ASSESSING THE VALUE OF PUBLIC INVESTMENT INTO BIOLOGICAL CONTROL RESEARCH FOR INVASIVE ALIEN PLANTS: THE ARC PPRI WEEDS RESEARCH DIVISION

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ABSTRACT

This study investigates the economic impact of the ARC PPRI Weeds Research Division. The Division researches appropriate methods of biological control for invasive alien plants (IAPs). These plants pose an increasing threat to environmental integrity and ecosystem service provision impacting on economic potential. Since the work of the Division is considered a public good, a predominantly descriptive approach has been adopted for the valuation process. A combination of quantitative cost analysis and a qualitative study of the impacts of research and invasive alien plants is used to deal with the challenges associated with non-market valuation. The study found that investment into the Weeds Division is a valuable activity that supports the long-term growth potential of the South African economy. The role of a well-functioning environment is highlighted as an essential base for the creation of sustained growth opportunities in any society. It was determined that investment into the Division should be increased into the future to support efficient spending of scarce state funds. Biological control research was found to provide strategic future growth potential, creating opportunities for the development of a competitive advantage in the biotechnology and environmental management sectors. The study adds to the increasing move towards a more holistic view of economic valuation, taking factors other than pure finance and econometrics into consideration. This is an important shift in prevailing economic thought, as a realisation is reached that a single, or even triple, bottom line is an outdated and insufficient decision making basis.

This thesis has not been submitted to a university other than Rhodes University, Grahamstown, South Africa. The work presented here is that of the author, unless otherwise stated.

The author has been funded by the Agricultural Research Council (ARC) for the purpose of this study. While this may be seen to represent an ethical infringement on the objectivity of the work, the author has in no way been led to provide a positive report based on this connection. This connection to the ARC has in no way influenced the research process or its outcomes. The work produced here was done independently through Rhodes University, with the express intention of providing an objective view on whether investment into biological control research is worthwhile.

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Lowell Martin Scarr   Date

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ARC	- The Agricultural Research Council
PPRI	- The Plant Protection Research Institute
IAP	- Invasive Alien Plant
WfW	- The Working for Water programme
Agent	- A biological control agent
Biocontrol	- Biological control (used interchangeably)
Cochineal	- A small insect that feeds on cactus
Complete control	- Situation where not further implementation of IAP control is needed
Control	- Steps taken to manage an invasive species
Conventional control	- Mechanical or chemical methods of IAP control
CVM	- Contingent valuation model
ES	- Economic Surplus
Spillover	- Unintentional usage or gains from research
Substantial control	- A situation where limited further IAP control is needed
Target	- An invasive alien plant targeted for biological control
Valuation	- An economic impact study
Weevil	- A small, seed feeding insect
WTP	- Willingness to pay

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CHAPTER 1

INTRODUCTION: THE WEEDS RESEARCH DIVISION

This study investigates the economic impact of the Agricultural Research Council (ARC) Plant Protection Research Institute's (PPRI) work into biological control (or biocontrol) of Invasive Alien Plants (IAPs). The unit under study is the Weeds Research Division, which is responsible for conducting the research necessary to select, quarantine and release biocontrol agents in South Africa (Plant Protection Research Institute, 2005).

1.1 Outlined Context of the Study

The Agricultural Research Council (ARC) is South Africa's leading agricultural research body. The organisation strives to drive research and development in the sector through the improvement of technologies and dissemination of information (Agricultural Research Council, 2012). It is the mission of the ARC to support innovation in the agricultural sector by producing relevant and new research in a range of fields. The Council is composed of a number of units, each with a focus on a specific area in the sector. The Plant Protection Research Institute is one of these units, with a mandate to provide public support services for the agricultural sector (Plant Protection Research Institute, 2006). The Institute conducts research into five main fields, namely Biosystematics, Insect Ecology, Pesticide Science, Plant Pathology and Microbiology, and Weeds Research.

