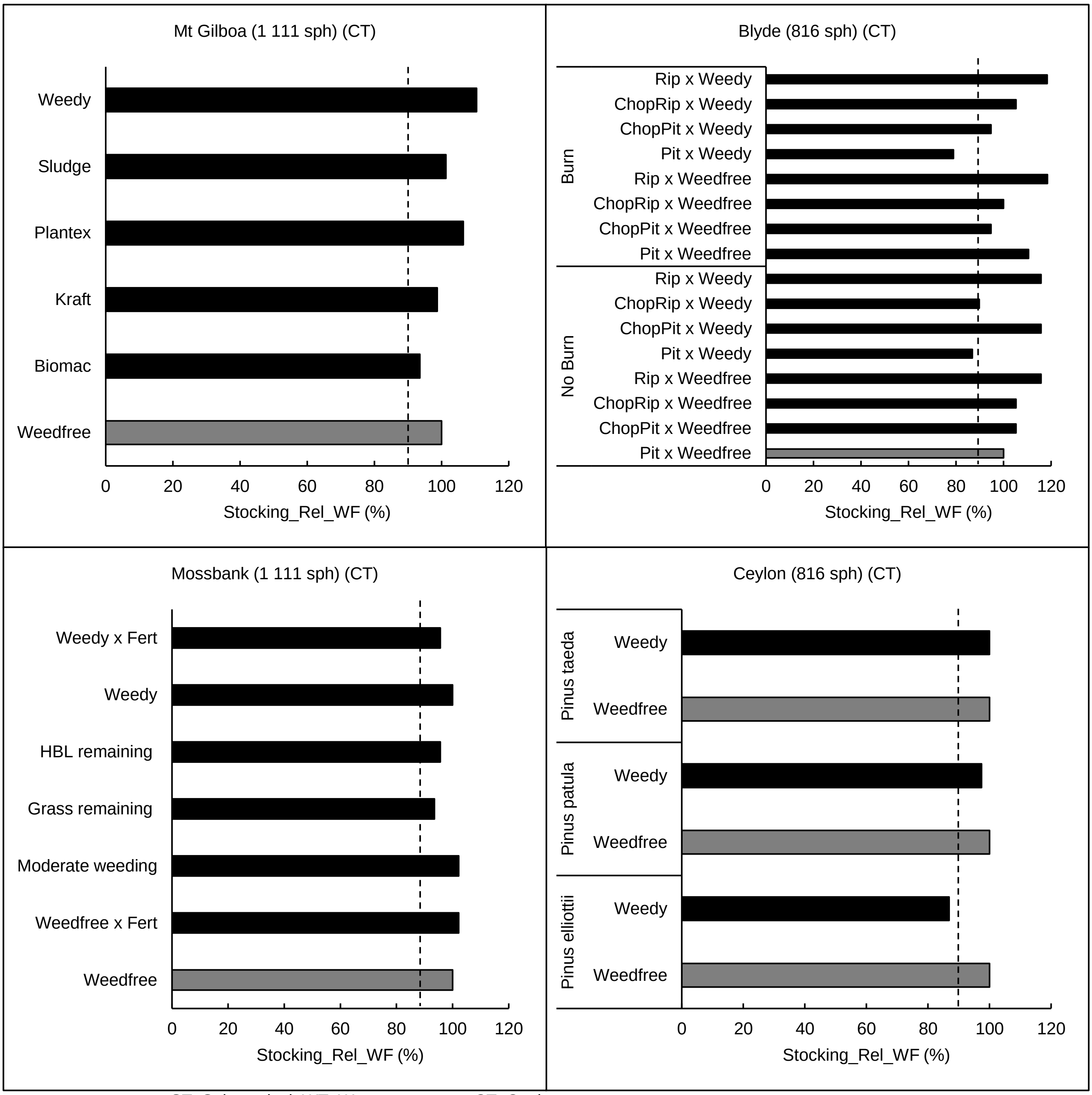
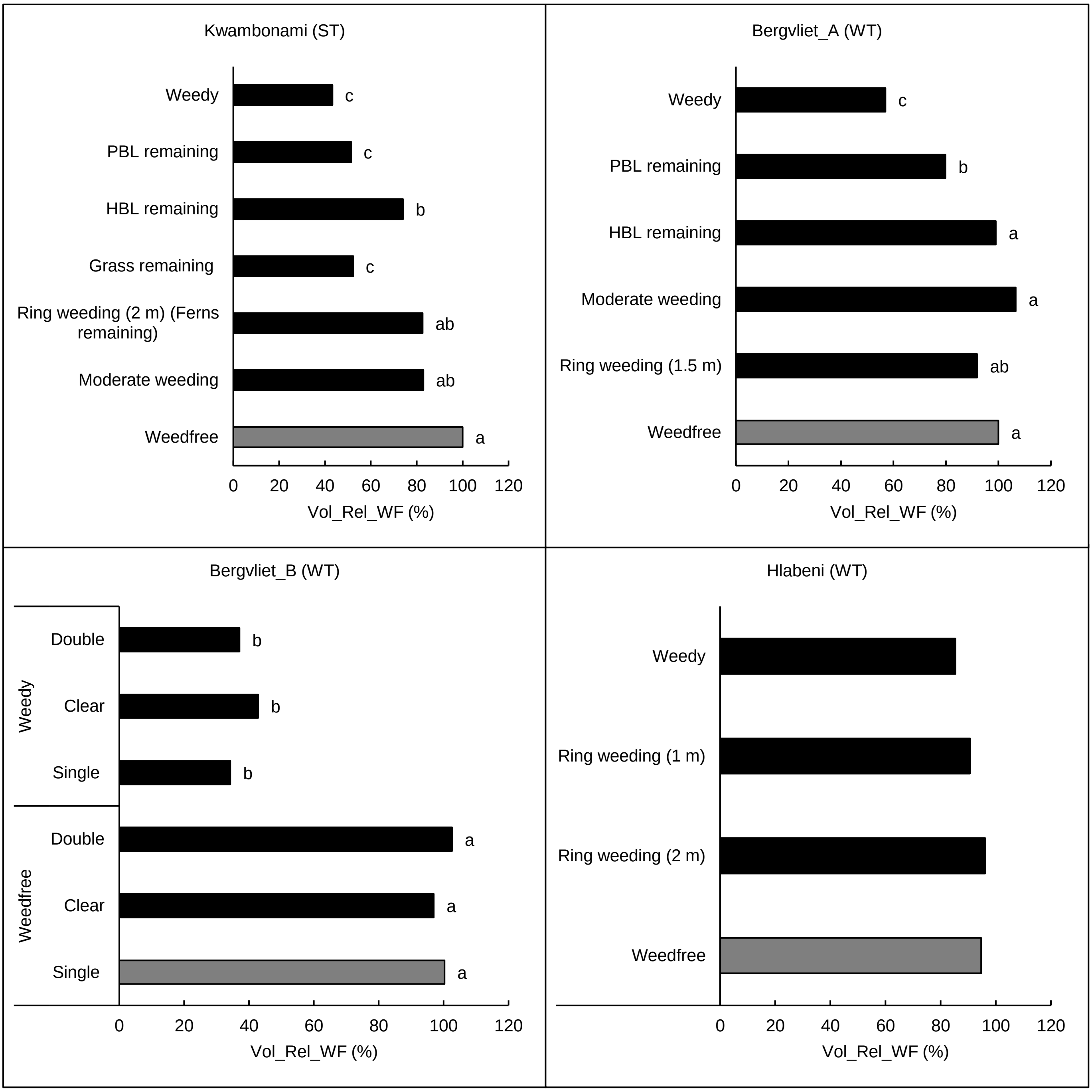


ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.



ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

Figure 4.3. Volume relative to overall best performing treatment (weedfree) within each of the 12 pine vegetation management trials in the summer rainfall region of South Africa. Within each trial, bars with different letters indicates significant differences, while bars with no letters or same letters indicates non significance differences ($p < 0.05$) as indicated by the Students *t*-test.

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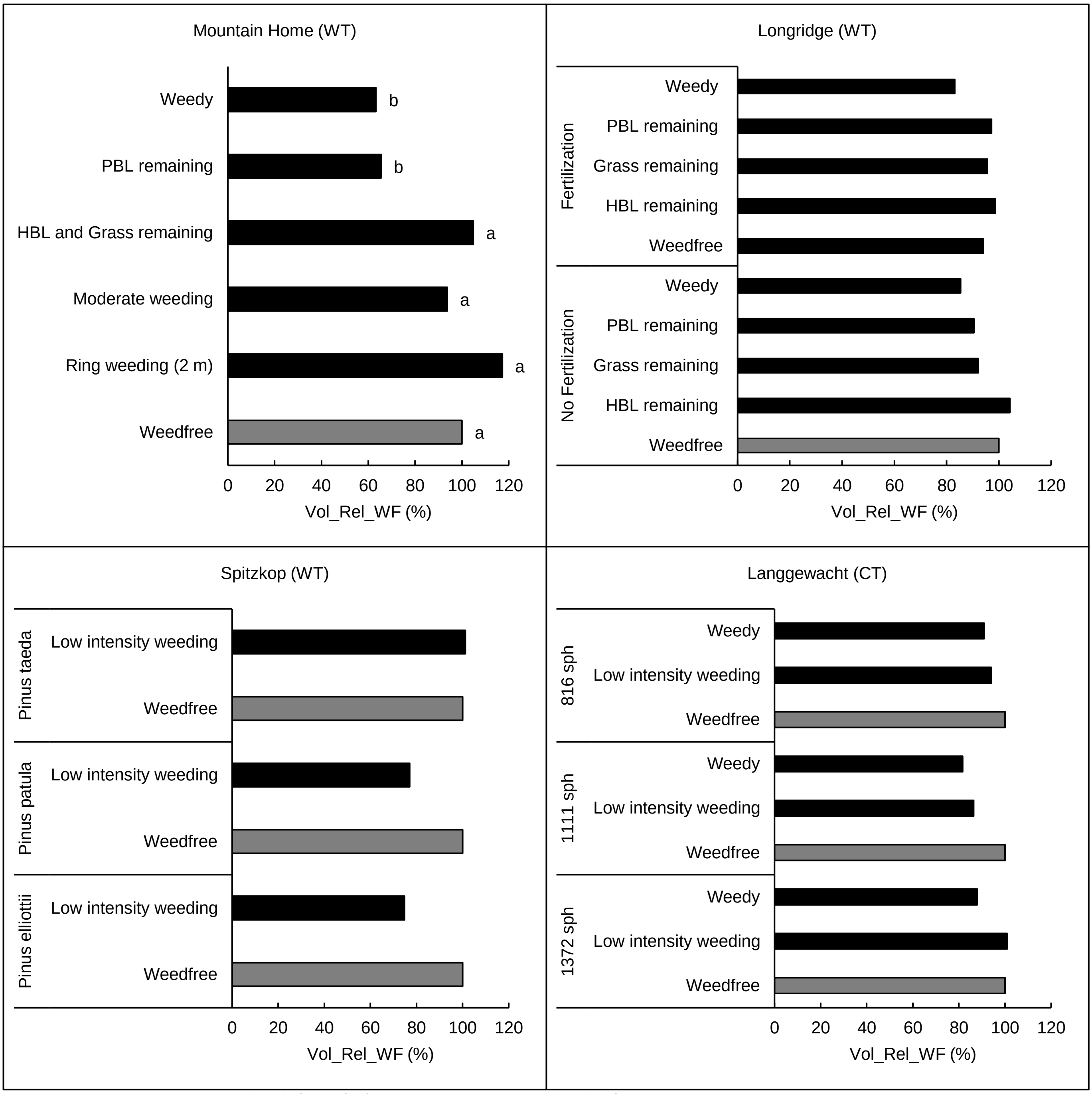

ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

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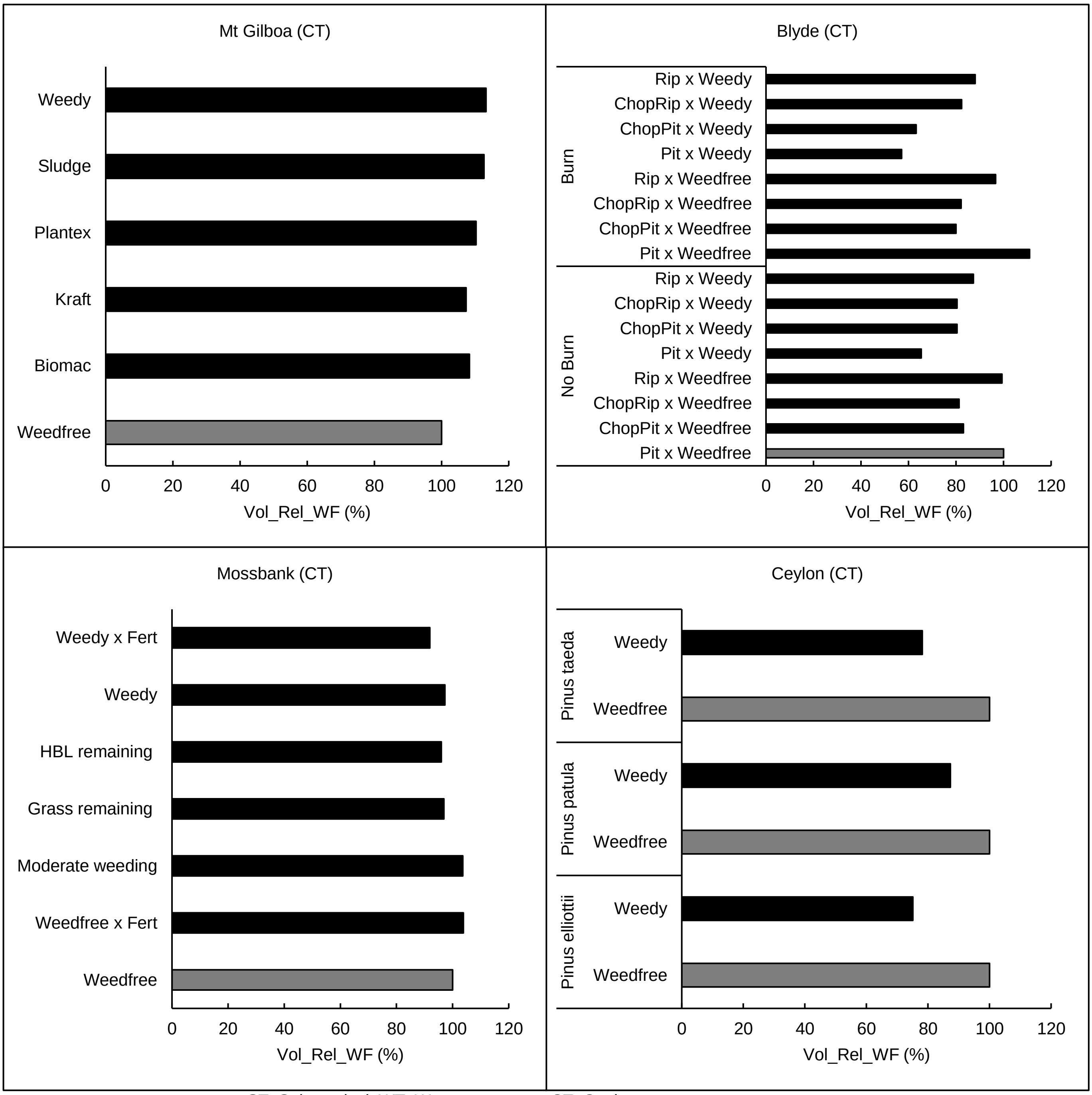


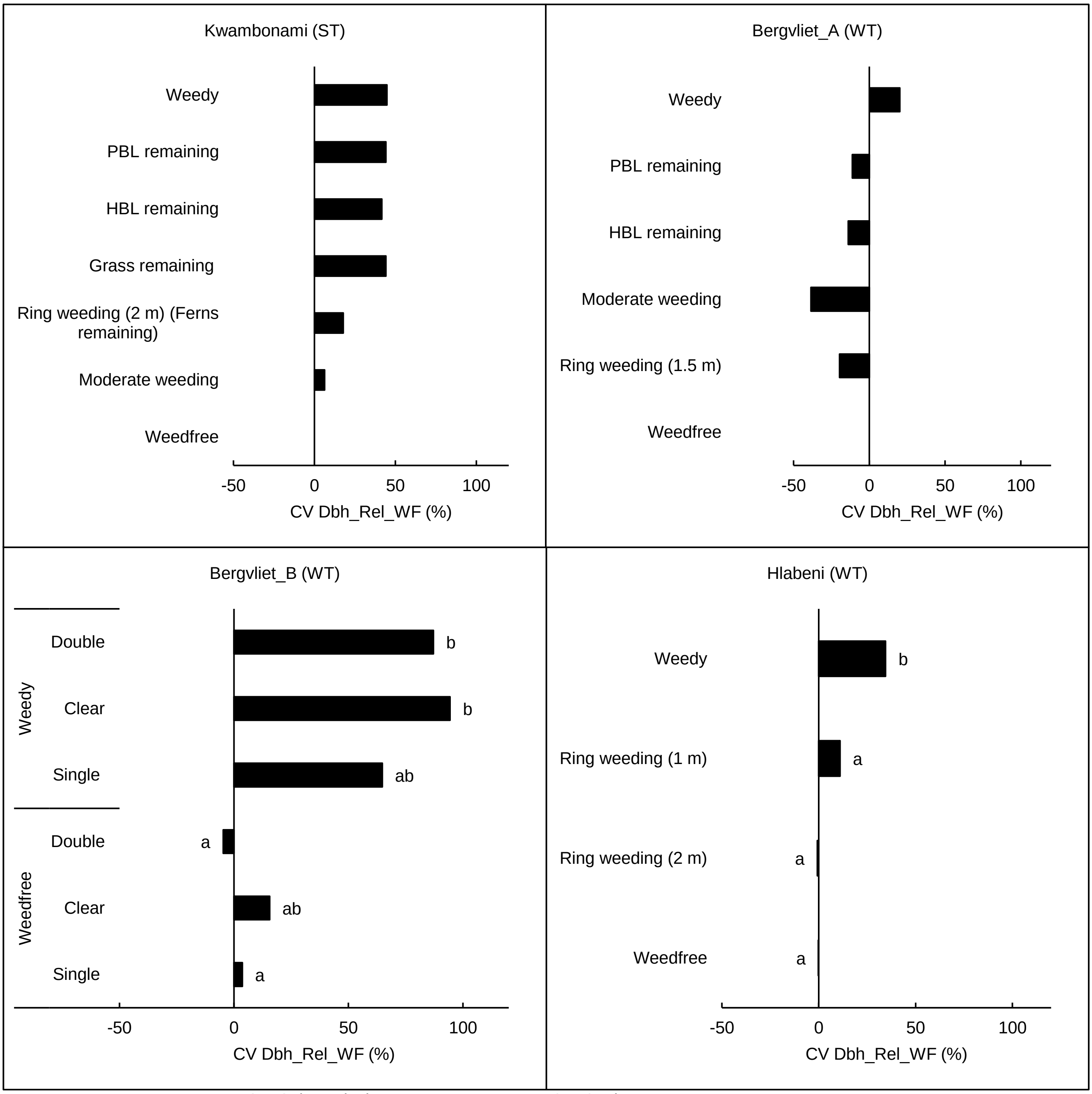
ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

4.4.3.2. Influence of slash management on tree performance (Bergvliet_B, Mt Gilboa and Blyde)

Bergvliet_B: The management of slash had a significant impact (*F* prob = < 0.05) on survival, with the Slash management x Vegetation management interaction significant for survival, volume and uniformity. Significantly higher mortality (10%) occurred for those treatments with a higher slash load (*Double*) compared to those treatments with the slash removed (*Clear*). Possible reasons for this could be due to increased ground temperatures (**Morris 1990; Allan 1997; Zabowski et al. 2000**) and shallower planting (**Rolando and Little 2006**) associated with increased levels of slash retention (**Ndlovu et al. 2019c**). For the Slash management x Vegetation management interaction, the *Weedfree* treatments had significantly higher survival ($\bar{x}$ = 737 sph versus $\bar{x}$ = 669 sph) and volume ($\bar{x}$ = 90.6 m^3 ha^{-1} versus $\bar{x}$ = 32.0 m^3 ha^{-1}) than the *Weedy* treatments, irrespective of slash management (*Clear*, *Single* and *Double*). Although the *Weedy* (24.9%) treatments had significantly higher variability compared to the *Weedfree* (15.8%) treatments (**Figure 4.4**), variability for the *Weedy* + *Single* s*lash treatment (*22.6 %) was low, and not significantly different to the Weed*free* + *Clear slash* treatment (20.0%).