The PPRI performs mainly scientific research and development (Thirtle *et al*, 1998), and has two main objectives: the development of effective management systems for plant disease, pests and invasive plants that are as minimally harmful to the environment as possible; and the promotion of the commercial use of beneficial organisms to improve the resilience, production and sustainability of the agricultural industry as a whole. These objectives are achieved through focussed research, the development of improved technologies and the transfer of these technologies to the public (Agricultural Research Council, 2010).

The Institute is classified as a public support service organisation, since the work it produces is largely scientific in nature spanning a wide range of plant related fields. The research is available for anyone to use and is done for the benefit of all South Africans (Black *et al*, 2008). Such work includes the analysis of pesticide residues, entomology and nematology research and the custodianship of these national databases, research into pests of stored grains, and weeds research, which is the focus of this thesis (Plant Protection Research Institute, 2012). Valuing these types of activities is challenging since they do not lead to easily measured changes in output levels, input costs, or other market based indicators. Instead, they tend to produce effects that are non-market in nature such as preserved biodiversity or improved knowledge (Plant Protection Research Institute, 2005). A challenge is therefore presented in terms of the estimation of the economic value of the Institute's work. This is because it is inherently difficult to place a value on a good such as a river system free from invasive water plants or a national scientific database (Tietenberg & Lewis, 2010).

The primary objective of the PPRIs Weeds Research Division is the protection of South Africa's natural resources and biodiversity from the threat posed by invasive alien plants (IAPs). This is achieved by researching the use of biological control agents to develop integrated pest management systems that are not harmful to the environment and result in long-term solutions to IAP management (Plant Protection Research Institute, 2006). The Division first began to research the use of biocontrol in 1913, to control the cactus *Opuntia vulgaris,* which was rapidly spreading across the country. Since then, 270 potential control agents have been tested with 106 of these having been deemed effective and safe for release (Klein, 2011). Of these 106 agents, 75 have become established on 48 IAP species with 21% of these IAPs having been brought under complete control and a further 38% brought under substantial control. It has previously been estimated that the use of biocontrol has thus far resulted in a 19.8% (R1.38 billion) saving in the cost of IAP control in South Africa (Plant Protection Research Institute, 2006).

The main challenge facing the PPRI Weeds Division is a lack of secure long-term funding. Due to difficulties associated with the valuation of public goods (Haab & McConnell, 2002), and in this case the value of public research, the Division often finds it difficult to motivate for sufficient levels of continued investment into its projects. To better understand this problem,

this study attempts to illustrate whether investment into biological control research is a valuable activity that should receive continued financial support into the future. Displaying the value that the Division provides to the South African economy is essential at a time of increased financial strain in the domestic economy, and will shed light on the value of conducting publically funded basic agricultural research.

An equivalent of over 12% of total land area of South Africa (121 909 000 ha) has been claimed by invasive alien plants (Henderson, 2011. and Le Maitre *et al*, 2000). The urgent need for sustainable solutions to current and future invasions is therefore highlighted as higher levels of invasion pose a greater long run cost to the economy. Van Wilgen *et al* (2001) noted that the environmental and economic impacts of IAP invasions are not fully understood, but indications are that total costs imposed are substantial. This was supported by Le Maitre *et al* (2002) who argued that in light of the available literature regarding the range of negative impacts and rate of spread of IAPs, a failure to clear and effectively control these species will result in an exponential increase in the clearing and control costs in the future. The spread of invasive alien plant species is a problem affecting large areas of the country, and imposes a range of costs onto the local economy and environment that are set to increase into the future. Considering this, Zimmermann *et al* (2004) remarked that given a limited budget and a range of other pressing social needs, South Africa needs to find a management solution that is able to deal with the problem at least cost and highest effectiveness.

South Africa is a world leader in the combating of IAPs both in terms of actual control and related research (Van Wilgen *et al*, 2004). The Working for Water (WfW) programme, a division of the Department of Environmental Affairs (Department of Environmental Affairs, 2013), is the main body pioneering large scale eradication of IAPs in the country (Working for Water, 2014). Van Wilgen *et al* (2001) noted that it was the negative impacts caused by IAPs on water availability that initially motivated for the creation of the WfW programme, especially considering that the majority of river systems in the country were in some way affected by invasive plants. The aim of the programme is to control IAPs that pose a threat to water resources thereby protecting this essential asset and ensuring long-term security of water supply. Between its inception in 1995 and April 2000, the State had spent approximately R1 billion on the WfW programme to aid in the eradication of important weed

species (Van Wilgen *et al*, 2001). The WfW is one of the Weeds Division's major funders, since it is the best equipped in the country to conduct much needed research into the use of biocontrol as an economically and environmentally viable control mechanism for IAPs such as Port Jackson and Black wattle*.* Not only does the Division conduct research into this field, but it also creates employment opportunities for many people in the science and IAP eradication and control sector (Working for Water, 2012).

Investment in projects such as researching biological control for invasive alien plants is almost entirely driven by the public sector, as is the case with the Weeds Research Division (Hill & Greathead, 2000). This is because biological control is largely seen as a public good, where the benefits of the research are distributed throughout communities and generally cannot be captured by private interests (Black *et al*, 2008). At a time of increased financial pressures due to turbulence in world markets and increased domestic demand for state funding, the necessity of identifying the impact that such a research institution has on the economy is increasing. This is to justify the large expenditure of public funds on the Weeds Division's work, which totals about R34 million per year (Khan, 2013). It is therefore necessary to develop a method for analysing the value of the Division's work that accounts for the non-market goods produced. Having developed a method, an understanding of the value produced must be ascertained to illustrate whether such investment is worthwhile and what future levels of investment are suitable.

The economic valuation conducted in this study is descriptive in nature, and combines a cost analysis of biological versus conventional forms of IAP control (Gittinger, 1995) with qualitative data regarding the impacts of research and the effects of invasive alien plants (IAPs). Van Wilgen *et al* (2001) noted that although much work has been done on the history, ecology and management of IAPs, to date few studies have investigated the value created through the research of biocontrol opportunities. It is this aspect of the IAP problem in South Africa that is investigated here.

The goals of the study are to

1) Illustrate the value of the PPRI Weeds Research Division's work to the South African economy.
2) Determine whether investment into biological control research is worthwhile, and whether this investment should be increased over time.

The study closely follows the paper by Van Wilgen and De Lange (2011), which conducts an analysis of the costs and benefits of biological control research for invasive alien plants at a national scale. Since the issues addressed in the Van Wilgen and De Lange paper are related to the issues needing to be considered in the analysis of the work of the Weeds Research Division, their paper has been used as a guideline in compiling this study. The important difference to note between these two studies is that Van Wilgen and De Lange (2011) considers the value of biological control quite broadly whereas this study focuses on the work carried out by the PPRI Weeds Research Division specifically, investigating what the economic impact of this research is at the national level. In addition to these sources significance has been given to the special edition of *African Entomology* (2011: 19(2)), which provided a review of the progress in biological control in South Africa for the period 1999-2010. This source has been used fairly extensively to gain insight into the success of biological control in the South African context.

The study investigates the value realised through conducting research; and more specifically how to value the work of a research institute and its impact on an economies development. This is undertaken to gain a balanced understanding of how to value the work of the Division. The importance of biological control as a means of IAP management is considered to understand whether this form of control should be invested in and if so, to what extent. Lastly, the study combines these insights to gain a meaningful understanding of the value provided by the Division to South Africa at large. A cost effectiveness analysis is used in comparison to conventional control to achieve this goal. This is complemented by qualitative data regarding the impacts of invasive plants and of research in general.

Chapter 1 provided a broad introduction to the topic and overview of the reason for conducting this analysis. The nature of the Plant Protection Research Institute's work has been described, and the need to value the work of the Weeds Division has been established. The goals of the research were identified, and the method of achieving these aims set out.