Mt Gilboa: No significant treatment differences were detected, indicating no difference between mulches tested, and/or that of the *Weedfree* and *Weedy* treatments. This may be attributed to the lack of competing vegetation at this trial site.

Blyde: Site preparation (*F* prob = < 0.05), Vegetation management (*F* prob = < 0.001), and the Site preparation x Vegetation management interaction (*F* prob = < 0.05) were significant (**Ndlovu et al. 2019a and 2019b**). For Site preparation, the *Rip* treatment (185.7 m^3 ha^{-1}) had significantly higher volume than the *ChopPit* (153.1 m^3 ha^{-1}), *ChopRip* (158.4 m^3 ha^{-1}) and *Pit* (166.8 m^3 ha^{-1}) treatments. Irrespective of vegetation management (*Weedfree* or *Weedy*), the *ChopPit*, *ChopRip* and *Rip* site preparation treatments performed significantly better than the *Pit x Weedy* (122.5 m^3 ha^{-1}) treatment. In contrast, the *Pit x Weedfree* treatments had the highest volume of all treatments (211.0 m^3 ha^{-1}), and was only significantly different to the *Pit x Weedy* treatment. In trials conducted by **Fallis and Duzan (1995)** and **Zwolinski and Donald (1995)**, ripping also resulted in lower vegetation biomass compared to other forms of soil preparation, and may even be used to achieve partial control of competitive vegetation in pine stands in SA (**Germishuizen and Marais 1981**).



ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

Figure 4.4. Coefficient of variation for diameter at breast height (Dbh) relative to overall best performing treatment (weedfree) for 12 pine vegetation management trials in the summer rainfall region of South Africa. Within each trial, bars with different letters indicates significant differences, while bars with no letters or same letters indicates non significance differences ($p < 0.05$) as indicated by the Students *t*-test.

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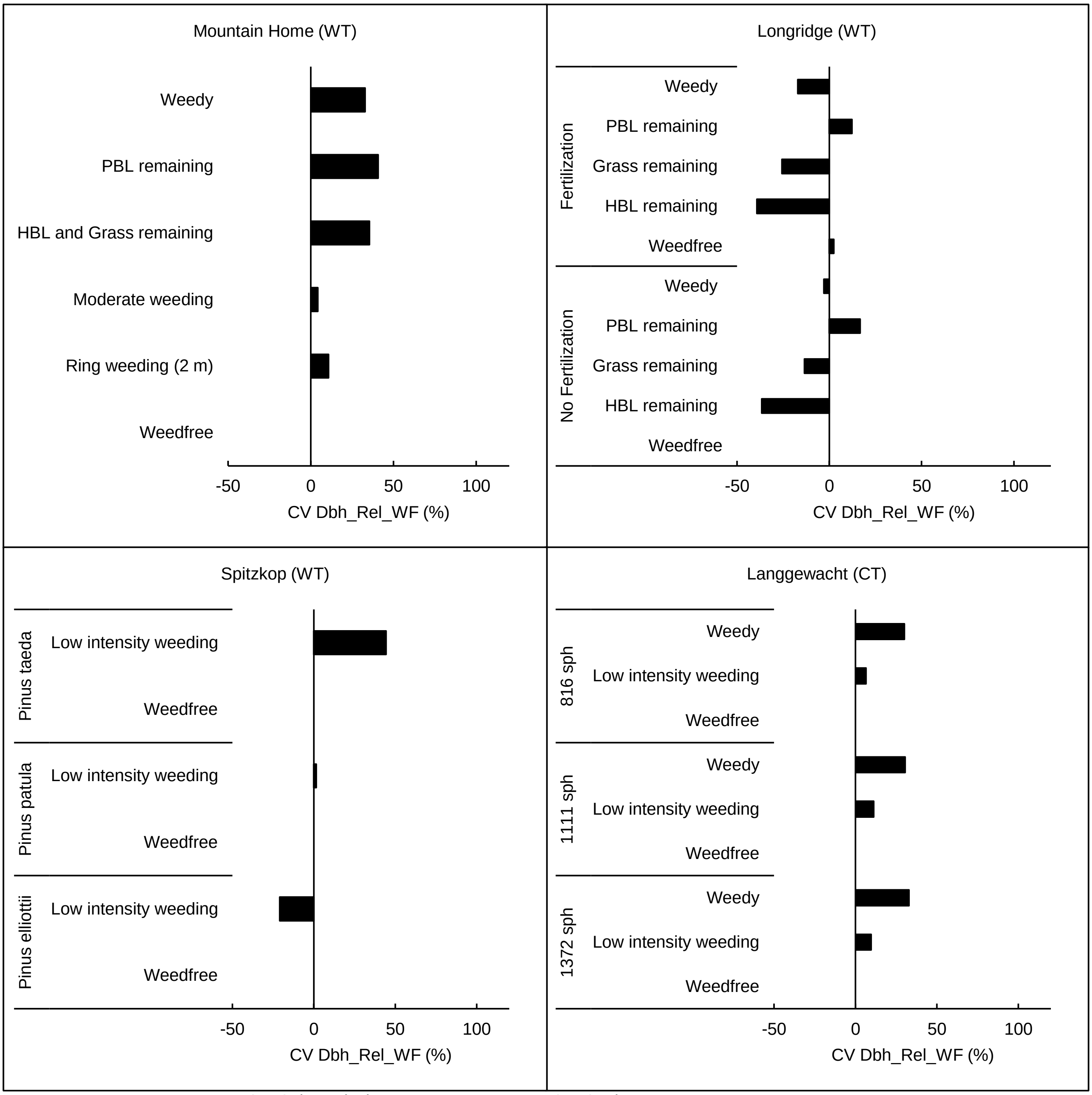

ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

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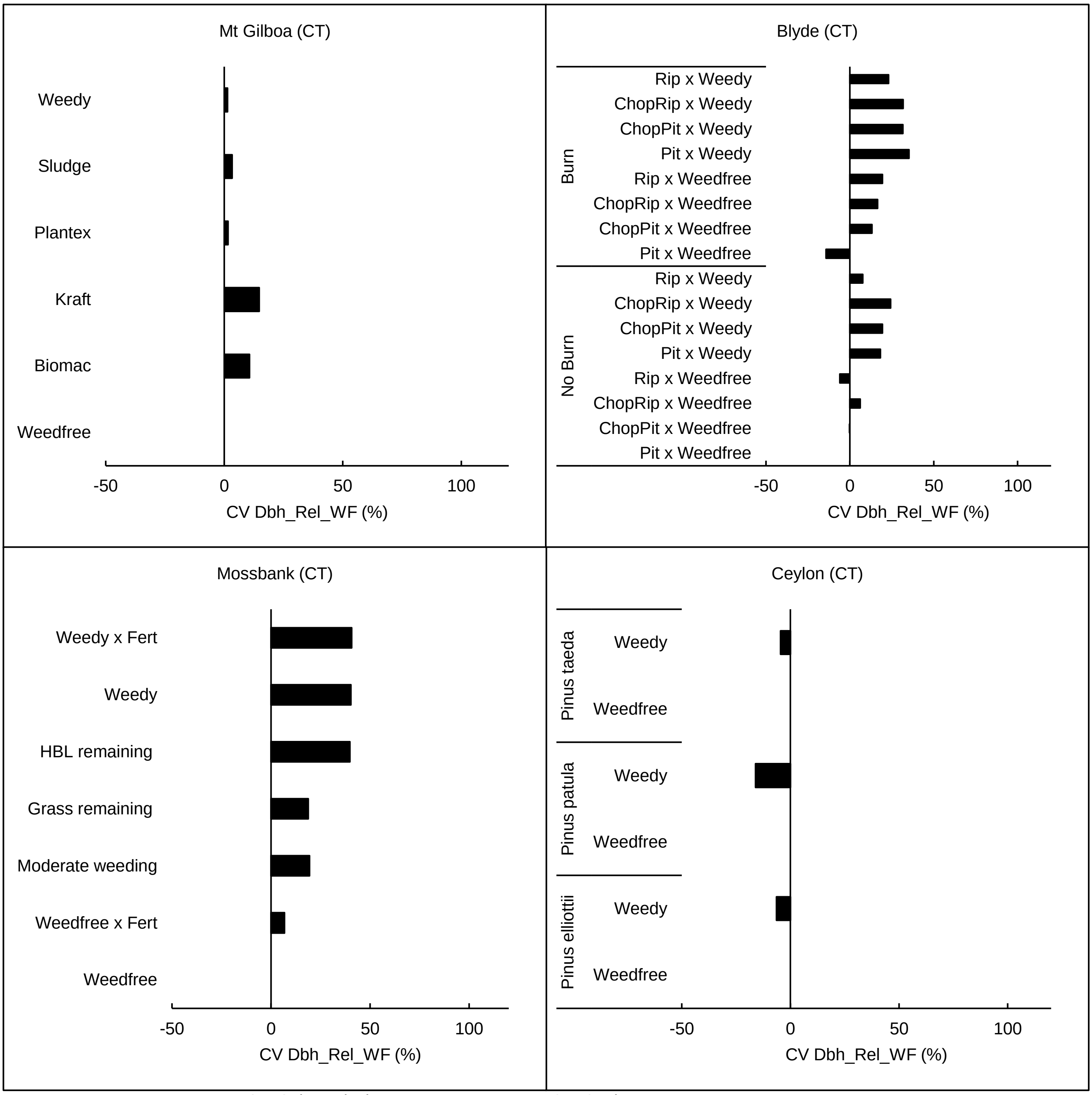

ST: Sub-tropical; WT: Warm temperate; CT: Cool temperate.

4.4.3.3. Influence of fertilization, species and spacing on tree performance (Hlabeni, Longridge, Spitzkop and Ceylon)

Hlabeni and Longridge: The addition of fertilizer in these two trials did not result in a significant improvement for any of the three tree growth responses at ca 9.6 years, nor were there any significant Fertilizer x Weeding interactions. Although fertilization may improve early growth of pine trees (**Rolando et al. 2007**), this response is site and species dependent, and at the low rates applied in these trials, may not always be sustained throughout the rotation (**Carlson 2001; Fox et al. 2007**).

Spitzkop and Ceylon: Although differences in volume at 9.5 years occurred at both sites in terms of Vegetation management (**Table 4.5 and Figure 4.3**), this was only weakly significant (*F* prob = < 0.06) at Spitzkop. Limited vegetation growth at the CT Ceylon site meant that it remained sub-competitive, with the same occurring at the WT Spitzkop site as a result of two unscheduled weeding operations within the *Weedy* treatment plots. At both sites, significant differences (*F* prob = < 0.05) occurred for the species planted (*P. elliottii*, *P. patula* and *P. taeda*). *Pinus elliottii* (104.0 m^3 ha^{-1}) and *P. patula* (109.2 m^3 ha^{-1}) had significantly higher volume than *P. taeda* (66.8 m^3 ha^{-1}) at Spitzkop, with *P. patula* (91.7 m^3 ha^{-1}) outperforming both *P. elliottii* (57.3 m^3 ha^{-1}) and *P. taeda* (52.2 m^3 ha^{-1}) at Ceylon. These results confirm data related to the matching of species-to-site, with site conditions considered unsuitable for *P. taeda* in terms of soil type, effective rooting depth and temperature (for *P. elliottii* as well) at Ceylon (**Smith et al. 2005**; **Little 2012**) (**Table 4.1**). At Spitzkop, the mean annual temperature would be considered too low for *P. taeda*.

4.4.4. Categorization of treatment-related risk (relative to the Weedfree treatment)

To allow for the categorization of treatment-related risk, treatment differences for survival, yield and uniformity were partitioned into three risk classes classified as a function of performance relative to the *Weedfree* treatment: Low; Moderate; or High (**Table 4.4**).

4.4.4.1. Survival (Stocking_Rel_WF)

Vegetation growth and abundance was higher on sites within the more productive ST and WT climate zones, which contributed to higher mortality (**Figure 4.2**). This resulted in Blyde and Ceylon having treatments classified as Moderate risk (80-89%), and

Kwambonambi, Bergvliet_A and Bergvliet_B having treatments classified as high risk (<79%) (**Table 4.6**). High risk treatments included the *Weedy* and *PBL remaining* treatments at Kwambonambi and Bergvliet_A, with the *Grasses* or *HBL remaining* also High risk for each of these sites respectively. The two *Weedy* treatments which contained slash (*Single* or *Double*) at Bergvliet_B were considered High risk, in contrast to the clearing of slash (*Clear*), which resulted in lower mortality. The two *Pit x Weedy* treatments (slash retained or burned) at Blyde, and the *P. elliottii x Weedy* treatment at Ceylon were considered Moderate risk, all the remaining treatments in all trials were classified as Low risk.

4.4.4.2. Volume (Vol_Rel_WF)

All treatments at Mt Gilboa and Mossbank were considered Low risk (90-100%), with two treatments at Blyde (*Pit* x *Weedy* treatments - slash retained or slash burned), Longridge (*Weedy* treatment with or without fertilizer), and Kwambonambi (*Moderate Weeding* and *Ring weeding*), and one at Ceylon (*P. patula x Weedy*) considered Moderate risk (80-89%). In all the remaining trials, the *Weedy* or *PBL remaining* treatments were considered High risk (<79%), together with the *Grass* and *Hbl* and *Grass remaining* at Kwambonambi and Mountain Home respectively.

Table 4.6. Risk categorization for selected growth responses for vegetation management treatments within 12 pine vegetation management trials in the summer rainfall region of South Africa (adapted from **Kliejunas et al. 2006**).

Trial name	Vegetation management treatments	Rotation end tree growth responses			Overall growth risk
		Survival	Volume	Uniformity	
1. Kwambonambi	Weedfree	L	L	L	L
	Moderate weeding	L	M	L	M
	Ring weeding (2 m) (Ferns remaining)	L	M	L	M
	Grass remaining	H	H	H	H
	HBL remaining	L	H	H	H
	PBL remaining	H	H	H	H
	Weedy	H	H	H	H
2. Bergvliet_A	Weedfree	L	L	L	L
	Ring weeding (1.5 m)	L	L	L	L
	Moderate weeding	L	L	L	L
	HBL remaining	H	L	L	H
	PBL remaining	H	H	L	H
	Weedy	H	H	M	H
3. Bergvliet_B	Clear x Weedfree	L	L	L	L
	Clear x Weedy	L	H	H	H
	Single x Weedfree	L	L	L	L
	Single x Weedy	H	H	H	H
	Double x Weedfree	L	L	L	L
	Double x Weedy	H	H	H	H
4. Hlabeni	Weedfree x NoFert	L	L	L	L
	Weedfree x Agri	L	L	L	L
	Weedfree x Max	L	L	L	L
	Weedfree x NPK	L	L	L	L
	Ring (2 m) x NoFert	L	L	L	L
	Ring (2 m) x Agri	L	L	L	L
	Ring (2 m) Max	L	L	L	L
	Ring (2 m) x NPK	L	L	L	L
	Ring (1 m) x NoFert	L	L	M	M
	Ring (1 m) x Agri	L	L	M	M
	Ring (1 m) Max	L	L	M	M
	Ring (1 m) x NPK	L	L	M	M
	Weedy x NoFert	L	H	M	H
	Weedy x Agri	L	H	H	H
	Weedy x Max	L	H	H	H
	Weedy x NPK	L	H	H	H
5. Mountain Home	Weedfree	L	L	L	L
	Ring weeding (2 m)	L	L	L	L
	Moderate weeding	L	L	L	L
	HBL and Grass Remaining	L	H	L	H
	PBL remaining	L	H	H	H
	Weedy	L	H	H	H
6. Longridge	Weedfree x No Fertilization	L	L	L	L
	HBL remaining x No Fertilization	L	L	L	L
	Grass Remaining x No Fertilization	L	L	L	L
	PBL Remaining x No Fertilization	L	L	L	L
	Weedy x No Fertilization	L	M	L	M
	Weedfree x Fertilization	L	L	L	L
	HBL remaining x Fertilization	L	L	L	L
	Grass Remaining x Fertilization	L	L	L	L
	PBL Remaining x Fertilization	L	L	L	L
	Weedy x Fertilization	L	M	L	M
7. Spitzkop	*P. elliottii* x Weedfree	L	L	L	L
	P. elliottii x Low intensity weeding	L	H	L	H
	P. patula x Weedfree	L	L	L	L
	P. patula x Low intensity weeding	L	H	L	H
	P. taeda x Weedfree	L	L	L	L
	P. taeda x Low intensity weeding	L	L	H	H
8. Langgewacht	2.7 m x Weedfree	L	L	L	L
	2.7 m x Low intensity weeding	L	L	L	L
	2.7 m x Weedy	L	H	M	H
	3 m x Weedfree	L	L	L	L
	3 m x Low intensity weeding	L	L	L	L
	3 m x Weedy	L	H	L	H
	3.5 m x Weedfree	L	L	L	L
	3.5 m x Low intensity weeding	L	L	L	L
	3.5 m x Weedy	L	H	L	H
9. Mt Gilboa	Weedfree	L	L	L	L
	Biomac	L	L	L	L
	Kraft	L	L	L	L
	Plantex	L	L	L	L
	Sludge	L	L	L	L
	Weedy	L	L	L	L

L: Low risk; M: Moderate risk and H: High risk

Continues from Table 4.6.