Chapter 2 continues the analysis by assessing whether investment into research is indeed valuable. This chapter describes the role that research plays in the development of an economy, and sets out various means for determining its contribution towards such progress.

Chapter 3 expands further on the context of the study by describing the problem that invasive alien plants pose to the environment and economy. This is done at both a domestic and global level to illustrate the wide ranging effects such plants have. The various methods of invasive plant management are also set out here, including the use of biological control measures.

Chapter 4 sets out the method that is employed in the study. This method is predominantly descriptive in nature, and draws on a wide variety of economic, scientific and social findings regarding the impact of invasive alien plants. The chapter sets out data sources and provides the framework that grounds the study. The set of indicators used to draw conclusions about the relative value of investment into conventional and biological control measures are established here.

Chapter 5 furnishes the method with data. This is then analysed and discussed in the context of the Weeds Research Division. Environmental impacts of alien plant invasions are considered, and where possible translated into economic impacts. The cost of biological as opposed to conventional control is examined and complemented by an analysis of the impacts of biological control on invasive *Acacia* species. This is done to help understand the value of the Weeds Division's work.

Chapter 6 is the final section of the thesis. Here conclusions regarding the value of the Weeds Research Division are set out based on the overall findings of the study. Recommendations are also made about the nature of current and future invasive management work.

CHAPTER 2

THE VALUE OF RESEARCH

Chapter two investigates the economic impact of conducting research. This is done by reviewing available literature on the value of research and how such value is determined. Findings from this literature are then used to inform choice of method, data used, and overall findings and recommendations that are made. The chapter first establishes whether conducting research is valuable, and the extent of this value. It then proceeds to investigate what comprises such value in terms of the costs and benefits realised through research work. A brief analysis is given of the effects of research spillovers and how these can best be integrated to increase economic value. Moving from here, a brief review is given of the impact of agricultural research in Southern Africa. This review is based on a number of local studies and aims to provide insight into the type of work done to date and the findings that this work has produced. The review is compiled to provide context for the valuation conducted in this study. The chapter then progresses to an investigation of the various methods that can be used to conduct an economic valuation. This analysis includes methods for examining both market and non-market goods. A focus on non-market goods is given because of the nature of the Institute's work, which is non-market based. Market goods are, however, at first considered since various aspects of this type of analysis are useful for a proper understanding of the task of economic valuation. The chapter ends with a brief overview of the literature and offers conclusions about its relevance for the valuation of the Weeds Division.

2.1 Is doing research valuable?

In establishing the value of the Weeds Division's research, first it is prudent to consider the economic value of conducting research *per se*, as well as the existence of research focussed institutes. This includes an understanding of what is meant by innovation and how this relates to economic growth. Having established what economic value there is in conducting such work, it is then required to consider how this value can be determined and appreciated. This is achieved by examining a range of methods available to assess economic value, to determine which method is most suitable to the task at hand (Economic Services Unit, 2013). In doing

this, methods for assessing both market and non-market goods are considered. Special attention is, however, given to non-market goods as this is the predominant type of output produced by the Weeds Division (Plant Protection Research Institute, 2006).

The value provided by research and research institutions to an economy's development has long been recognised. Vang *et al* (2007) noted the global awareness of the value presented by universities and other publically funded research institutes as drivers of knowledge based growth and innovation. Without these research driven organisations, there is a tendency for an economy to rely on existing technologies and therefore stagnate. Wiebe *et al* (2001) supported this idea with the finding that sufficient levels of research are essential for the sustained development of economies by creating new opportunities for growth. By providing sufficient support for research organisations, a government ensures the economy is dynamic and responds to available niches that may be created. Ashiem and Coenen (2005) argued that knowledge is the most strategic and important resource for growth in today's globalised economic context. Furthermore, learning was identified as the fundamental source of competitiveness. It is through new research findings, improved scientific methods and the development of skills in this sector that a range of prospects for future development are established. From this, the idea of the learning economy (Lundvall, 2010) and knowledge based economy (OECD, 1996) have arisen as key descriptive terms for contemporary development. These terms describe an economy that is geared towards exploiting incremental improvements in competitive advantage by making use of continuous research innovation and development.

The OECD released a report in 1996 entitled 'The knowledge based economy', which details the importance of increased knowledge in driving an economy's growth. The report recognised the extensive value the creation of knowledge produces, with over 50% of the GDP of major OECD economies generated through knowledge based activities (OECD, 1996). It was noted that while a large portion of this knowledge-based growth is in the information technology sector, this does not equate to the sum of the knowledge based economy. Rather, a view that includes a broader take on knowledge creation and the skills to use this information is held as essential to sustained growth (OECD, 1996). As such, research into a variety of fields is supported with the view that an insufficient amount constrains human

capital growth, which further hinders economic growth. The idea of knowledge raising the returns on investment is suggested, having a feedback of increased accumulation of knowledge (OECD, 1996). This is achieved through new and improved methods of production, products and services that decrease cost and increase efficiency. Overall, although this report was compiled almost 20 years ago, it provides insight into the emergence of the knowledge based economy and the importance of the continuous creation of knowledge to the sustained growth of an economy. This insight is useful when considering the PPRI Weeds Division, which is a research driven organisation focussing on the South African environmental context.

In discussion of the function of research institutes in economic growth, Vang *et al* (2007) noted a split in the view of their role in society. This spilt is between understanding such an institute as either having a generative or developmental role (Gunasekara, 2006). The generative role is understood as the contribution of the institute to regional development through the production of new knowledge and trained personnel (Mowery & Sampat, 2005). Under this view, the role of the research institute is to produce basic scientific knowledge and train staff. The newer view of a development role, on the other hand, is understood by Vang *et al* (2007) as the contribution of the institute to the creation of new knowledge and trained staff, as well as its contribution to regional governance procedures and the development of economically useful knowledge. Etzkowitz (2002) remarked that according to this view there is a blurring of the distinction between research and industry, as these two sectors begin to interact more closely to serve a common purpose of development. This shift sees research institutes as more important drivers of growth than previously held, with increased interaction between research, industry and the state leading to improved economic performance (Vang *et al*, 2007). Etzkowitz and Klofsten (2005) stated that under this newer view, research institutions are seen as the incubators of increased interaction between academia and new business opportunities, leading to increased success amongst these firms. Vang *et al* (2007) stated that the development approach has been increasingly adopted as the dominant view of the role of research institutions. Through their existence, research institutions promote innovation and cost saving, as well as improved governance structures and policy making. This supports the work of the PPRI Weeds Division as the institute not only produces valuable scientific knowledge, but also leads to improved decision making practices and governance as well as increased cost efficiency in environmental management.

Considering that the PPRI Weeds Division is publically funded (Plant Protection Research Institute, 2005), it is insightful to gain a brief understanding of whether public investment into research should indeed be made. Salter and Martin (2001) identified two models for understanding the economic effects of publicly funded research and the need thereof. The first is the traditional model, which emphasises government's role in the correction of market failure (Pavitt, 1998). This model assumes that a purely market driven economy will result in the optimal level of research being conducted into the right areas, and that government should only intervene in an economy when there is market failure. Metcalfe (1995) contrasted this to the evolutionary approach, which recognises that markets are inherently flawed and focuses on the improvement of efficiency through structural change by means of government funded research into specific areas. When considered in conjunction with Braverman (1974), who noted the importance of public research in overcoming inefficiencies in the market, it would appear that the evolutionary approach is better for understanding the need for publicly funded research in the economy (Verspagen, 1993).