Trial name	**Vegetation management treatments**	**Rotation end tree growth responses**			**Overall growth risk**
		Survival	Volume	Uniformity	
10. Blyde	No Burn				
	Pit x Weedfree	L	L	L	L
	ChopPit x Weedfree	L	L	M	M
	ChopRip x Weedfree	L	L	M	M
	Rip x Weedfree	L	L	L	L
	Pit x Weedy	M	L	H	H
	ChopPit x Weedy	L	L	M	M
	ChopRip x Weedy	L	M	M	M
	Rip x Weedy	L	L	M	M
	Burn				
	Pit x Weedfree	L	L	L	L
	ChopPit x Weedfree	L	L	M	M
	ChopRip x Weedfree	L	L	M	M
	Rip x Weedfree	L	L	L	L
	Pit x Weedy	M	L	H	H
	ChopPit x Weedy	L	L	M	M
	ChopRip x Weedy	L	M	M	M
	Rip x Weedy	L	L	M	M
11. Mossbank	Weedfree	L	L	L	L
	Weedfree x Fertilization	L	L	L	L
	Moderate weeding	L	L	L	L
	Grass remaining	L	L	L	L
	HBL remaining	L	L	H	H
	Weedy	L	L	H	H
	Weedy x Fertilization	L	L	H	H
12. Ceylon	*P. elliottii* x Weedfree	L	L	L	L
	P. elliottii x Weedy	M	H	L	H
	P. patula x Weedfree	L	L	L	L
	P. patula x Weedy	L	M	L	M
	P. taeda x Weedfree	L	L	L	L
	P. taeda x Weedy	L	H	L	H

L: Low risk; M: Moderate risk and H: High risk

4.4.4.3. Uniformity (Dbh CV_Rel_WF)

Variability ranged between -39-94% relative to the *Weedfree* treatments, with all treatments classified as Low risk (90-100%) at Longridge, Mt Gilboa and Ceylon. Depending on the treatment, High or Moderate variability in the remaining trials was associated with the lack of weeding (*Weedy* treatment), less intensive weeding (*Low* or *Moderate weeding*), selective weeding (*PBL*, *HBL* or *Grass remaining*), or reduced area weeded (*1 m Ring weeding*). Moderate levels of variability also occurred in all four *Weedfree* treatments that were chopper-rolled at Blyde (*ChopPit* + *ChopRip* - slash retained or burned), indicating that this form of slash management is not conducive to the development of a uniform stand.

4.4.4.4. Overall growth response risk rating

The overall risk rating for each vegetation management treatment was based on the combined risk related to survival, yield and uniformity (**Table 4.6**). With the exception of Blyde, all the *Weedfree* treatments in the remaining trials, and all treatments at Mt Giboa, received a Low overall risk rating. The non-weed related variability associated with the chopper-rolled treatments at Blyde resulted in those four *Weedfree* treatments (*ChopPit* + *ChopRip* - slash retained or burned) receiving an overall Moderate risk rating. In general, Moderate and High risk were associated with reduced area or intensity of weeding, or the selective retention of vegetation groups depending on the herbicide used.

4.4.5. Vegetation management operations

The number of vegetation management operations and quantity of herbicide applied through the rotation was directly related to site productivity, with more operations and herbicide used for the *Weedfree* treatments in the ST (9 weeding operations; 14.9 kg of herbicides applied ha^{-1} or 1.5 kg ha^{-1} yr^{-1}) and WT ($\bar{x}$ = 8 weeding operations; $\bar{x}$ = 11.6 kg of herbicides applied ha^{-1} or 1.2 kg ha^{-1} yr^{-1}) climate zones compared to the CT ($\bar{x}$ = 6 weeding operations; $\bar{x}$ = 8.5 kg of herbicides applied ha^{-1} or 0.9 kg ha^{-1} yr^{-1}) climate zone (**Table 4.7**).

Table 4.7. Number of vegetation control operations and total quantity herbicide use (formulated product) up to 10.4 years in 12 vegetation management trials implemented on pines in the summer rainfall region of South Africa. For each weeding treatment, the values in parentheses represent the rates of herbicide application adjusted to account for weeding distances and vegetation loads associated within each trial.

Trial name	Vegetation management treatments	Type and number of weeding operations used at each trial									
		Pre-plant spray[1] (kg ha^{-1})	Ring (1-2 m)	[1]Coning (kg ha^{-1})	[1]Chemical Hoe (kg ha^{-1})	[1]Spot spray (kg ha^{-1})	Manual operation s (n)	Herbicide operations (n)	Total number weeding operations (n)	Total quantity herbicide applied (kg ha^{-1})	Quantity herbicide applied annually (kg ha^{-1} yr^{-1})
1. Kwambonambi	Weedfree	1 (4.0)	2	1 (3.7)	1 (3.7)	4 (0.9)	2	7	9	14.9	1.5
	Moderate weeding	1 (4.0)	1	1 (3.7)	1 (3.7)	2 (0.9)	1	5	6	13.1	1.4
	Ring weeding (2 m) (Ferns remaining)	1 (4.0)	6	-	1 (3.3)	1 (0.9)	8 (2 slash)	3	11	8.2	0.9
	Grass remaining	1 (4.0)	1	1 ([2]2.5)	1 ([2]2.5)	4 ([2]0.9)	1	7	8	12.6	1.3
	HBL remaining	1 (4.0)	1	1 ([3]3.0)	1([3]3.0)	4 ([3]0.9)	1	7	8	13.6	1.4
	PBL remaining	1 (4.0)	1	1 ([4]2.8)	1 ([4]2.8)	4 ([4]0.9)	1	7	8	13.2	1.4
	Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
2. Bergvliet_A	Weedfree	1 (4.0)	2	1 (3.7)	1 (3.7)	4 (0.9)	2	7	9	14.9	1.6
	Ring weeding (1.5 m)	1 (4.0)	6	-	1 (3.5)	2 (0.9)	6	4	10	9.3	1.0
	Moderate weeding	1 (4.0)	1	1 (3.7)	1 (3.7)	3 (0.9)	3 (2 slash)	6	9	14.0	1.5
	HBL remaining	1 (4.0)	1	-	1 ([3]2.8)	2 ([3]0.9)	3 (2 slash)	4	7	8.6	0.9
	PBL remaining	1 (4.0)	1	-	1 ([4]2.5)	2 ([4]0.9)	3 (2 slash)	4	7	8.1	0.9
	Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
3. Bergvliet_B	Clear x Weedfree	1 (4.0)	2	1 (2.2)	1 (2.2)	4 (0.6)	2	7	9	10.8	1.2
	Clear x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	1.2
	Single x Weedfree	1 (4.0)	2	1 (2.2)	1 (2.2)	4 (0.6)	2	7	9	10.8	1.2
	Single x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
	Double x Weedfree	1 (4.0)	2	1 (2.2)	1 (2.2)	4 (0.6)	2	7	9	10.8	0.4
	Double x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
4. Hlabeni	Weedfree	1 (4.0)	2	1 (2.1)	1 (2.1)	3 (0.6)	2	6	8	10.1	1.1
	Ring weeding (2 m)	1 (4.0)	3	-	1 (1.9)	3 (0.6)	4 (1 slash)	5	9	7.7	0.8
	Ring weeding (1 m)	1 (4.0)	3	-	1 (2.1)	3 (0.6)	4 (1 slash)	5	9	7.9	0.8
	Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
5. Mountain Home	Weedfree	1 (4.0)	2	1 (3.6)	1 (3.6)	2 (0.9)	2	5	7	12.9	1.2
	Ring weeding (2 m)	1 (4.0)	6	-	-	2 (0.9)	6	3	9	5.8	0.6
	Moderate weeding	1 (4.0)	1	1 (3.6)	1 (3.6)	2 (0.9)	1	5	6	12.9	1.2
	HBL and Grasses Remaining	1 (4.0)	1	1 ([2+3]2.0)	1 ([2+3]2.0)	2 ([2+3]0.9)	1	5	6	9.2	0.9
	PBL remaining	1 (4.0)	1	1 ([4]2.8)	1 ([4]2.8)	2 ([4]0.9)	1	5	6	11.3	1.1
	Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4

[1]Roundup® (isopropylamine salt of glyphosate 360 g a.i. kg^{-1}) a non-selective herbicide was used for all weeding operations expecting for the following treatments: [2]Grass remaining, [3]HBL remaining and [4]PBL remaining where Fusilade® (fluasifop-p-butyl 150 g a.i. kg^{-1}) (grass selective herbicide), MCPA® (potassium salt phenoxy compound 400 g a.i. kg^{-1}) (broadleaf selective herbicide) and Garlon® 480 EC (triclopyr (pyridyloxy compound) (as butoxy ethyl ester) 480 g a.i. kg^{-1}) were applied.

Continues from Table 4.7.

Trial name	Vegetation management treatments	Type and number of weeding operations used at each trial									
		Pre-plant spray[1] (kg ha^{-1})	Ring (1 m)	[1]Coning (kg ha^{-1})	[1]Chemical Hoe (kg ha^{-1})	[1]Spot spray (kg ha^{-1})	Manual operations (n)	Herbicide operations (n)	Total number weeding operations (n)	Total quantity herbicide applied (kg ha^{-1})	Quantity herbicide applied annually (kg ha^{-1} yr^{-1})
6. Longridge	Weedfree	1 (4.0)	2	1 (2.1)	1 (2.1)	3 (0.6)	2	6	8	10.1	1.0
	Grass remaining	1 (4.0)	2	1 ([2]1.5)	1 ([2]1.5)	2 ([2]0.5)	2	5	7	8.0	0.8
	HBL remaining	1 (4.0)	2	1 ([3]1.8)	1 ([3]1.8)	2 ([3]0.6)	2	5	7	8.8	0.9
	PBL remaining	1 (4.0)	2	1 ([4]1.7)	1 ([4]1.7)	2 ([4]0.6)	2	5	7	8.5	0.9
	Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
7. Spitzkop	*P. elliottii* x Weedfree	1 (4.0)	1	1 (3.7)	1 (1.5)	3 (0.6)	1	6	7	10.9	1.2
	P. elliottii x Low intensity weeding	1 (4.0)	-	-	-	-	2 slash	1	3	4.0	0.4
	P. patula x Weedfree	1 (4.0)	1	1 (3.7)	1 (1.5)	3 (0.6)	1	6	7	10.9	1.2
	P. patula x Low intensity weeding	1 (4.0)	-	-	-	-	2 slash	1	3	4.0	0.4
	P. taeda x Weedfree	1 (4.0)	1	1 (3.7)	1 (1.5)	3 (0.6)	1	6	7	10.9	1.2
	P. taeda x Low intensity weeding	1 (4.0)	-	-	-	-	2 slash	1	3	4.0	0.4
8. Langgewacht	2.7 m x Weedfree	1 (4.0)	1	1 (2.1)	1 (2.1)	2 (0.6)	1	5	6	9.3	1.0
	2.7 m x Low intensity weeding	1 (4.0)	-	-	1 (2.1)	1 (0.6)	1 slash	3	4	6.7	0.7
	2.7 m x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
	3 m x Weedfree	1 (4.0)	1	1 (2.1)	1 (2.1)	2 (0.6)	1	5	6	9.5	1.0
	3 m x Low intensity weeding	1 (4.0)	-	-	1 (2.1)	1 (0.6)	1 slash	3	4	6.7	0.7
	3 m x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
	3.5 m x Weedfree	1 (4.0)	1	1 (2.1)	1 (2.1)	2 (0.6)	1	5	6	9.6	1.0
	3.5 m x Low intensity weeding	1 (4.0)	-	-	1 (2.1)	1 (0.6)	1 slash	3	4	6.8	0.7
	3.5 m x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
9. Mt Gilboa	Weedfree	1 (4.0)	2	-	1 (1.4)	2 (0.6)	2	4	6	6.6	0.7
	Biomac	1 (4.0)	-	-	1 (1.4)	2 (0.6)	-	4	4	6.6	0.7
	Kraft	1 (4.0)	-	-	1 (1.4)	2 (0.6)	-	4	4	6.6	0.7
	Plantex	1 (4.0)	-	-	1 (1.4)	2 (0.6)	-	4	4	6.6	0.7
	Sludge	1 (4.0)	-	-	1 (1.4)	2 (0.6)	-	4	4	6.6	0.7
	Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4

[1]Roundup® (isopropylamine salt of glyphosate 360 g a.i. kg^{-1}) a non-selective herbicide was used for all weeding operations expecting for the following treatments: [2]Grass remaining, [3]HBL remaining and [4]PBL remaining where Fusilade® (fluasifop-p-butyl 150 g a.i. kg^{-1}) (grass selective herbicide), MCPA® (potassium salt phenoxy compound 400 g a.i. kg^{-1}) (broadleaf selective herbicide) and Garlon® 480 EC (triclopyr (pyridyloxy compound) (as butoxy ethyl ester) 480 g a.i. kg^{-1}) were applied.

Continues from Table 4.7.

Trial name	Vegetation management treatments	Type and number of weeding operations used at each trial									
		Pre-plant spray[1] (kg ha^{-1})	Ring (1 m)	[1]Coning (kg ha^{-1})	[1]Chemical Hoe (kg ha^{-1})	[1]Spot spray (kg ha^{-1})	Manual operations (n)	Herbicide operations (n)	Total number weeding operations (n)	Total quantity herbicide applied (kg ha^{-1})	Quantity herbicide applied annually (kg ha^{-1} yr^{-1})
10. Blyde	No Burn										
	ChopPit x Weedfree	1 (4.0)	1	1 (2.2)	1 (2.2)	2 (0.6)	1	5	6	9.6	1.0
	ChopPit x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
	ChopRip x Weedfree	1 (4.0)	1	1 (2.2)	1 (2.2)	2 (0.6)	1	5	6	9.6	1.0
	ChopRip x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
	Pit x Weedfree	1 (4.0)	1	1 (2.2)	1 (2.2)	2 (0.6)	1	5	6	9.6	1.0
	Pit x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
	Rip x Weedfree	1 (4.0)	1	1 (1.5)	1 (1.5)	2 (0.6)	1	5	6	8.1	0.9
	Rip x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
	Burn										
	ChopPit x Weedfree	1 (4.0)	1	1 (3.7)	1 (3.7)	2 (0.6)	1	5	6	12.5	1.3
	ChopPit x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
	ChopRip x Weedfree	1 (4.0)	1	1 (3.7)	1 (3.7)	2 (0.6)	1	5	6	12.5	1.3
	ChopRip x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
	Pit x Weedfree	1 (4.0)	1	1 (3.7)	1 (3.7)	2 (0.6)	1	5	6	12.5	1.3
	Pit x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
	Rip x Weedfree	1 (4.0)	1	1 (2.2)	1 (2.2)	2 (0.6)	1	5	6	9.6	1.0
	Rip x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
11. Mossbank	Weedfree	1 (4.0)	2	-	1 (1.4)	2 (0.6)	2	4	6	6.6	0.6
	Weedfree x Fertilization	1 (4.0)	2	-	1 (1.4)	2 (0.6)	2	4	6	6.6	0.6
	Moderate weeding	1 (4.0)	2	-	1 (1.4)	2 (0.6)	2	4	6	6.6	0.6
	[2]Grass remaining	1 (4.0)	2	-	1 ([2]1.0)	2 ([2]0.5)	2	4	6	6.0	0.6
	[3]HBL remaining	1 (4.0)	2	-	1 ([3]1.2)	2 ([3]0.6)	2	4	6	6.4	0.6
	Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
	Weedy x Fertilization	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
12. Ceylon	*P. elliottii* x Weedfree	1 (4.0)	2	-	1 (1.5)	2 (0.6)	2	4	6	6.7	0.7
	P. elliottii x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
	P. patula x Weedfree	1 (4.0)	2	-	1 (1.5)	2 (0.6)	2	4	6	6.7	0.7
	P. patula x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4
	P. taeda x Weedfree	1 (4.0)	2	-	1 (1.5)	2 (0.6)	2	4	6	6.7	0.7
	P. taeda x Weedy	1 (4.0)	-	-	-	-	-	1	1	4.0	0.4

[1]Roundup® (isopropylamine salt of glyphosate 360 g a.i. kg^{-1}) a non-selective herbicide was used for all weeding operations expecting for the following treatments: [2]Grass remaining, [3]HBL remaining and [4]PBL remaining where Fusilade® (fluasifop-p-butyl 150 g a.i. kg^{-1}) (grass selective herbicide), MCPA® (potassium salt phenoxy compound 400 g a.i. kg^{-1}) (broadleaf selective herbicide) and Garlon® 480 EC (triclopyr (pyridyloxy compound) (as butoxy ethyl ester) 480 g a.i. kg^{-1}) were applied.

These results are similar to those obtained from a survey carried out on herbicide-use within the forestry industry in South Africa, with increased herbicide quantities and spraying operations with increased site productivity (CT<WT<ST) (**Chapter 2)**.

The highest number of operations ($\bar{x}$ = 10) occurred in the *Weedfree* and *Ring weeding* treatments, with the *Weedy* treatments the least ($\bar{x}$ = 1). Even though the various *Ring weeding* treatments received the same number operations as the *Weedfree* treatments (trial specific), due to the reduced area weeded, the quantity of herbicides applied was less ($\bar{x}$ = 7.8 kg ha^{-1} versus $\bar{x}$ = 11.9 kg ha^{-1} herbicide used). This trend was similar for the *Moderate intensity* weeding treatments although fewer weeding operations occurred ($\bar{x}$ = 7) and less herbicides were used ($\bar{x}$ = 11.7 kg ha^{-1}) as compared to the *Weedfree* treatments, yet more than the *Ring weeding* treatments.

In general, less herbicide ($\bar{x}$ = 10.3 kg ha^{-1}) was used for the selective control treatments (*Grass remaining*, *HBL remaining* and *PBL remaining*). Although this may in part be attributed to the reduced rates of application used (fluasifop-p-butyl @ 3 kg ha^{-1}, methylphenoxyacetic acid @ 2.5 kg ha^{-1}and triclopyr (as butoxy ethyl ester) @ 2.5 kg ha^{-1} compared to glyphosate @ 4 kg ha^{-1}) once the desired species becomes dominant on the site through selective weeding, the suppression of new emergents would also have resulted in the reduced need for follow-up control.

The slash management treatments (*Clear*, *Single* and *Double*) at Bergvliet_B, different species planted (*P. elliottii*, *P. patula* and *P. taeda*) at Spitzkop and Ceylon, and the three planting spacings (*2.7 m x 2.7 m*, *3 m x 3 m*, and *3.5 m x 3.5 m*) at Langgewacht, did not influence the number of weeding operations, nor the quantity of herbicides applied. The use of various mulches (biomach, kraft, plantex and sludge) at Mt Gilboa negated the need for 2 x ring weeding operations compared to the *Weedfree* treatment but did not alter the quantity of herbicides applied (6.6 kg ha^{-1}).

At Blyde, both slash management (*Burnt* and *Unburnt*) and site preparation (*Pit*, *Rip*, *ChopPit* and *ChopRip*) had a direct influence on the quantity of herbicides applied. For slash management, the burning of residues stimulated the earlier development of vegetation (**Little et. al 2007**), resulting in more herbicides applied compared to the unburned *Weedfree* treatment ($\bar{x}$ = 11.8 kg ha^{-1} compared to $\bar{x}$ = 9.2 kg ha^{-1}). The reduced occurrence of vegetation associated with the *Rip* treatments, meant that herbicide use was also the lowest ($\bar{x}$ = 8.9 kg ha^{-1}) compared to the 11.1 kg ha^{-1} for all the remaining weedfree treatments combined.

4.4.6. Linking weeding intensity (number of weeding operations and herbicide use) to tree growth risk

Within forestry, the ideal vegetation management treatment from a purely economic perspective would be one where tree performance is not impacted by competing vegetation (highest yield obtained), together with the lowest inputs in terms of weeding operations and herbicide-use (lowest treatment costs). Within these trials, there was a direct link between improved tree performance and increased weeding intensity and herbicide-use (**Tables 4.5, 4.7 and 4.8**). Irrespective of the preferred vegetation management treatment, any associated environmental and/or social impacts also need to be considered when selecting a treatment regime. For example, there is the potential for active ingredients to move off-site and accumulate within watersheds or catchments for those treatments that rely on the use of herbicides (even where low quantities are applied) (**Baillie 2016**). Likewise, labour-intensive manual weeding treatments are generally more costly than where herbicides are used and are also not considered ergonomically favourable (**Little et al. 2002; Wagner et al. 2006; Steenkamp 2007; Willoughby et al. 2009; McEwan and Steenkamp 2014**). Treatments within each trial were therefore partitioned into three broad scenarios based on tree performance and herbicide-use (**Table 4.8**).

Table 4.8. Two-way table linking overall tree growth responses to herbicide use for various vegetation management treatments within 12 pine vegetation management trials in the summer rainfall region of South Africa. Darker shading indicates more desirable treatment options in terms of optimum tree performance (survival, growth and uniformity), together with reduced herbicide-use.

Trials	*Herbicide use rating	Tree growth risk response rating		
		Low	Moderate	High
Kwambonambi	Low	-	-	Weedy
	Moderate	-	Ring (2 m) (Ferns remaining)	-
	High	Weedfree	Moderate weeding	Grass remaining HBL remaining PBL remaining
Bergvliet_A	Low	-	-	Weedy
	Moderate	Ring weeding (1.5 m)	-	HBL remaining PBL remaining
	High	Weedfree	Moderate weeding	
Bergvliet_B	Low	-	-	Weedy regardless of slash management
	Moderate	-	-	-
	High	Weedfree regardless of slash management	-	-
Hlabeni	Low	-	-	Weedy with/without fertilization
	Moderate	Ring weeding (2 m) with/without fertilization	Ring weeding (1 m) with/without fertilization	-
	High	Weedfree with/without fertilization	-	-
Mountain Home	Low	-	-	Weedy
	Moderate	Ring weeding (2 m)	-	HBL and Grass Remaining
	High	Weedfree Moderate weeding	-	PBL remaining
Longridge	Low	Weedy with fertilization	Weedy without fertilization	-
	Moderate	HBL remaining with/without fertilization Grass remaining with/without fertilization PBL remaining with/without fertilization	-	-
	High	Weedfree with fertilization	Weedfree without Fertilization	-
Spitzkop	Low	-	-	Low intensity weeding all species
	Moderate	-	-	-
	High	Weedfree all species	-	-
Langgewacht	Low	-	-	Weedy with spacing (2.7 x 2.7 m, 3 x 3 m and 3.5 x3.5 m)
	Moderate	Weedfree with spacing (2.7 x 2.7 m, 3 x 3 m and 3.5 x3.5 m) Low intensity weeding with spacing (2.7 x 2.7 m and 3.5 x 3.5 m)	Low intensity weeding with spacing (3 x 3 m)	-
	High	-	-	-

*Herbicide use rating based on total quantities of herbicides applied ha^{-1} for that treatment
Low: <5 kg ha^{-1}
Moderate: 5-10 kg ha^{-1}
High: >10 kg ha^{-1}

Continues from Table 4.8.

Trials	*Herbicide use rating	Tree growth risk response rating Low	 Moderate	 High
Mt Gilboa	Low	Weedy	-	-
	Moderate	Weedfree All mulching treatments	-	-
	High	-	-	-
Blyde	Low	-	No Burn x ChopPit x Weedy No Burn x ChopRip x Weedy No Burn/Burn x Rip x Weedy	No Burn/Burn x Pit x Weedy Burn x ChopPit x Weedy Burn x ChopRip x Weedy
	Moderate	No Burn x Pit x Weedfree No Burn/Burn x Rip x Weedfree	No Burn x ChopPit x Weedfree No Burn x ChopRip x Weedfree	-
	High	Burn x Pit X Weedfree	Burn x ChopPit x Weedfree Burn x ChopRip x Weedfree	-
Mossbank	Low	-	Moderate weeding	Weedy with/without fertilization
	Moderate	Weedfree with/without fertilization Grass remaining	-	HBL remaining
	High	-	-	-
Ceylon	Low	-	Weedy with *P. patula*	Weedy with *P. elliottii* Weedy with *P. taeda*
	Moderate	Weedfree all species	-	-
	High	-	-	-

*Herbicide use rating based on total quantities of herbicides applied ha^{-1} for that treatment
Low: <5 kg ha^{-1}
Moderate: 5-10 kg ha^{-1}
High: >10 kg ha^{-1}

4.4.6.1. Maximisation of timber production

This approach is favoured by most forest companies within SA, whereby silvicultural inputs are structured to ensure optimum yield is obtained in a sustainable manner (taking economic, environmental and/or social impacts into consideration) (**Little and Dyer 2002; Little et al. 2018b**). For example, in a study on the financial performance of vegetation management on *E. smithii*, **Little et al. (2018b)** found that even though the weedfree treatment was labour-intensive and used the most herbicides of all treatments (it was also the most expensive to implement), it had the highest yield as well as highest return on investment compared to the other treatments. Similar trends were obtained when comparing the treatments that formed part of this trial series, especially those trials situated in the ST and WT climate zones (**Table 4.8**). Within these trials the *Weedfree* treatments had the lowest tree growth risk rating, albeit it with an associated High herbicide-use rating (>10 kg ha^{-1} herbicides applied), the exception to this was the *Weedfree* treatment (without fertilization) at Longridge, which had a Moderate tree growth risk and High herbicide-use rating. In addition to the *Grass remaining* treatment at Mossbank, all the *Weedfree* treatments in the CT trials had risk ratings that varied between Low to Moderate for tree growth, and between Moderate to High risk for herbicide-use. At Blyde, only the *Pit* and *Rip* treatments (irrespective of slash management) were classified as Low risk for tree growth, with the remaining *Weedfree* treatments classified as Moderate risk. Due to the lack of competing vegetation at both Longridge and Mt Gilboa, the *Weedy* treatments (with fertilization at Longridge) were classified as Low risk for tree growth and herbicide-use.

4.4.6.2. Compromise between timber production and reduced herbicide use

This approach focusses on those treatments whereby optimum tree growth is balanced against reduced herbicide-use. Within this scenario, treatments will be selected based on a Low to Moderate risk for tree growth responses and herbicide-use rating (0-10 kg ha^{-1} herbicides applied). Across all trials, 18 treatments fulfilled these criteria and included the following: *Ring weeding (2 m) (Ferns remaining)* treatment at Kwambonambi; *Ring weeding (1.5 m)* treatment at Bergvliet_A; *Ring weeding (1 and 2 m)* irrespective of fertilization at Hlabeni; *Ring weeding (2 m)* at Mountain Home; all treatments (except for *Weedfree*) at Longridge; *Low intensity weeding* irrespective of planting spacing at Langgewacht; *Weedy* and all mulching treatments at Mt Gilboa; the *Unburnt Weedy* treatments with *ChopPit*, *ChopRip* and *Rip* (including the *Burnt* treatment for *Rip* only) at Blyde; the *Moderate intensity* weeding at Mossbank and the *Weedy* treatment planted with *P. patula* at Ceylon.

4.4.6.3. Focus on reduced herbicide-use

If the focus were to reduce any environmental and/or social impacts (through a reduction in herbicide-use and labour units), then all the remaining treatments would be included, together with a resultant loss in timber production. The treatments within this scenario could be further partitioned into two broad groups, those that used:

- less than 5 kg ha^{-1} herbicide: most *Weedy* treatments, especially those situated in ST and WT climate zones, together with the *Low intensity weeding* treatment at Spitzkop; or
- between 5-10 kg ha^{-1} herbicide applied: most of the *Selective weeding* treatments.

4.5. Conclusions

Tree growth responses (survival, yield and uniformity) obtained for the 12 trials were a function of inherent site conditions, previous land use, species planted and the management of competing vegetation. Generally, the trials situated within the ST and WT climate zones had better tree growth compared to the CT climate zone, which can be attributed to the higher mean annual temperatures and increased number of growth days associated with these climatic zones. As for tree performance, weed abundance and growth was higher on these sites, which resulted in higher levels of weeding required, or increased competition in terms of yield and uniformity if uncontrolled. Within specific trials, the more intensive the weeding (number of weeding operations and/or area treated), the better the growth obtained (*Weedfree* treatments always optimum).

Since tree growth responses are linked to weeding intensity (and hence herbicide use), if tree growth is most important with the aim to maximise yield, then complete vegetation management is required (*Weedfree* treatments). However, herbicide use can be reduced while obtaining similar tree growth responses as that of full vegetation management. Competing vegetation within ST and WT climate zones can be managed through clearing any vegetation within a ≥1.0 m ring width. For the CT climate zone, treatment responses varied among trials with no clear trend. Although some of the *Weedy* treatments did not cause significant growth responses, these treatments cannot be recommended due to the variability in results obtained for this treatment within this climate zone.

The combined results from the 12 trials indicates the importance of vegetation management in terms of ensuring optimal pine production, with a higher intensity of weeding favoured, albeit with higher herbicide use. Although the economic viability of the various treatments needs to be determined, this chapter focussed on linking the level of weed control to tree growth and herbicide use. By doing this, the information from this trial series can also be used for the determination of social and environmental risk factors associated with each vegetation management treatment tested (which is currently lacking in SA).

CHAPTER 5. LINKING PULPWOOD TREE VOLUME AND FINANCIAL PERFORMANCES TO DIFFERENT METHODS OF VEGETATION MANAGEMENT WITHIN COMMERCIAL FORESTRY SOUTH AFRICA

5.1. Introduction

The forestry industry within SA contributes significantly towards economic growth (responsible for 9.8% of the country's agricultural Gross Domestic Product (GDP) and 4.9% of South Africa's manufacturing GDP) and job creation (employing over 149 000 people and estimated to indirectly support well over half a million South Africans) (**Siry et al. 2005; FSA 2020**). However, the area under commercial forestry plantations has declined by ca. 25% (305 755 ha) from 1996 to 2020 (**FSA 2020**). Despite this decline, the total roundwood productivity has increased by 4.9 m^3 ha^{-1} per annum over the same period (**FSA 2020**). Amongst other factors, these gains can be attributed to the introduction and planting of new species and/or hybrid combinations, tree improvement, improved species to site matching, management of risk and use of intensive silvicultural practices (**Swain and Gardner 2003**; **du Toit et al. 2010; Little et al. 2018b**). Comprehensive research into the effects of site preparation (slash and soil management), vegetation management and fertilization have enabled the optimization of productivity on a site-specific bases, be that for tree form, timber volume, and/or timber quality (**Wagner et al. 2006; Willoughby et al. 2009; du Toit et al. 2010; Rolando et al. 2017; Ndlovu et al. 2019**).

Of the various intensive silvicultural practices carried out during tree establishment, the appropriate management of competing vegetation is necessary to reduce both the short- and long-term negative impacts of this vegetation on timber/wood production (**Wagner et al. 2006; Roberts et al. 2018; Ndlovu et al. 2019**). Various vegetation management methods (mostly labour intensive) are used within SA to ensure that competing vegetation is kept to a minimum or predetermined level that will not negatively impact planted trees (**Zutter et al. 1987; Little et al. 2006; Wagner et al. 2006).** Although a combination of appropriate control measures for the integrated management of vegetation is always preferred, over the past five decades, the effectiveness and relatively low cost of herbicides (**Dales and Golob 1997; Little et al. 2006; Wagner et al. 2006**), has led to the dependence on their continued availability to the near exclusion of most non-herbicide methods (or those where herbicides are used at reduced rates) for improving tree growth (**Little et al. 2006; Wagner et al. 2006; Willoughby et al. 2009; Baillie 2016; Rolando et al. 2017**).

Within SA, alternative practices, or methods where herbicides are used at reduced rates have been investigated (hereafters referred to as “methods that reduce herbicides”) (**Eccles and Little 1995; Little and Schumann 1996; Little and Rolando 2001; Tu et al. 2001; Little et al. 2002, 2006; Little 2014**). These methods include, for example, reducing the area treated (spot or strip spraying), the targeted control of specific/competitive vegetation types, the development of standards for cover-cropping and the adjustment of weed control standards according to site productivity (**Little et al. 2006; Little 2014**). Even though methods that reduce herbicides have been shown to not compromise tree growth (**Zutter et al. 1987; Little et al. 2006; Little and Payn 2016; Roberts et al. 2016, 2018; Ndlovu et al. 2019**), they have not always been adopted commercially. This raises the question as to whether the economic impacts of these methods have been adequately assessed such that the grower has the ability to make an informed decision on whether to adopt them or not?

Any resource implications relating to vegetation control will only be realised at the end of the rotation when the trees are harvested (ranging from 7 to 30 years depending on tree species and target product/market). Consequently, forest managers must select between different vegetation control options (including methods that reduce herbicides) that will determine different economic returns at rotation end. However, choosing between these vegetation control methods would be simpler if the investment outcomes (or return on investment) associated with each choice could be estimated at the start of the rotation. These outcomes could then guide managers in making more informed decisions (**Ham and Jacobson 2011**). Although there is data linking vegetation management treatments to productivity and costs, especially for eucalypts in South Africa, this is mostly on an individual trial basis (**Little et al. 2002, 2018; Roberts et al. 2016, 2018**) with a focus on the determination of those practices that favour the highest volume and/or profit (**Wagner et al. 2006; Rolando and Little 2009)**. Limited literature could be found comparing the cost:benefit associated with vegetation control in two genera (pines and eucalypts) that included longer-term tree growth data (linked to various vegetation management practices) for multiple-data sets that spanned different (climatic/physiographic) growing regions. The benefits of a combined comparison of this nature would be the ability to compare similar treatments across sites thereby allowing for a better understanding of overall trends as well as the robustness or repeatability of various practices. Such an approach would increase the level of confidence with which recommendations could be made.

In the work reported here, seven eucalypt and twelve pine vegetation management trials implemented during the 1990s in the summer-rainfall region of SA were selected to evaluate the cost-effectiveness of different vegetation control options (herbicide versus methods that reduce use of herbicides).

5.2. Materials and methods

For an in-detail description for each of the chosen trials used, please refer to chapters 3 (eucalypt trials) and 4 (pine trials).

5.2.1. Cost assumptions used for all vegetation management treatments in both eucalypt and pine trial series

The cost effectiveness of the various vegetation management treatments was determined using a combination of merchantable volume (yield) obtained at rotation end for the eucalypt trials (**Table 3.5 pages 55-56**), and data around 10 years for the pine trials (**Table 4.5 pages 94-96**), and vegetation control operations used (which will have a direct influence on the total costs of vegetation management) (**Tables 3.6 pages 57-58 and 4.7. pages 113-115**). To determine the vegetation management costs, the different types and number of vegetation control events were recorded for all seven eucalypt and twelve pine trials. To standardise the variation in cost over time due to the implementation of the trials between 1990 to 2008, the actual weeding costs for 2020 were used for all trials. These costs were calculated by averaging actual current weeding operation costs from three commercial companies. The labour cost was based on the national daily minimum wage (R187 which excludes the additional costs to company (such as overheads, transport, medical cover, pension, etc.) (**DOL 2020**).

5.2.2. Net present value (NPV)

Any profit gained from vegetation management (or lack thereof) is affected both directly and indirectly by the method of vegetation management, as any improvement in yield (or volume) needs to be taken into consideration together with the vegetation management cost over the rotation. To calculate this the number of vegetation management operations and estimated cost for each treatment was determined. The cost of pulpwood timber delivered to the mill is based on the international average pulpwood price of 2019 (R 1 379 tonne^{-1} for both *Eucalyptus* and *Pinus* species) (**WRI 2020**). For each treatment, volume ha^{-1} was converted to tonnes ha^{-1} using eucalypt/pine-specific conversion factors (*E. grandis* x *E. camaldulensis* = 0.75; *E. grandis* x *E. urophylla* = 0.70; *E. smithii* = 0.81; *E. dunnii* = 0.88; and all *Pinus* species = 1.00) (**Kotze et al. 2012**). The gross income per hectare (R ha^{-1}) could then be calculated for each treatment, while the nett income was derived from subtracting only the vegetation management expenses occurred throughout the rotation. Ideally, all costs over the whole rotation should be taken into consideration, however the large differences between the trials in terms of the different site conditions, species grown, practices used for site preparation and planting, meant that the determination of actual costs would not be feasible. As the aim for the costing exercise were to test overall principles relating to vegetation management, no harvesting (including transport) or establishment (marking, pitting, planting or fertilisation etc.) costs have been included as these are common to all treatments. Rather, only the vegetation management costs (and those associated with vegetation management) and timber yield (volume) were used for the calculation of the "gross and nett income". The treatments where the four different mulching material (kraft paper. biomac. plantex and sludge) was used at Mt Gilboa, was also excluded from the costing, as this was new experimental material with zero basis for the cost thereof. However, if the cost of the mulching treatments where included, the overall cost of the vegetation management treatment would increase. Net present value (NPV) was used to calculate the difference between the present value of cash inflow and the present value of cash outflows, discounted at 6% over a 7-10 year period (depended on trial duration) (**Ham and Jacobson 2011**; **Little et al. 2018b; Investopedia 2021**). The cash outflows consisted of the total costs for all the different weeding operations ha^{-1}, while the cash inflow consisted of the income generated ha^{-1} at the final year of each trial (equation 5).

Equation 5. $\text{NPV} = \sum_{t=1}^{n} \frac{Rt}{(1+i)^t}$

where:

Rt: Net cash inflow-outflows during a single period t

i: Discount rate

t: Number of timer periods

From this, the NPV Profit for each treatment, relative to each trial's *Weedy* treatment was then calculated (expressed as a %).

5.2.3. Tree performance and financial risk associated with reduced levels of vegetation management for both eucalypt and pine trial series

To determine the risk associated with reduced levels of vegetation management in terms of volume and profit, the treatments within each trial were partitioned into one of the three risk classes (Low, Moderate or High) relative to that trials *Weedfree* treatment for volume, and *Weedy* treatment for profit percentage. Although the criteria used to partition the risk classes were selected to illustrate principles, they can be adjusted to correspond with company-specific tree performance criteria.

(i) Vol_Rel_WF: The same data from **Chapter 3.4.3.2.** Volume (Vol_Rel_WF) (**page 70**) and **Chapter 4.4.4.2**. Volume (Vol_Rel_WF) (**page 109**) from the eucalypt and pine trials respectably were used (**Table 3.7, page 71; Table 4.6, pages 110-111**).

(ii) Financial risk: Due to the wide range in NPV profit percentages obtained across the various trials (from -3% to 171%) (**Table 5.1**), each trial NPV profit percentage was divided into three equal classes. From this, NPV profit for each vegetation management treatment (both eucalypt and pine trial data sets) were partitioned into three risk classes (Low, Moderate or High) relative to that trial's *Weedy* treatment (Profit_Rel_Weedy) (in most instances the *Weedy* treatment generated the lowest NPV) (**Table 5.1**). Vegetation management treatments classified as Low risk generated more NPV profit compared to the High risk treatments, which generated similar NPV profit to the various *Weedy* treatments.

Table 5.1. Risk categorization for tree growth (volume) and financial risk relating to vegetation management within seven vegetation management trials implemented on eucalypts in the summer rainfall region of South Africa.

Vegetation management trials		Volume (Vol_Rel_WF (%))			[1]Financial risk (Profit_Rel_Weedy (%))		
		High (%)	Moderate (%)	Low (%)	High (%)	Moderate (%)	Low (%)
Eucalypt trial sets	1. Fairbreeze	<79	80-89	>90	<20	21-40	>41
	2. Oaklands				<14	15-28	>29
	3. KT				<5	6-10	>11
	4. Mountain Home				<43	44-86	>87
	5. Enon				<10	11-20	>21
	6. Tweefontein				<19	20-38	>39
	7. Draycott				<17	18-34	>35
Pine trial sets	1. Kwambonambi	<79	80-89	>90	<43	44-86	>87
	2. Bergvliet (Est)				<28	29-56	>57
	3. Bergvliet (Collab)				<85	86-170	>171
	4. Hlabeni				<4	5-8	>9
	5. Mountain Home				<28	29-56	>57
	6. Longridge				<6	7-12	>13
	7. Spitzkop				<11	12-22	>23
	8. Langgewacht				<7	8-14	>15
	9. Mt Gilboa				<-8	-7-4	>-3
	10. Blyde				<23	24-46	>47
	11. Mossbank				<2	3-4	>5
	12. Ceylon				<10	11-20	>21

[1]Based on individual trials NPV profit range obtained.

5.2.4. Linking of vegetation management treatment volume to financial risk for all eucalypt and pine trial series

For all trials, two-way contingency tables were used to link the financial risk (Profit_Rel_Weedy) for each treatment within each trial with the volume risk (Vol_Rel_WF) obtained for that treatment for both eucalypt and pine trials. This allows for the categorization of the cost-effectiveness of vegetation management treatment (lower more desirable) with that of tree volume responses obtained (higher more desirable).

5.3. Results and Discussion

A detailed description to tree growth response for volume obtained relating to vegetation management treatments, for both eucalypt and pine pulpwood chosen trials, can be obtained in **Chapter 3** (Linking eucalypt rotation end data to vegetation management treatments and herbicide use: results from seven pulpwood trials, South Africa) and **Chapter 4** (Linking pine performance to vegetation management treatments and herbicide use: results from 12 pulpwood trials, South Africa).

5.3.1. Vegetation management treatment costs for both eucalypt and pine trials

Differences in terms of the costs incurred occurred due to the different number of vegetation management operations (**Tables 5.2 and 5.3**) and quantity of herbicide used (formulated product) (**Table 3.6, pages 57-58; Table 4.7, pages 113-115**). For all trials, the *Weedfree* treatment was the most intensively weeded and thus expensive treatment with an average cost of R3 600 ha^{-1} over the trial period (range = R1 802 – R5 449), however, these treatments also resulted into the highest merchantable volume due to the lack of interspecific competition.

Due to higher vegetation growth, the cost of vegetation management for the *Weedfree* treatments within the ST and WT climate zones was higher compared to the cost of those within the CT climate zones ($\bar{x}$ = R4 305 ha^{-1} compared to $\bar{x}$ = R2 308 ha^{-1}) (**Tables 5.2 and 5.3**). The eucalypt *Weedfree* treatments also cost more to maintain compared to the pine *Weedfree* treatments in the ST/WT climate zones ($\bar{x}$ = R4 939 compared to $\bar{x}$ = R3 670) due to more intensive weeding required over a shorter period. In contrast, the cost to maintain the *Weedfree* treatment was similar for both eucalypt and pine trials ($\bar{x}$ = R2 319 ha^{-1} compared to $\bar{x}$ = R2 296 ha^{-1}) for those trials within the CT climate zone.

The *Weedfree* treatments ($\bar{x}$ = R4 460 ha^{-1}) cost more to implement than the various *Row weeding* and *Ring weeding* treatments ($\bar{x}$ = R3 533 ha^{-1} and $\bar{x}$ = R3 322 ha^{-1} respectively). Weeding costs increased with increased row weeding distances (0.9 m $\bar{x}$ = R3 030 ha^{-1}; 2 m $\bar{x}$ = R3 951 ha^{-1}). For the pine vegetation management trial at Hlabeni, the marginal increase in the cost between the 1 m and 2 m *Ring weeding* treatments was attributed to the limited development (time and abundance) of mostly annual herbaceous broadleaves at the site. The costs associated with the *Moderate intensity weeding* treatments in different trials was site dependent. For example, the *Moderate intensity weeding* treatments cost ca. R1 300 less than the *Weedfree* treatments at Kwambonambi and Mountain Home, yet were similar in cost at Enon, Bergvliet_A and Mossbank. This is directly related to the number of weeding operations scheduled within the *Moderate intensity weeding* treatments compared to the *Weedfree* treatments (3 less at Kwambonambi; 2 less at Mountain Home; and 1 less at Enon, Bergvliet_A and Mossbank).

Table 5.2. Treatment costs for seven eucalypt vegetation management trials implemented in the summer rainfall region of South Africa.

Trial name	Vegetation management treatments	Number of manual operations (n)	Number of herbicide operations (n)	Total number of operations (n)	Labour cost (R ha^{-1})	Herbicide cost (R ha^{-1})	Total vegetation management cost (R ha^{-1})	[1]Merchantable volume converted to tonnes (tonnes ha^{-1})	[2]Income (R ha^{-1})	Net present value (NPV) (R ha^{-1})	NPV Profit (Profit_Rel_ Weedy) (%)
1. Fairbreeze	Weedfree (manual)	7	3	10	R4 525	R408	R4 934	168.3	R232 149	R149 567	60
	Weedfree (chemical)	2	8	10	R3 179	R1 061	R4 240	143.9	R198 452	R127 785	36
	-Ring weeding (0.5 m)	-	7	7	R2 207	R1 112	R3 318	156.0	R215 145	R139 810	49
	Row weeding (1.2 m)	2	7	9	R2 506	R691	R3 197	139.5	R192 438	R124 811	33
	Ring weeding (0.5 m)	-	7	7	R2 207	R1 112	R3 318	147.4	R203 325	R131 949	41
	Cowpea	2	3	4	R2 057	R571	R2 628	118.9	R163 925	R106 404	13
	Velvet bean	2	3	4	R2 057	R571	R2 628	120.8	R166 517	R108 128	15
	Inter-row weeding (1.2 m)	2	6	8	R2 506	R691	R3 197	127.4	R175 641	R113 640	21
	Weedy	-	1	1	R224	R314	R538	103.6	R142 877	R94 483	0
2. Oaklands	Burnt x Weedfree	2	8	10	R3 665	R1 061	R4 727	216.5	R298 507	R193 838	42
	Unburnt x Weedfree	2	8	10	R3 665	R1 061	R4 727	200.7	R276 733	R179 357	32
	Unburnt x Row weeding (2 m)	2	7	9	R2 992	R738	R3 730	199.7	R275 385	R179 455	32
	Unburnt x HBL remaining	2	7	9	R3 179	R3 319	R6 498	172.7	R238 163	R168 146	12
	Unburnt x Grass remaining	2	7	9	R3 179	R891	R4 070	163.5	R225 513	R151 980	7
	Burnt x Weedy	-	1	1	R224	R314	R538	156.5	R215 767	R145 952	4
	Unburnt x Weedy	-	1	1	R224	R314	R538	150.0	R206 850	R142 959	0
3. KT	<u>1 852 sph (2.7 x 2 m)</u>										
	Weedfree	2	8	10	R4 413	R1 036	R5 449	245.1	R338 052	R206 689	16
	Row weeding (1.8 m)	2	7	9	R3 291	R700	R3 991	230,4	R317 761	R195 405	9
	Row weeding (0.9 m)	2	7	9	R2 955	R543	R3 498	217.9	R300 524	R185 076	4
	Weedy	-	1	1	R224	R314	R538	208.3	R287 226	R179 671	0
	<u>1 481 sph (2.7 x 2.5 m)</u>										
	Weedfree	2	8	10	R3 815	R1 061	R4 876	277.0	R381 983	R234 825	27
	Row weeding (1.8 m)	2	7	9	R2 842	R705	R3 547	248.9	R343 174	R211 794	15
	Row weeding (0.9 m)	2	7	9	R2 506	R524	R3 030	224.9	R310 177	R191 600	4
	Weedy	-	1	1	R224	R314	R538	215.4	R297 076	R185 851	0

[1]For each trial, rotation-end volume (ha^{-1}) was converted to tonnes ha^{-1} using eucalypt-specific conversion factors (*E. grandis* x *E. camaldulensis* = 0.75; *E. grandis* x *E. urophylla* = 0.70; *E. smithii* = 0.81; and *E. dunnii* = 0.88).
[2]Cost of pulpwood timber delivered to the mill based on tonnes at 2019 (R 1 379 tonne^{-1} for *Eucalyptus* spp.).

Continues from Table 5.2.

Trial name	Vegetation management treatments	Number of manual operations (n)	Number of herbicide operations (n)	Total number of operations (n)	Labour cost (R ha^{-1})	Herbicide cost (R ha^{-1})	Total vegetation management cost (R ha^{-1})	[1]Merchantable volume converted to tonne (tonne ha^{-1})	[2]Income (R ha^{-1})	Net present value (NPV) (R ha^{-1})	NPV Profit (Profit_Rel_ Weedy) (%)
4. Mountain Home	Weedfree	3	7	10	R4 114	R1 141	R5 255	226.3	R312 089	R179 551	117
	Sweet potato (1.2 m)	2	7	9	R2 842	R611	R3 453	237.3	R327 210	R190 246	129
	Grass remaining	2	6	8	R3 142	R632	R3 773	220.4	R303 985	R176 170	112
	Sweet potato	2	6	8	R3 142	R775	R3 916	213.4	R294 308	R170 297	105
	Row weeding (2 m)	2	7	9	R3 142	R812	R3 954	210.1	R289 711	R167 559	102
	Row weeding (1.2 m)	2	7	9	R2 842	R611	R3 453	202.5	R279 308	R161 893	95
	HBL remaining	2	6	8	R3 142	R2 366	R5 508	133.6	R184 230	R103 572	26
	Weedy	-	1	1	R224	R314	R538	103.1	R142 134	R83 590	0
5. Enon	Weedfree	2	7	9	R3 516	R879	R4 395	336.6	R464 151	R270 376	29
	Moderate intensity	2	6	8	R3 142	R879	R4 021	303.7	R418 745	R243 847	16
	Low intensity	2 slash	5	7	R2 581	R714	R3 295	301.5	R415 718	R242 875	16
	Row weeding (2 m)	2	7	9	R3 142	R677	R3 819	320.2	R441 504	R257 538	23
	Weedy	-	1	1	R224	R314	R538	258.9	R357 083	R210 818	0
6. Tweefontein	Improved x Fertilization x Weedfree	1	5	6	R2 281	R555	R2 836	177.3	R244 543	R150 619	57
	Improved x NoFertilization x Weedfree	1	5	6	R2 281	R555	R2 836	177.1	R244 198	R150 403	57
	Unimproved x Fertilization x Weedfree	1	5	6	R2 281	R555	R2 836	139.6	R192 485	R117 958	23
	Unimproved x NoFertilization x Weedfree	1	5	6	R2 281	R555	R2 836	136.8	R188 578	R115 507	21
	Improved x Fertilization x Weedy	-	1	1	R224	R314	R538	166.8	R229 948	R143 734	49
	Improved x NoFertilization x Weedy	-	1	1	R224	R314	R538	137.4	R189 498	R118 355	23
	Unimproved x Fertilization x Weedy	-	1	1	R224	R314	R538	130.5	R179 960	R112 370	17
	Unimproved x NoFertilization x Weedy	-	1	1	R224	R314	R538	111.8	R154 103	R96 148	0
7. Draycott	Improved x Fertilization x Weedfree	1	4	5	R1 346	R455	R1 802	179.6	R247 686	R153 626	48
	Improved x NoFertilization x Weedfree	1	4	5	R1 346	R455	R1 802	145.3	R200 375	R123 942	20
	Unimproved x Fertilization x Weedfree	1	4	5	R1 346	R455	R1 802	133.2	R183 721	R113 494	10
	Unimproved x NoFertilization x Weedfree	1	4	5	R1 346	R455	R1 802	130.7	R180 187	R111 276	8
	Improved x Fertilization x Weedy	-	1	1	R224	R314	R538	183.3	R252 763	R158 048	52
	Improved x NoFertilization x Weedy	-	1	1	R224	R314	R538	178.6	R246 324	R154 008	48
	Unimproved x Fertilization x Weedy	-	1	1	R224	R314	R538	153.1	R211 070	R131 889	27
	Unimproved x NoFertilization x Weedy	-	1	1	R224	R314	R538	120.5	R166 221	R103 750	0

[1]For each trial, rotation-end volume (ha^{-1}) was converted to tonnes ha^{-1} using eucalypt-specific conversion factors (*E. grandis* x *E. camaldulensis* = 0.75; *E. grandis* x *E. urophylla* = 0.70; *E. smithii* = 0.81; and *E. dunnii* = 0.88).
[2]Cost of pulpwood timber delivered to the mill based on tonnes at 2019 (R 1 379 tonne^{-1} for *Eucalyptus* spp.).

Table 5.3. Treatment costs for 12 pine vegetation management trials implemented in the summer rainfall region of South Africa.

Trial name	Vegetation management treatments	Number of manual operations (n)	Number of herbicide operations (n)	Total number of operations (n)	Labour cost (R ha^{-1})	Herbicide cost (R ha^{-1})	Total vegetation management cost (R ha^{-1})	[1]Merchantable volume converted to tonnes (tonnes ha^{-1})	[2]Income (R ha^{-1})	Net present value (NPV) (R ha^{-1})	NPV Profit (Profit_Rel_Weedy) (%)
	Weedfree	2	7	9	R3 104	R1 178	R4 282	266.1	R366 952	R200 840	128
	Moderate intensity	1	5	6	R2 057	R1 036	R3 093	220.6	R304 207	R166 870	90
1. Kwambonambi	Ring weeding (2 m) (Ferns remaining)	4	3	7	R2 786	R644	R3 430	219.8	R303 104	R165 915	89
	Grass remaining	1	7	8	R2 618	R1 011	R3 629	139.1	R191 819	R103 671	18
	HBL remaining	1	7	8	R2 618	R3 918	R6 536	196.8	R271 387	R145 342	65
	PBL remaining	1	7	8	R2 618	R2 541	R5 159	136.6	R188 371	R100 296	14
	Weedy	-	1	1	R224	R314	R538	115.0	R158 585	R88 015	0
	Weedfree	2	7	9	R3 029	R1 178	R4 207	113.7	R156 792	R88 814	70
	Ring weeding (1.5 m)	4	4	8	R2 917	R730	R3 647	104.5	R144 106	R81 794	56
2. Bergvliet_A	Moderate intensity	2 (1 slash)	6	8	R2 861	R1 107	R3 968	121.2	R167 135	R95 182	82
	HBL remaining	2 (1 slash)	4	6	R2 169	R1 966	R4 135	112.6	R155 275	R88 022	68
	PBL remaining	2 (1 slash)	4	6	R2 169	R1 427	R3 597	90.8	R125 213	R70 742	35
	Weedy	-	1	1	R224	R314	R538	64.8	R89 359	R52 353	0
	Clear x Weedfree	2	7	9	R3 029	R848	R3 877	84.2	R116 112	R65 026	208
	Clear x Weedy	-	1	1	R224	R314	R538	31.6	R43 576	R25 254	20
3. Bergvliet_B	Single x Weedfree	2	7	9	R3 029	R848	R3 877	92.2	R127 144	R71 556	239
	Single x Weedy	-	1	1	R224	R314	R538	26.5	R36 544	R21 092	0
	Double x Weedfree	2	7	9	R3 029	R848	R3 877	95.5	R131 695	R74 250	252
	Double x Weedy	-	1	1	R224	R314	R538	38.0	R52 402	R30 478	45
	Weedfree	2	6	8	R2 581	R785	R3 366	324.8	R447 899	R246 842	10
4. Hlabeni	Ring weeding (2 m)	3	5	8	R2 581	R604	R3 185	329.8	R454 794	R250 898	12
	Ring weeding (1 m)	3	5	8	R2 581	R595	R3 176	310.9	R428 731	R236 354	5
	Weedy	-	1	1	R224	R314	R538	292.7	R403 633	R224 848	0
	Weedfree	3	5	8	R3 067	R1 021	R4 087	200.9	R277 041	R150 733	55
	Ring weeding (2 m)	4	3	7	R2 730	R455	R3 186	235.6	R324 892	R178 383	83
5. Mountain Home	Moderate intensity	1	5	6	R1 646	R1 021	R2 666	188.3	R259 666	R142 425	46
	HBL and Grasses Remaining	1	5	6	R2 094	R1 178	R3 273	210.7	R290 555	R159 084	63
	PBL remaining	1	5	6	R2 094	R2 105	R4 200	131.5	R181 339	R97 194	0
	Weedy	-	1	1	R224	R314	R538	127.2	R175 409	R97 409	0

[1]For each trial, volume at 9.4 years (ha^{-1}) was converted to tonnes ha^{-1} using pine-specific conversion factors (*all pine species = 1*).
[2]Cost of pulpwood timber delivered to the mill based on tonnes at 2019 (R1 379 $tonne^{-1}$ *Pinus* spp.).
HBL: Herbaceous broadleaves; PBL: Perennial broadleaves.

Continues from Table 5.3.

Trial name	Vegetation management treatments	Number of manual operations (n)	Number of herbicide operations (n)	Total number of operations (n)	Labour cost (R ha^{-1})	Herbicide cost (R ha^{-1})	Total vegetation management cost (R ha^{-1})	[1]Merchantable volume converted to tonne (tonne ha^{-1})	[2]Income (R ha^{-1})	Net present value (NPV) (R ha^{-1})	NPV Profit (Profit_Rel _Weedy) (%)
6. Longridge	Weedfree	2	6	8	R2 581	R785	R3 366	129.6	R178 718	R96 533	12
	Grass remaining	2	5	7	R2 356	R704	R3 061	125.4	R172 927	R93 576	9
	HBL remaining	2	5	7	R2 356	R1 915	R4 271	135.5	R186 855	R100 178	16
	PBL remaining	2	5	7	R2 356	R1 476	R3 832	125.4	R172 927	R92 829	8
	Weedy	-	1	1	R224	R314	R538	112.6	R155 275	R86 167	0
7. Spitzkop	*P. elliottii* x Weedfree	1	6	7	R1 646	R864	R2 509	119.0	R164 101	R89 227	32
	P. elliottii x Low intensity	2 slash	1	3	R972	R314	R1 286	89.0	R122 731	R67 384	0
	P. patula x Weedfree	1	6	7	R1 646	R864	R2 509	123.4	R170 169	R92 615	28
	P. patula x Low intensity	2 slash	1	3	R972	R314	R1 286	95.1	R131 143	R72 081	0
	P. taeda x Weedfree	1	6	7	R1 646	R864	R2 509	66.4	R91 566	R48 724	-4
	P. taeda x Low intensity	2 slash	1	3	R972	R314	R1 286	67.2	R92 669	R50 597	0
8. Langgewacht	Weedfree (1 372 sph)	1	5	6	R1 496	R738	R2 234	89.8	R123 834	R66 988	17
	Low intensity (1 372 sph)	1 slash	3	4	R1 159	R526	R1 685	90.6	R124 937	R68 169	19
	Weedy (1 372 sph)	-	1	1	R224	R314	R538	75.1	R103 563	R57 291	0
	Weedfree (1 111 sph)	1	5	6	R1 459	R738	R2 197	100.7	R138 865	R75 419	20
	Low intensity (1 111 sph)	1 slash	3	4	R1 159	R526	R1 685	87.0	R119 973	R65 397	4
	Weedy (1 111 sph)	-	1	1	R224	R314	R538	82.2	R113 354	R62 758	0
	Weedfree (816 sph)	1	5	6	R1 421	R738	R2 159	85.9	R118 456	R64 060	7
	Low intensity (816 sph)	1 slash	3	4	R1 159	R526	R1 685	80.8	R111 423	R60 623	2
	Weedy (816 sph)	-	1	1	R224	R314	R538	78.1	R107 700	R59 601	0
9. Mt Gilboa	Weedfree	2	4	6	R1 795	R518	R2 313	143.3	R197 631	R108 131	-13
	Biomac	-	4	4	R898	R518	R1 416	155.2	R214 059	R118 177	-5
	Kraft	-	4	4	R898	R518	R1 416	153.8	R212 118	R117 093	-6
	Plantex	-	4	4	R898	R518	R1 416	158.1	R217 987	R120 371	-3
	Sludge	-	4	4	R898	R518	R1 416	161.4	R222 574	R122 932	-1
	Weedy	-	1	1	R224	R314	R538	162.3	R223 863	R124 465	0

[1]For each trial and treatment within, volume at 9.4 years (ha^{-1}) was converted to tonnes ha^{-1} using pine-specific conversion factors (*all pine species = 1*).
[2]Cost of pulpwood timber delivered to the mill based on tonnes at 2019 (R1 379 tonne^{-1} *Pinus* spp.).
HBL: Herbaceous broadleaves; PBL: Perennial broadleaves.

Continues from Table 5.3.

Trial name	Vegetation management treatments	Number of manual operations (n)	Number of herbicide operations (n)	Total number of operations (n)	Labour cost (R ha^{-1})	Herbicide cost (R ha^{-1})	Total vegetation management cost (R ha^{-1})	[1]Merchantable volume converted to tonne (tonne ha^{-1})	[2]Income (R ha^{-1})	Net present value (NPV) (R ha^{-1})	NPV Profit (Profit_Rel_Weedy) (%)
10. Blyde	Unburnt										
	ChopPit x Weedfree	1	5	6	R1 384	R754	R2 137	166.2	R229 190	R133 593	26
	ChopPit x Weedy	-	1	1	R224	R314	R538	160.9	R221 881	R130 793	23
	ChopRip x Weedfree	1	5	6	R1 384	R754	R2 137	162.6	R224 225	R130 655	23
	ChopRip x Weedy	-	1	1	R224	R314	R538	160.9	R221 881	R130 793	23
	Pit x Weedfree	1	5	6	R1 384	R754	R2 137	200.1	R275 938	R161 263	52
	Pit x Weedy	-	1	1	R224	R314	R538	130.7	R180 235	R106 143	0
	Rip x Weedfree	1	5	6	R1 384	R644	R2 028	198.8	R274 145	R160 312	51
	Rip x Weedy	-	1	1	R224	R314	R538	174.6	R240 773	R141 975	34
	Burnt										
	ChopPit x Weedfree	1	5	6	R1 421	R989	R2 410	160.1	R220 778	R128 341	21
	ChopPit x Weedy	-	1	1	R224	R314	R538	126.4	R174 306	R102 633	-3
	ChopRip x Weedfree	1	5	6	R1 421	R989	R2 410	164.3	R226 570	R131 769	24
	ChopRip x Weedy	-	1	1	R224	R314	R538	164.8	R227 259	R133 976	26
	Pit x Weedfree	1	5	6	R1 421	R989	R2 410	222.0	R306 138	R178 866	69
	Pit x Weedy	-	1	1	R224	R314	R538	114.3	R157 620	R92 756	-13
	Rip x Weedfree	1	5	6	R1 421	R754	R2 175	193.4	R266 699	R155 757	47
	Rip x Weedy	-	1	1	R224	R314	R538	176.1	R242 842	R143 199	35
11. Mossbank	Weedfree	2	4	6	R1 795	R518	R2 313	200.8	R276 903	R152 397	2
	Weedfree x Fertilization	2	4	6	R1 795	R518	R2 313	208.5	R287 522	R158 326	6
	Moderate intensity	2	4	6	R1 795	R518	R2 313	208.1	R286 970	R158 018	6
	Grass remaining	2	4	6	R1 795	R530	R2 325	194.6	R268 353	R147 613	-1
	HBL remaining	2	4	6	R1 795	R1 047	R2 843	192.7	R265 733	R145 667	-3
	Weedy	-	1	1	R224	R314	R538	195.2	R269 181	R149 771	0
	Weedy x Fertilization	-	1	1	R224	R314	R538	184.5	R254 426	R141 531	-6
12. Ceylon	*P. elliottii* x Weedfree	2	4	6	R1 720	R526	R2 246	65.4	R90 187	R48 177	29
	P. elliottii x Weedy	-	1	1	R224	R314	R538	49.1	R67 709	R37 270	0
	P. patula x Weedfree	2	4	6	R1 720	R526	R2 246	98.0	R135 142	R73 280	12
	P. patula x Weedy	-	1	1	R224	R314	R538	85.5	R117 905	R65 299	0
	P. taeda x Weedfree	2	4	6	R1 720	R526	R2 246	58.6	R80 809	R42 940	24
	P. taeda x Weedy	-	1	1	R224	R314	R538	45.8	R63 158	R34 729	0

[1]For each trial, volume at 9.4 years (ha^{-1}) was converted to tonnes ha^{-1} using pine-specific conversion factors (*all pine species = 1*).
[2]Cost of pulpwood timber delivered to the mill based on tonnes at 2019 (R1 379 tonne^{-1} *Pinus* spp.).
HBL: Herbaceous broadleaves; PBL: Perennial broadleaves.

The *Broadleaves remaining*, *HBL remaining* and *PBL remaining* treatments cost more to maintain than the *Weedfree* treatments ($\bar{x}$ = R5 104 ha^{-1} and $\bar{x}$ = R4 313 ha^{-1} respectively), even though less herbicides were used. This was due to the higher cost of the selective herbicide that was used for the control of the various grass species costing more than glyphosate (R417 kg^{-1} for fluazifop-p-butyl 150 g a.i. kg^{-1}, compared to R78 kg^{-1} for isopropylamine salt of glyphosate 360 g a.i. kg^{-1}). Of the *Selective control* treatments, the *Grasses remaining* treatment cost the least ($\bar{x}$ = R3 463 ha^{-1}). In terms of the *Cover crop* treatments (cowpea, velvet bean and sweet potato) ($\bar{x}$ = R3 058 ha^{-1}), the total vegetation management cost was ca. R1 752 (or 36%) less than the respective *Weedfree* treatments ($\bar{x}$ = R4 810 ha^{-1}) due to reduced weeding operations required once the cover crops became established. The mulching treatments at Mt Gilboa also cost ca. R879 (or 39%) less than the *Weedfree* treatment ($\bar{x}$ = R1 416 ha^{-1} and $\bar{x}$ = R2 313 ha^{-1} respectively) due to the mulch negating the need for initial ring weeding operations. Factors such as slash management, fertilization, improved genetic material and different species that were also tested in selected trials, did not have a direct influence on vegetation management cost (or more specifically on the number of vegetation management operations and/or quantity of herbicides applied), with there being no difference between these treatments and the *Weedfree* treatments within the same trials. Although there is an additional cost associated with the implementation/use of these treatments (for example the application of a fertilizer, or the planting at a higher density), if a detailed cost-benefit analysis were carried out where these treatments were used, the financial outcomes may have been different, but in terms of the total weeding cost, these costs remained the same. Although site preparation (pitting and chopper rolling compared to ripping) did have an influence on vegetation abundance and growth at Blyde, this resulted in a 5% increase in weeding costs compared to prescribed burning, which increased the cost of weeding operations by ca. 10%.

5.3.2. Vegetation management cost as a function of final yield

For the chosen vegetation management option to be economically viable, it must in general be: (i) cheaper to implement than an opposing approach with non-significant volume differences between the two or; (ii) if more expensive to implement, then the additional cost must be offset by a significant gain in profit. To determine this the additional NPV profit generated relative to the *Weedy* treatments was calculated (**Tables 5.2 and 5.3**).

With the exception of a few treatments in four pine trials (Spitzkop, Mt Gilboa, Blyde and Mossbank), the vegetation management treatments resulted in increased profits relative to the *Weedy* treatments. Relative to the *Weedy* treatments, the profit range was larger for the treatments in trials situated within the ST and WT climate zone (-3 to 255%) compared to those in the CT climate zones (-13 to 69%). The *Weedfree* treatments produced the highest profit relative to the *Weedy* treatments in four of the seven eucalypt trials, and in three of the 12 pine trials (**Tables 5.2 and 5.3**). Across all trials, the highest profit was achieved for those treatments where:

(i) similar volume was obtained to the *Weedfree* treatment, but with less labour or herbicides ha^{-1} used (for example the *Moderate weeding* at Bergvliet_A; *Ring weeding (2 m)* at Hlabeni; *Sweet potato (1.2 m)* at Mountain Home; *Low intensity weeding* at Langgewacht);

(ii) the competing vegetation did not cause a significant reduction in tree volume per ha^{-1} (for example the *Weedy* treatments with fertilization at Tweefontein and Draycott; *Weedy* treatment at Mt Gilboa and all the vegetation treatments at Mossbank); or

(iii) site conditions were improved through manipulation of the soil and/or organic matter properties (for example the slash and/or site preparation methods used at Blyde).

5.3.3. Financial risk (Profit_Rel_Weedy)

To allow for the categorization of treatment-related risk in terms volume (Vol_Rel_WF) and financial risk (Profit_Rel_Weedy), treatment differences relative to the respective *Weedfree* treatments for volume risk, and treatment differences relative to the respective *Weedy* treatment for financial risk were calculated. Specific criteria were then used to partition the relative differences of the treatments for each trial into three risk classes: Low; Moderate; or High.

For volume risk responses obtained for the eucalypt and pine vegetation management treatments, please refer to **Chapter 3.4.3.2. Volume (Vol_Rel_WF) (page 70)** for the eucalypt trials and **Chapter 4.4.4.2. Volume (Vol_Rel_WF) (page 109)** for the pine trials.

Trends for financial risk were similar to the volume risk categorisation for most of the treatments, with a Low financial risk assigned to those treatments where the vegetation was kept at a sub-competitive level, or where it was kept away from the trees in the form of a ≥2.0 m row, or ≥1.5 m ring weeding (**Tables 5.4 and 5.5**). The *Cover crop* treatment at Mountain Home where sweet potatoes were planted within the interrow was also classified as a Low risk (**Table 5.4**), in addition to the plantex and sludge mulching treatments at Mt Gilboa (**Table 5.5**). Treatments that were considered a High financial risk included all the *Weedy* treatments across the eucalypt trials except for the *Weedy* treatments at Mountain Home, Tweefontein and Draycott (classified as either Low or Moderate risk) (**Table 5.4**). For the pine trials, the *Selective control* treatments (*Grass remaining* and *PBL remaining* treatments at Kwambonambi, *PBL remaining* treatment at Mountain Home, and *Grass remaining* and *HBL remaining* treatments at Mossbank) and most of the *Weedy* treatments (except for those at Mt Gilboa and Blyde with these treatments classified as either Low or Moderate risk) were classified as High risk as well (**Table 5.5**). Where *Cover crops* were used (cowpea and velvet bean treatments at Fairbreeze), together with the *Weedfree* treatments at Mt Gilboa, Draycott (unimproved genetic), and Spitzkop (*P. taeda*) were also categorised as a High risk. The remaining treatments across the eucalypt and pine trials were considered Moderate risk (80-89%) (**Tables 5.4 and 5.5**).

Table 5.4. Categorization of tree growth and financial risk for vegetation management treatments within seven eucalypt trials, South Africa.

Trial name	Vegetation management treatments	Volume risk (volume)	Financial risk (NPV profit)
1. Fairbreeze	Weedfree (manual)	L	L
	Weedfree (chemical)	M	M
	-Ring weeding (0.5 m)	L	L
	Row weeding (1.2 m)	M	M
	Ring weeding (0.5 m)	M	L
	Cowpea	H	H
	Velvet bean	H	H
	Inter-row weeding (1.2 m)	H	M
	Weedy	H	H
2. Oaklands	Unburnt x Weedfree	L	L
	Burnt x Weedfree	L	L
	Unburnt x Row weeding (2 m)	L	L
	Unburnt x HBL remaining	H	H
	Unburnt x Grass remaining	H	H
	Unburnt x Weedy	H	H
	Burnt x Weedy	H	H
3. KT	1 852 sph (2.7 x 2.0 m)		
	Weedfree	L	L
	Row weeding (1.8 m)	L	M
	Row weeding (0.9 m)	M	H
	Weedy	M	H
	1 481 sph (2.7 x 2.5 m)		
	Weedfree	L	L
	Row weeding (1.8 m)	L	M
	Row weeding (0.9 m)	H	H
	Weedy	H	H
4. Mountain Home	Weedfree	L	L
	Sweet potato (1.2 m)	L	L
	Grass remaining	L	L
	Sweet potato	L	L
	Row weeding (2 m)	L	L
	Row weeding (1.2 m)	M	H
	HBL remaining	H	H
	Weedy	H	L

Trial name	Vegetation management treatments	Volume risk (volume)	Financial risk (NPV profit)
5. Enon	Weedfree	L	L
	Moderate intensity	L	M
	Low intensity	M	M
	Row weeding (2 m)	L	L
	Weedy	H	H
6. Tweefontein	Improved x Fertilization x Weedfree	L	L
	Improved x NoFertilization x Weedfree	L	L
	Unimproved x Fertilization x Weedfree	L	M
	Unimproved x NoFertilization x Weedfree	H	M
	Improved x Fertilization x Weedy	H	L
	Improved x NoFertilization x Weedy	H	M
	Unimproved x Fertilization x Weedy	H	H
	Unimproved x NoFertilization x Weedy	H	H
7. Draycott	Improved x Fertilization x Weedfree	L	L
	Improved x NoFertilization x Weedfree	M	M
	Unimproved x Fertilization x Weedfree	L	H
	Unimproved x NoFertilization x Weedfree	L	H
	Improved x Fertilization x Weedy	H	L
	Improved x NoFertilization x Weedy	H	L
	Unimproved x Fertilization x Weedy	M	M
	Unimproved x NoFertilization x Weedy	H	H

L: Low risk; M: Moderate risk; H: High risk

Table 5.5. Categorization of tree growth and financial risk for vegetation management treatments within 12 pine trials, South Africa.

Trial name	Vegetation management treatments	Volume risk (volume)	Financial risk (NPV profit)
1. Kwambonambi	Weedfree	L	L
	Moderate intensity	L	L
	Ring weeding (2 m) (Ferns remaining)	L	L
	Grass remaining	H	H
	HBL remaining	L	M
	PBL remaining	H	H
	Weedy	H	H
2. Bergvliet_A	Weedfree	L	L
	Ring weeding (1.5 m)	L	L
	Moderate intensity	L	L
	HBL remaining	H	L
	PBL remaining	H	M
	Weedy	H	H
3. Bergvliet_B	Clear x Weedfree	L	L
	Clear x Weedy	L	H
	Single x Weedfree	L	L
	Single x Weedy	H	H
	Double x Weedfree	L	L
	Double x Weedy	H	H
4. Hlabeni	Weedfree x NoFert	L	L
	Weedfree x Agri	L	L
	Weedfree x Max	L	L
	Weedfree x NPK	L	L
	Ring (2 m) x NoFert	L	L
	Ring (2 m) x Agri	L	L
	Ring (2 m) Max	L	L
	Ring (2 m) x NPK	L	L
	Ring (1 m) x NoFert	L	M
	Ring (1 m) x Agri	L	M
	Ring (1 m) Max	L	M
	Ring (1 m) x NPK	L	M
	Weedy x NoFert	L	H
	Weedy x Agri	L	H
	Weedy x Max	L	H
	Weedy x NPK	L	H
5. Mountain Home	Weedfree	L	L
	Ring weeding (2 m)	L	L
	Moderate intensity	L	M
	HBL and Grass Remaining	L	L
	PBL remaining	L	H
	Weedy	L	H
6. Longridge	Weedfree	L	L
	Grass remaining	L	M
	HBL remaining	L	L
	PBL remaining	L	M
	Weedy	L	H
7. Spitzkop	*P. elliottii* x Weedfree	L	L
	P. elliottii x Low intensity	L	H
	P. patula x Weedfree	L	L
	P. patula x Low intensity	L	H
	P. taeda x Weedfree	L	H
	P. taeda x Low intensity	L	H
8. Langgewacht	Weedfree (1 372 sph)	L	L
	Low intensity (1 372 sph)	L	L
	Weedy (1 372 sph)	L	H
	Weedfree (1 111 sph)	L	L
	Low intensity (1 111 sph)	L	H
	Weedy (1 111 sph)	L	H
	Weedfree (816 sph)	L	M
	Low intensity (816 sph)	L	H
	Weedy (816 sph)	L	H
9. Mt Gilboa	Weedfree	L	H
	Biomac	L	M
	Kraft	L	M
	Plantex	L	L
	Sludge	L	L
	Weedy	L	L

L: Low risk; M: Moderate risk; H: High risk

Continues from Table 5.5.

Trial name	Vegetation management treatments	Volume risk (volume)	Financial risk (NPV profit)
10. Blyde	Unburnt		
	ChopPit x Weedfree	L	M
	ChopPit x Weedy	L	M
	ChopRip x Weedfree	L	M
	ChopRip x Weedy	M	M
	Pit x Weedfree	L	L
	Pit x Weedy	L	H
	Rip x Weedfree	L	L
	Rip x Weedy	L	M
	Burnt		
	ChopPit x Weedfree	L	M
	ChopPit x Weedy	L	H
	ChopRip x Weedfree	L	M
	ChopRip x Weedy	M	M
	Pit x Weedfree	L	L
	Pit x Weedy	L	H
	Rip x Weedfree	L	L
	Rip x Weedy	L	M
11. Mossbank	Weedfree	L	M
	Weedfree x Fertilization	L	L
	Moderate intensity	L	L
	Grass remaining	L	M
	HBL remaining	L	H
	Weedy	L	M
	Weedy x Fertilization	L	H
12. Ceylon	*P. elliottii* x Weedfree	L	L
	P. elliottii x Weedy	H	H
	P. patula x Weedfree	L	M
	P. patula x Weedy	M	H
	P. taeda x Weedfree	L	L
	P. taeda x Weedy	H	H

L: Low risk; M: Moderate risk; H: High risk

5.3.4. Linking financial risk to volume risk

The ideal vegetation management scenario would be where the best growth is obtained with the least amount of input or cost to ensure the highest possible financial return is attained. Taking the above into consideration, the treatments within each trial were partitioned into two broad scenarios based on the volume and financial risk (**Tables 5.4 and 5.5**).

5.3.4.1. Maximising timber production and financial return

Although most of the *Weedfree* treatments were more costly to implement (**Tables 5.2 and 5.3**), the increased volume obtained meant that this treatment was also the most desirable (Low volume and financial risk: **Tables 5.6 and 5.7**). As for the *Weedfree* treatments, the *Row (2 m)* and *Ring weeding (1.5 m and 2 m)* treatments, *Moderate intensity* weeding treatments within the pine trials and the sweet potato *Cover crop* treatment could also be considered a viable option. Although the *Grass remaining* treatment at Mountain Home (at both eucalypt and pine trials) was classified as Low risk for both financial and volume classifications, this treatment cannot be recommended as this same treatment at Oaklands was classified as High risk (**Tables 5.4 and 5.6**). The improved genetic material planted at both Draycott and Tweefontein when kept weed free performed better than the unimproved genetic material and were also considered Low risk.

Table 5.6. Two-way table linking rotation-end volume to financial risk for various vegetation management treatments within seven eucalypt trials in the summer rainfall region of South Africa. Darker shading indicates more desirable treatment options in terms of optimum tree performance together with reduced financial risk.

Trials	[1]Financial risk (NPV profit)	Volume risk (volume) Low	Moderate	High
1. Fairbreeze	Low	Weedfree (manual) -Ring weeding (0.5 m)	-	Weedy
	Moderate	Ring weeding (0.5 m)	Weedfree (chemical) Row weeding (1.2 m)	Inter-row weeding (1.2 m)
	High	-	-	Cowpea Velvet bean
2. Oaklands	Low	Weedfree (burnt + unburnt) Unburnt x Row weeding (2 m)	-	-
	Moderate	-	-	-
	High	-	-	Unburnt x Broadleaves remaining Unburnt x Grasses remaining Weedy (burnt + unburnt)
3. KT	Low	Weedfree (1 852 + 1 481 sph)	-	-
	Moderate	Row weeding (1.8 m) (1 852 + 1 481 sph)	-	-
	High	-	Row weeding (0.9 m) (1 852 sph) Weedy (1 852 sph)	Row weeding (0.9 m) (1 481 sph) Weedy (1 481 sph)
4. Mountain Home	Low	Weedfree Sweet potato Sweet potato (1.2 m) Grasses remaining Row weeding (2 m)	Row weeding (1.2 m)	-
	Moderate	-	-	-
	High	-	-	Broadleaves remaining Weedy
5. Enon	Low	Weedfree Row weeding (2 m)	-	-
	Moderate	Moderate intensity	Low intensity	-
	High	-	-	Weedy
6. Tweefontein	Low	Improved Weedfree (Fertilization + NoFertilization)	-	Improved x Fertilization x Weedy
	Moderate	Unimproved x Fertilization x Weedfree	-	Unimproved x NoFertilization x Weedfree Improved x NoFertilization x Weedy
	High	-	-	Unimproved Weedy
7. Draycott	Low	Improved x Fertilization x Weedfree	-	Improved x Weedy (Fertilization + NoFertilization)
	Moderate	-	Improved x NoFertilization x Weedfree Unimproved x Fertilization x Weedy	-
	High	Unimproved x Weedfree (Fertilization + NoFertilization)	-	Unimproved x NoFertilization x Weedy

[1]Based on individual trials NPV Profit (Profit_Rel_Weedy) (%). See Table 5.1 page 135.

Table 5.7. Two-way table linking volume (at 9.4 years) to financial risk for various vegetation management treatments within 12 pine trials in in the summer rainfall region of South Africa. Darker shading indicates more desirable treatment options in terms of optimum tree performance together with reduced financial risk.

Trials	[1]Financial risk (NPV profit)	Volume risk (volume) Low	Moderate	High
1. Kwambonambi	Low	Weedfree Moderate intensity Ring weeding (2 m) (Ferns remaining)	-	-
	Moderate	-	-	-
	High	HBL remaining	-	Grass remaining PBL remaining Weedy
2. Bergvliet_A	Low	Weedfree Ring weeding (1.5 m) Moderate intensity	-	HBL remaining
	Moderate	-	-	PBL remaining
	High	-	-	Weedy
3. Bergvliet_B	Low	Clear x Weedfree Single x Weedfree Double x Weedfree	-	-
	Moderate	-	-	-
	High	Clear x Weedy	-	Single x Weedy Double x Weedy
4. Hlabeni	Low	Weedfree (Fertilization + NoFertilization) Ring weeding (2 m) (Fertilization + NoFertilization)	-	-
	Moderate	Ring weeding (1 m) (Fertilization + NoFertilization)	-	-
	High	Weedy (Fertilization + NoFertilization)	-	-
5. Mountain Home	Low	Weedfree Ring weeding (2 m) HBL and Grass Remaining	-	-
	Moderate	Moderate intensity	-	-
	High	PBL remaining Weedy	-	-
6. Longridge	Low	Weedfree (Fertilization + NoFertilization) HBL remaining (Fertilization + NoFertilization)	-	-
	Moderate	Grass remaining (Fertilization + NoFertilization) PBL remaining (Fertilization + NoFertilization)	-	-
	High	Weedy (Fertilization + NoFertilization)	-	-
7. Spitzkop	Low	*P. elliottii* x Weedfree *P. patula* x Weedfree	-	-
	Moderate	-	-	-
	High	*P. elliottii* x Low intensity *P. patula* x Low intensity *P. taeda* x Weedfree *P. taeda* x Low intensity	-	-
8. Langgewacht	Low	Weedfree (1 372 sph) Low intensity (1 372 sph) Weedfree (1 111 sph)	-	-
	Moderate	Weedfree (816 sph)	-	-
	High	Weedy (1 372 + 1 111 + 816 sph) Low intensity (1 111 + 816 sph)	-	-

[1]Based on individual trials NPV Profit (Profit_Rel_Weedy) (%). See Table 5.1 page 135.

Continues from Table 5.7.

Trials	[1]Financial risk (NPV profit)	Volume risk (volume) Low	Moderate	High
9. Mt Gilboa	**Low**	Plantex Sludge Weedy	-	-
	Moderate	Biomac Kraft	-	-
	High	Weedfree	-	-
10. Blyde	**Low**	Pit x Weedfree (Burnt and Unburnt) Rip x Weedfree (Burnt and Unburnt)	-	-
	Moderate	ChopPit x Weedfree (Burnt and Unburnt) ChopPit x Weedy (Unburnt) ChopRip x Weedfree (Burnt and Unburnt) Rip x Weedy (Burnt and Unburnt)	ChopRip x Weedy (Burnt and Unburnt)	-
	High	Pit x Weedy (Burnt and Unburnt) ChopPit x Weedy (Burnt)	-	-
11. Mossbank	**Low**	Weedfree x Fertilization Moderate intensity	-	-
	Moderate	Weedfree Grass remaining Weedy	-	-
	High	HBL remaining Weedy x Fertilization	-	-
12. Ceylon	**Low**	*P. elliottii* x Weedfree *P. taeda* x Weedfree	-	-
	Moderate	*P. patula* x Weedfree	-	
	High	-	*P. patula* x Weedy	*P. elliottii* x Weedy *P. taeda* x Weedy

[1]Based on individual trials NPV Profit (Profit_Rel_Weedy) (%). See Table 5.1 page 135.

The *Selective control* treatments varied, with both *Grass remaining* and *HBL* treatments at Mountain Home (eucalypt and pine sites respectively) and *HBL remaining* treatment at Longridge classified as Low risk (**Tables 5.4 and 5.5**). Whereas the *Grass remaining* and *PBL remaining* treatments at Longridge were classified as Moderate risk, with the remaining *Selective control* treatments in all other trials classified as High risk. At Spitzkop, the matching of species to site had a direct influence on financial risk, with *P. elliotti* and *P. patula* classified as Low risk, and *P. taeda* as High risk. Since there were no significant differences in treatment volume at Mt Gilboa, both the *Weedy* and mulching (plantex and sludge) treatments were classified as Low risk for both volume and financial risk. In contrast the increased ring weeding operations and herbicides used for the *Weedfree* treatment meant that the financial risk was classified as High, although the volume risk was Low. The method of site preparation at Blyde had a direct impact on financial risk, with both the *Pit* and *Rip Weedfree* treatments classified as Low risk for both volume and financial, irrespective of method of slash management (Burnt versus Unburnt).

5.3.4.2. Compromise between timber production and financial return

This approach focusses on the selection of treatments whereby volume is balanced against the cost of vegetation management and financial return (nett profit) when these costs are deducted. As the number weeding operations and herbicides used are linked to vegetation management operations (regardless of whether a selective spray, ring or row weeding is used), the treatments classified as Low to Moderate risk for volume, and Low to Moderate risk for financial risk would be preferred.

A total of 10 treatments across the eucalypt trials and 20 treatments across the pine trials fulfilled these criteria and included the following treatments (**Tables 5.6 and 5.7**):

(i) Eucalypt trials: Vegetation management treatments included the *Row weeding (1.2 and 1.8 m)*, *Ring weeding (0.5 m)*, *Moderate intensity* and *Low intensity* weeding treatments. Although the unimproved genetic material that was not weeded (*Weedy* treatment) at Draycott also fulfilled the criteria, this treatment is not recommended as the general trend for the remaining unimproved genetic material treatments were classified High risk for either (or both) volume and financial return.

(ii) Pine trials: Vegetation management treatments included the *Ring weeding (1 m)*, *Moderate intensity* weeding, *Grass remaining*, *Weedfree* with 816 sph, two mulching treatments (biomac and kraft), *Weedfee* and *Weedy* without fertilization at Mossbank, and the *P. patula Weedfee* treatment at Ceylon. Whereas at Blyde, any of the three site preparation methods tested (ChopPit, ChopRip and Rip) irrespective of vegetation management could be considered.

5.4. Conclusions

Compared with the *Weedy* treatments, vegetation control during the establishment phase (planting to canopy closure) resulted in significant improvements of ca. 53% in volume across the eucalypt and pine trials. This trend was similar to the NPV obtained, with the outcomes illustrating the financial benefits of adequate vegetation management, confirming the importance of establishment vegetation control in both eucalypt and pine plantations managed on a pulpwood regime in South Africa.

Within this trial series, there was a direct link between volume/NPV obtained to the intensity of vegetation management operations, in particular for those trials located within the ST and WT climate zones. For the trials within the CT climate zone, the variation between treatments was lower due to reduced competition from vegetation. Since the volume obtained was linked to weeding intensity (and hence cost), if tree volume is most important with the aim to maximise volume and financial return, then complete vegetation management is required (*Weedfree* treatments). However, competing vegetation within ST and WT climate zones can be managed through clearing any vegetation within a ≥1.2 m row width for eucalypt pulpwood regimes, or clearing any vegetation within a ≥1.0 m ring width for pine pulpwood regimes. The planting of sweet potatoes within the interrow (no methods that reduce herbicides tested in CT climate zones) could also be a desired treatment, however within this trial series, the actual cost of sweet potatoes was not considered and therefore the profit relative to the *Weedy* treatment could be lower if these costs were included.

CHAPTER 6. DEVELOPMENT OF AN HERBICIDE USE RISK MODEL FOR VEGETATION MANAGEMENT

6.1. Introduction

Within commercial plantations vegetation management is used to ensure that limited site resources (water, nutrients, light and physical growing space) are channelled into usable forest products rather than into non-target plant species, or weeds (**Wagner et al. 2006; Little and Rolando 2008; Willoughby et al. 2009**). To ensure competing vegetation is adequately controlled, various vegetation management options (mostly labour intensive) are used within SA and include: the physical and/or mechanical removal of weeds; herbicide application to either the foliage, basal stem or cambium layer; and cultural control methods that incorporate practices common to good land management (**Zutter et al. 1987; Little et al. 2006; Wagner et al. 2006; Little and Payn 2016; Roberts et al. 2016, 2018; Ndlovu et al. 2019**).

With the worldwide trend to reduce the reliance on herbicides used for managing competitive vegetation, understanding rotation-end growth responses and the cost-effectiveness for all available vegetation management methods is important, in particular those with reduced and/or no herbicide use. As part of this dissertation, the tree growth responses and financial returns were evaluated from a series of eucalypt/pine trials that included various physical, chemical and cultural vegetation management treatments. This evaluation showed, for example, that rotation end tree volume (m^3 ha^{-1}) was negatively impacted by competing vegetation in five of the seven eucalypt trials (**Table 3.5, pages 55-56**) and eight of the twelve pine trials (**Table 4.5, pages 94-96**). Those treatments where all competing vegetation was controlled on a regular basis throughout the rotation (e.g. *Weedfree* treatments), resulted in the best tree growth responses of all treatments, together with the highest financial returns. However, these treatments also had a greater dependence on the use of herbicides.

To better understand the potential benefits and risks of different vegetation management operations and practices, as well as factors that have an impact on their overall effectiveness, it is important that this information is combined within a logical framework to allow for informed decision making to occur. If these assessments (around vegetation management) were incorporated into an herbicide use risk model, they could potentially provide an indication of various outcomes/possibilities for different vegetation management scenarios (**Willoughby et al. 2004; Kliejunas et al. 2006**).

6.2. Integrated risk models

Integrated risk assessment is defined as a science-based approach that combines the process of risk estimation for humans, biota, and natural resources into one assessment (**Bontje et al. 2004**). These integrated risk assessments identify more than one risk at any given time, which leads to greater decision-making efficiency in terms of sustainable forest management once these risks are known (**Girdžiūtėa 2012**). Various integrated risk evaluation methods exist, each using an equally diverse range of associated procedures (**Suter et al. 2003; Willoughby et al. 2004; Hardaker and Lien 2007; Toledo et al. 2011; Girdžiūtėa 2012**).

For example, in the United Kingdom (UK) and European Union, a decision tree system was developed by **Willoughby et al. (2004)**, focussing on reducing pesticide use in forestry. The first step of this decision system relates to identifying a specific problem, for example the removal of exotic vegetation from a wetland area. Once a specific problem is identified, the next step involves choosing which control option would be most suited, for example take no action, avoid the problem, or take remedial action (**Figure 6.1**). If the problem cannot be avoided, remedial action is required. Different possible actions are then listed in terms of chemical and non-chemical methods. If non-chemical methods are not available for that specific “problem”, the chemical method chosen will be the one which combines cost-effectiveness with low environmental and social impacts.

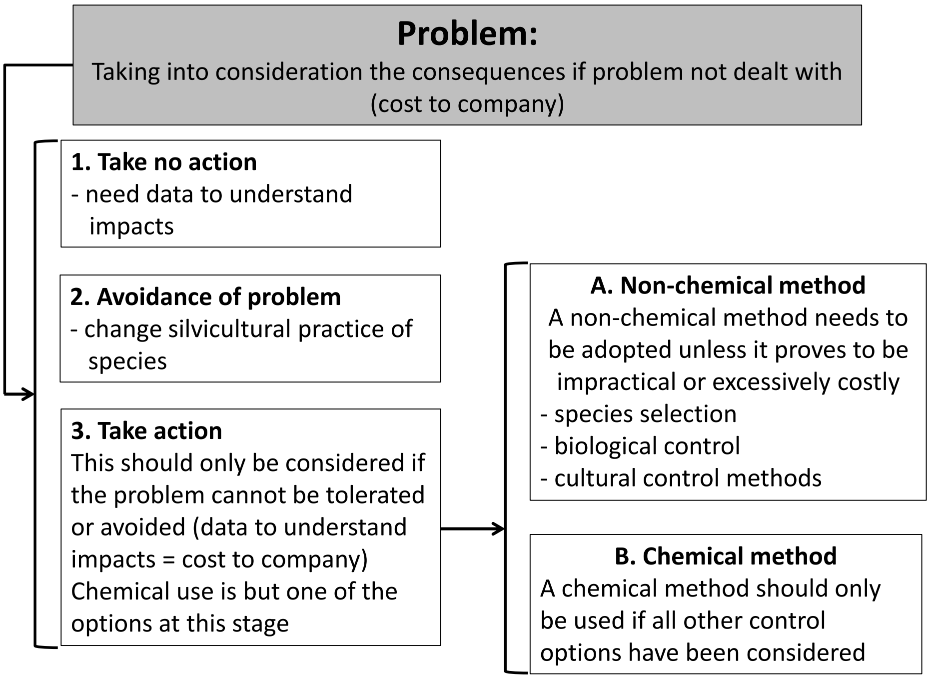

Figure 6.1. Example of a vegetation management decision key (extracted from **Willoughby et al. 2004)**

In the United States, a risk evaluation model was developed by **Kliejunas et al. (2006)** to estimate the likelihood and consequences associated with the introduction of insects and/or pathogens into the United States through the importation of unprocessed logs and chips from Australia. This risk evaluation model was based on eleven individual pest risk assessments, with the specific objectives to: (i) identify potential pest organisms that may be introduced with imported unprocessed logs and chips from Australia; (ii) assess the potential for introduction (entry and establishment) once within the United States; and (iii) estimate the potential economic and environmental impacts these pests may have on forest resources and urban trees if they become established in the United States.

Based on these objectives, seven possible risk indicators were partitioned into two parts: (i) likelihood of introduction; and (ii) consequences once the pest becomes established. Each indicator used within the assessment had different rating criteria (high, moderate, or low risk) for either the economic, environmental or social pest risk potential. A combination of these rating criteria provided an overall risk rating in terms of the potential for introduction and consequences if introduced (**Table 6.2**).

Table 6.2. Estimating economic, environmental and social risks to determine the potential for introduction, and consequences if introduced, of pests/pathogens in the United State (extracted from **Kliejunas et al. 2006**).

Economic damage potential	Environmental damage potential	Social and political considerations	Consequences of pest (overall risk)
H	L, M, H	L, M, H	H
L, M, H	H	L, M, H	H
M	M	L, M, H	M
M	L	L, M, H	M
L	M	L, M, H	M
L	L	M, H	M
L	L	L	L

L: low; M: moderate; H: high

The development of this risk evaluation model has allowed for the implementation of mitigation measures to recognise and reduce the introduction of pests/pathogens that could cause potential damage if established in the United State.

Development of a vegetation management risk model based on a combination of risk-based models

Although most risk assessment processes start with identifying various risk factors that could impact on the enterprise (**Suter et al. 2003; Willoughby et al. 2004; Kliejunas et al. 2006; Girdžiūtėa 2012**), it is often difficult to choose the most efficient evaluation method. Even though the decision tree system developed by **Willoughby et al. (2004)** is logical, appropriate data is required to enable decisions to be made in terms of the necessity to take action, as well as which method (non-pesticide or pesticide) would be best suited to overcome that specific problem (**Figure 6.1**). Since most of the vegetation management research trials implemented in SA have produced robust tree growth-response data (and associated costs), decisions around the need to take action, avoid the problem, or take no action can be determined. As these data sets are associated with trials that occur across diverse growing conditions, utilize different species, have different weed species and levels of competition etc. (**Tables 3.1 page 44 and 4.1 pages 80-81**), the principles underlying the decision tree system would need to be adapted to take these differences into account.

In addition, the range in treaments (within, and between trials) in terms of performance (survival, growth, uniformity), method of control, herbicides used, costs etc. would mean that the chosen method must allow for treatment comparisons, both within and between trials. One way to overcome this is to develop rating criteria, similar to those of **Kliejunas et al. (2006)**, but for vegetation management treatments.

A combination (and adaptation) of the decision tree system used by **Willoughby et al. (2004)** with the risk categories (high, medium or low risk) used by **Kliejunas et al. (2006)**, would highlight a sequence of logical steps to follow regarding vegetation management in eucalypt/pine pulpwood plantations. This information is then incorporated into the global Köppen climate classes (CT, WT and ST) which were adapted to timber growing regions of SA by **Smith et al. (2005a)** (**Figure 6.2**).

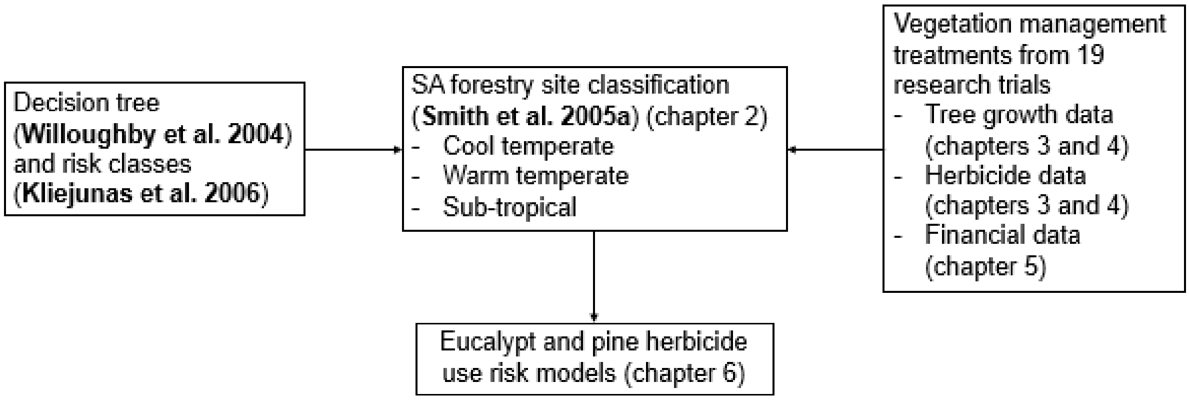

Figure 6.2. Parameters used to develop herbicide use risk models

6.3. Parameters used in this thesis for the herbicide use risk model

Within forestry, the ideal vegetation management treatment would be one where tree growth is not impacted by competing vegetation, and which made use of the lowest input in terms of weeding operations and herbicide use. Based on the overall findings that formed part of this dissertation, there was a direct link between improved tree performance with that of increased weeding intensity, herbicide use, and hence costs. As such, the herbicide financial risk model has been adapted to include overall tree growth risk (**Table 3.7 page 71** for the eucalypt trials and **Table 4.6 pages 110-111** for the pine trials), financial risk (**Table 5.4 page 137** for eucalypt trials and **Table 5.5 pages 138-139** for pine trials) and herbicide risk (**Table 3.8. page 75** for the eucalypt trials and **Table 4.8 pages 118-119** for the pine trials). This risk model also incorporates site productivity in terms of climate zone, as sites situated in the ST climate zones have more vigorous vegetation growth, requiring more intensive management in comparison to the WT and CT climate zones (**Figure 6.2**).

6.4. The model

The herbicide use risk model is based on a decision tree system and includes the various vegetation management methods from 19 vegetation management research trials. This decision tree system uses three different approaches to vegetation management for each of three climate zones (CT, WT and ST). This allows for different outcomes within each climate zone in terms of: (i) maximising volume as the main criterion; (ii) optimising volume together with reduced herbicide use; and (iii) reduced herbicide use as the main criterion. For each approach, various vegetation management methods are available that are aligned with the management objectives.

Note:

Although some treatments were only implemented within the ST and WT climate zone trials (for example the *2m Row weeding* treatment and *Sweet potato* (*1.2 m*) treatment), it is likely that these treatments would also be viable options within the CT climate zone. This is due to the trials situated within the ST and WT climate zones experiencing higher levels of weed abundance and growth compared to the CT climate zone, which resulted in increased weeding. Based on this assumption, all the treatments categorised as low risk in either ST and/or WT climate zone trial, could also be considered low risk treatments in CT climate zone trials, even though there is no data to support these specific treatments. This approach was applied for both the eucalypt and pine herbicide use risk models.

6.4.1. Maximising volume

For this approach, vegetation management inputs are structured to ensure maximum volume is obtained, yet in a sustainable and cost-effective manner. Vegetation management methods listed for this approach are intensive, with an overall emphasise on controlling competing vegetation (through the use of herbicide-based techniques in these trials), especially on the more productive sites (**Annexures 4 + 5**).

For eucalypts, the vegetation management treatments included the *Weedfree* treatment, *2 m Row weeding* treatment and *Sweet potato* (where the sweet potatoes were grown within the tree interrow) (**Annexure 4**). Of these, the *Sweet potato* treatment used the least herbicide, followed by the *2 m Row weeding* treatment.

The pines included a wider range of vegetation management treatments from which to select compared to the eucalypts (**Annexure 5**). As for the eucalypts, most of the *Weedfree* treatments were also included, including those where the slash had been retained or burned, or where the site had been manually pitted or ripped. Also included were the *Ring weeding* (*1.5* and *2 m*) treatments, with the *2 m Ring weeding* treatment registering reduced herbicide use compared to the *Weedfree* treatments.

In general, these vegetation management treatments all ensured that competing vegetation was kept away from the planted crops, resulting in unrestricted growth. Since there was a direct link between tree volume obtained with that of financial return (NPV), the additional cost of theses more intensive vegetation management treatments was offset by the increase in volume.

6.4.2. Compromise between volume and herbicide use (balance between optimising volume with that of reduced herbicide use)

Within any given trial, the chosen vegetation management treatment will often be the one that fulfils management objectives in terms of improved yield whilst taking reduced costs, ease of implementation and protection of the site into account. Often "next best" treatments that were implemented were herbicide is used at reduced rates, and although not significantly different from the best, did not fulfil one or more of the above criteria. This approach focusses on the selection of treatments whereby optimum tree growth is balanced against reduced herbicide use and financial return. This approach includes "next best" treatments that may or may not be significantly different to the best performing treatments, but were herbicides was applied at reduced rates. Since the number weeding operations and herbicide use are linked to vegetation management operations (regardless of whether a selective spray, ring or row weeding is used), the treatments classified as Low to Moderate risk for tree growth responses, and Moderate risk for herbicide use rating (5-10 kg ha^{-1} herbicides applied) was included.

For eucalypts, *Row weeding* (*1.2* and *1.8 m*), *Moderate/Low intensity*, or the planting of *Sweet potatoes* (within the tree row and interrow) fulfilled the criteria for this scenario (**Annexure 4**). Within the WT and ST climate zones, the *Low weeding intensity* treatment used the least herbicides, followed by the various *Row weeding* treatments.

For pines in the CT climate zone, the *Weedfree* treatment when planted at 816 sph, or where the slash was either chopper-rolled and pitted or ripped (*Choppit* or *Choprip*) were included, all with similar quantities of herbicide applied and financial return (**Annexure 5**). However, where the slash was burnt prior to planting (in contrast to where it was retained), more weed growth occurred resulting in an increase in the quantity of herbicides applied. As these treatments were only tested in the CT climate zone, they cannot be recommended for use within the warmer climate zones (WT and ST) due to the unknown influence of slash management on vegetation growth/competition. Within the WT and ST climate zone, three vegetation management treatments can be selected, a *1 m Ring weeding, Grasses remaining* or *Moderate intensity* weeding, with the *Moderate intensity* weeding treatment using marginally more herbicide that the other two treatments.

6.4.3. Focussing only on reducing herbicide use

If the focus were on a reduction in herbicide use so-as-to reduce any environmental and/or social impacts, then all the vegetation management options not included in the above two approaches could be considered. These treatments included all the *Weedy* treatments across all three-climate zone, albeit with a loss of timber volume (and profit) (**Annexure 4 and 5**). The only other treatment that could be included within this category would be the *Weedfree manual* treatment. Although this specific treatment optimised tree volume (to a level similar to, or better than that of *Weedfree* treatments using herbicides), it did require an increase in the use of labour. Although not discussed in this dissertation, there is a move away from the use of manual labour for silvicultural operations in South Africa, not only due to increased costs, but also due to ergonomic concerns around the physical nature associated with manual weeding operations (**Ramantswana et al. 2020**).

6.5. Conclusions

Decisions relating to the selection of the best vegetation management methods are complex and require long term data, with a risk model developed to aid in decision-making. The application of treatments (vegetation management options) from 19 vegetation management trials to the herbicide use risk model indicated that the more intensive the weeding operation (such as the *Weedfree* treatments), the higher the tree volume, particularly on the more productive sites. Based on the criteria used in this model, this translates into lower overall tree growth and financial risk ratings compared to the other methods. However, these methods also rely on the use of more herbicides compared to the other methods. If reduced herbicide use is the main criterion, then either the manual weeding can be carried out (*Weedfree manual*) or *Weedy* treatments can be used. However, the manual weeding is more costly (and labour intensive), with the *Weedy* treatment resulting in a significant loss in tree growth and profit, especially on the more productive sites in the WT and ST climate zones. This risk model will not only assist foresters with choosing the most appropriate site-specific vegetation management methods to use (based on their management objectives), it will also provide them with an indication of the magnitude of loss (volume and profit), should a less intensive approach be followed.

CHAPTER 7. OVERALL CONCLUSIONS

7.1. Summary of the major findings and their significance for forestry in SA

The overall aim of this dissertation was to develop an herbicide use risk model for vegetation management within commercial eucalypt and pine pulpwood regimes of South Africa. To achieve the aim of the study, four objectives were formulated (**Chapter 1.3, pages 6-9**).

The first objective was to quantify herbicide use within the forestry industry of SA (**Chapter 2**). This objective was achieved through conducting an herbicide survey sent to various forestry plantation managers. Results from the herbicide survey indicated that 16 different active ingredients (herbicide formulations) were used, with glyphosate-based products accounting for 97%, while metazachlor and triclopyr butoxy ethyl ester accounted for 2% of total active ingredient used. Regardless of climate zone (sub-tropical - ST, warm temperate - WT, cool temperate - CT), most herbicide was applied during the re-establishment phase. Over the survey period (2017-2018), 188 288 kg of herbicide a.i. was applied over 343 784 ha, which equated to an average rate of application of 0.55 kg a.i. ha^{-1}. The survey not only benchmarked herbicide use in SA, but also highlighted areas were herbicides can be reduced across different tree growth stages and climate zones.

The second objective was to quantify and link tree growth responses (survival, growth, uniformity) and herbicide use for various vegetation management treatments (chemical, physical, cultural) that were included within 19 pine and eucalypt pulpwood trials (**Chapters 3 and 4**). Tree growth responses obtained within these trials were a function of inherent site productivity, previous land use, species planted and the manner in which the competing vegetation was managed. In general, tree growth, weed abundance, and hence competition (if uncontrolled) was higher within the ST and WT climate zones than the CT climate zone, which can in part be attributed to the higher mean annual temperatures and increased number of growth days associated with these climatic zones. The higher weed abundance in the ST and WT climate zones resulted in higher levels of weeding required (and hence more herbicides applied), or increased competition in terms of yield and uniformity if uncontrolled. The combined results from these 19 trials indicated the importance of vegetation management in terms of ensuring tree production, with a higher intensity of weeding favoured, albeit with corresponding increase in the use herbicides.

The third objective was focussed on understanding the cost-benefits for the various vegetation management treatments that were included within the 19 trials (**Chapter 5**). This was achieved by calculating the total vegetation management cost for each treatment within each trial, and together with yield, the determination of the net present value (NPV). There was a direct link between increased tree growth (volume) and financial return (NPV) with that of the intensity of vegetation management required (and a corresponding increase in herbicide use). This link was more pronounced for those trials located within the more productive ST and WT climate zones. As a consequence, if a company wishes to maximise volume and financial return, then intensive vegetation management is required (*Weedfree* treatments). However, if the focus were to reduce the amount of herbicide (based on environmental and/or social constraints), then either the manual removal of competing vegetation is required, or no vegetation management after planting, albeit with negative impacts on both tree growth and financial returns.

Using the outcomes from Objectives 2 and 3, the fourth objective focussed on the development of a functional herbicide use risk model for the management of vegetation within commercial eucalypt and pine pulpwood plantations in SA (**Chapter 6**). An existing pest risk evaluation model was combined with a decision tree to develop an herbicide use risk model. Treatment data from the 19 trials were then incorporated into this risk model to provide the end-user with options in terms of vegetation management treatments based on their site, species planted, costs, and company objectives. The outcomes were similar to those obtained for Objectives 2 and 3, for example, if the focus were on a reduction in herbicide use and labour so as to reduce any environmental and/or social impacts, then reduced weeding is required, albeit with negative impacts on both tree growth and financial returns. Whereas, if the focus were to maximise volume and financial return, then more intensive vegetation management is required (*Weedfree* treatments). A compromise is also possible whereby vegetation management methods are balanced against tree growth responses obtained, financial return and quantity of herbicide applied (*Row weeding* treatments).

Overall, the outcomes from this dissertation provides benchmark data and derived information as to the necessity for various vegetation management options (and associated herbicide use) within the commercial forestry sector of SA. In addition, the herbicide use risk model will assist with decision making around which vegetation management method is most appropriate (in terms of timber volume, costs and herbicide use) for different species and site productivities.

7.2. Limitations and future research direction

The various components contained within this dissertation each involved objective-specific aspects of vegetation management such as the quantification of tree growth responses, financial return, or herbicide use. However, due to the magnitude of this study, it was not possible to cover every aspect of vegetation management, and subsequently each of the objectives had certain limitations. For example, the herbicide survey (**Objective 1**) was restricted to planted areas only, and therefore total use for the whole forestry sector could not be determined (for example herbicide use in conservation areas, along road verges, within fire breaks etc.). Regardless, the herbicide survey can be used as a baseline for future herbicide use surveys within commercial plantations across SA. It is recommended that this survey be conducted periodically (every five years) to allow benchmarking of past, current or future herbicide use across various timber species grown, end-product produced and vegetation management phases. In future research, the scope of the survey can also be increased to consider other pesticides as well, such as insecticides and fungicides.

Although the data that formed part of this study were obtained from 19 studies which allowed for the development of broad principles associated with the management of vegetation in SA, these data were obtained from research trials only (**Objectives 2 and 3**). In addition, these data dealt exclusively with vegetation management within pulpwood stands (rotation end for eucalypts and 10 years for pine), which meant that other genera planted, trees grown for different end-use products (poles, sawn timber, mining timber, veneer, etc.), and other biotic risks (pathogens and insect pests) were not included. Future research should be expanded to include these aspects, in addition to the incorporation of data from commercial operations.

Using the outcomes of each of the objectives, an herbicide use risk model was developed (**Objective 4**). Even though the risk model included various aspects of vegetation management, limitations still remained. For example, forestry companies are measured against a combination of economic, environmental and social criteria, however only the economic component were dealt with in detail. Generic environmental criteria were used (in terms of a product being more or less hazardous), with any negative social aspects only alluded to (for example reduced risk to spraying operator if less herbicide is applied). Future studies should focus on both the environmental fate of pesticides (as applied commercially within SA), as well as the social impacts of applying pesticides in plantations on operations, and/or surrounding communities. These studies could then be combined with the herbicide use risk model (**Objective 4**) to develop a truly intergraded vegetation management risk model, were data from all three aspects (economic, environmental and social) are included. This would also allow for the identification of areas of High-risk and of areas where a reduction in herbicides can be achieved, together with transparency in reporting (to external auditors or certification bodies).

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Annexure 1. Summary report for plagiarism test using Turnitin

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Annexure 2. Research Ethics Committee (Human) approval report

NELSON MANDELA
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PO Box 77000, Nelson Mandela University, Port Elizabeth, 6031, South Africa mandela.ac.za

Chairperson: Research Ethics Committee (Human)
Tel: +27 (0)41 504 2347
Sharlene.Govender@mandela.ac.za

Ref: [H18-SCI-NRM-002] / Approval]

24 April 2020

Dr KM Little
Faculty: Science

Dear Dr Little

THE DEVELOPMENT OF AN INTEGRATED PESTICIDE RISK MODEL FOR PLANTATION FORESTS IN SOUTH AFRICA

PRP: Dr KM Little
PI: Mr JC Roberts

Your above-entitled annual progress report (APR) was reviewed by REC-H EXCO for approval. We take pleasure in informing you that the Research Ethics Committee (Human) has approved your report. Please note the following as you continue your study to its completion:

1. In the event of a requirement to extend the period of data collection (i.e. for a period in excess of 1 calendar year from date of original approval of study), completion of an extension request is required (form RECH-005 available on Research Ethics Committee (Human) portal)
2. In the event of any changes made to the study (excluding extension of the study), completion of an amendments form is required (form RECH-006).
3. Immediate submission (and possible discontinuation of the study in the case of serious events) of the relevant report to RECH (form RECH-007) in the event of any unanticipated problems, serious incidents or adverse events observed during the course of the study.
4. Immediate submission of a Study Termination Report to RECH (form RECH-008) upon expected or unexpected closure/termination of study.
5. Immediate submission of a Study Exception Report of RECH (form RECH-009) in the event of any study deviations, violations and/or exceptions.
6. Acknowledgement that the study could be subjected to passive and/or active monitoring without prior notice at the discretion of Research Ethics Committee (Human).

Please quote the ethics clearance reference number in all correspondence and enquiries related to the study. For speedy processing of email queries (to be directed to Imtiaz.Khan@mandela.ac.za), it is recommended that the ethics clearance reference number together with an indication of the query appear in the subject line of the email.

We wish you well with the continuation of your study.

Yours sincerely

Dr S Govender
Chairperson: Research Ethics Committee (Human)

Cc: The Office of Research Development
Faculty Officer: Science

Annexure 3. Herbicide use survey (Please see attached excel spreadsheet)

Annexure 4. Eucalypt herbicide use risk model (Please see attached excel spreadsheet)

Annexure 5. Pine herbicide use risk model (Please see attached excel spreadsheet)

Annexure 6. Map of trial locations