Moving from the value of research and related institutes, it is useful to explore what is meant by innovation. This will facilitate an understanding of the role that the Weeds Division plays in fostering innovation. To date, the general understanding of innovation has focussed mainly on the creation of new products. Ashiem and Coenen (2005) identified the populous view of innovation as being obsessed with high-tech industries, neglecting knowledge development and innovation in other sectors. The new consensus that has arisen over the last decade, however, identifies innovation as any work that will produce an economic benefit or saving. Edquist (2001), for example, promoted the idea of innovation as any creation or research that is of, or will create, economic value. This broader view of innovation, which not only embraces high-tech industries, includes radically new creations and improvements to existing technologies, and is concerned with both what is produced and how it is produced. Vang *et al* (2007) supported this view by stating that there has been a shift away from understanding innovation as simply research and development towards a broader concept that includes competence building and increased value adding. In this regard the work of the PPRI Weeds Division can be seen as driving growth through innovation. It may not be directly creating new products, but through its research, the Division improves the overall national scientific competence as well as skills of individuals.

What is found is that conducting research in any form is an economically valuable activity. It not only increases opportunities for new innovation and progress but also supports the development of human and institutional capital (Donovan, 2011). The literature supports the idea of conducting research for the sake of creating economic opportunities. There is therefore support for carrying out work like researching biological control of invasive plants, as this leads to a creation of economic value that enhances economic growth. It must at this stage be noted that only an overview of the value created through conducting research is given in this study. There exists a plethora of additional literature that is dedicated to the purpose of illustrating that research is a valuable activity. The purpose of this section is only to provide a brief insight into this literature in support of conducting research in this context.

Having established the importance of research to an economy's sustained development, it is now necessary to consider how the valuation of such work can be conducted. This is needed to understand what aspects should be considered when carrying out a valuation exercise. The following sections outline the basic principles of valuation, and introduce some factors to be kept in mind.

2.2 Analysing the value of research

A useful place to begin a valuation exercise of any task or activity is to first gain an understanding of what is required in carrying out the task and the outcomes or consequences thereof. As Wessels *et al* (1998) reminded, when trying to determine an estimate of the value of any activity it is necessary to first accurately identify the benefits and costs related to that activity. Doing this allows a deeper understanding of the impact such work has in terms of the investment made and outcomes achieved. The same is therefore the case with research, and in this situation the research of the PPRI Weeds Division; the benefits and costs associated with the work must be identified in order to determine whether the work is of significant value or not (David *et al*, 1992). The costs should include any expense, in monetary or other terms, which are laid out or incurred in conducting the work. The benefits, on the other hand, include all positive outputs or products that are realised.

Considering the non-market nature of the work of the Weeds Division, it is useful to think about how the benefits of this work can be properly accounted for. This is because it is especially difficult to determine the value of something such as preserved biodiversity or environmental integrity, which are some of the major benefits provided through the Division's work (Scholes & Biggs, 2005). It is noted by Wiebe *et al* (2001) that a lack of information about the non-market inputs and outputs of research poses a problem in the estimation of the related benefits. It is therefore necessary to determine a way of accounting for most if not all these benefits when analysing the impact of research.

Taking into account the relatively recent change in political dispensation, as well as the impact of politics on investment spending (Killick, 2004), it is insightful to briefly consider the impact that these factors may impose on a research institute and the value it creates. In terms of the effect of a change in political leadership, Jayne and Jones (1997) specified that one must always keep in mind any policy changes or differences in infrastructure that may be evident at the time and place of the research. It is necessary to do this since such changes could lead to a skewed estimation of benefits of the research. This is because structural change can result in a change in the usefulness and applicability of the work that in turn can lead to a biased conclusion regarding the value that it holds. Regarding the impact of politics on investment spending, Pinto and Pinto (2007) stated that it is important to remember that projects are planned and implemented under a certain political context and different areas may be given different levels of priority to align potentially conflicting objectives into a balanced agenda. Hollingsworth (2000) extended this by noting that understanding the various objectives that broadly dominate the political context is essential to making a well informed decision on which a project should be chosen. In terms of economic decision making and value assessment, Gittinger (1995) suggested that the more difficult it is to identify and value these various objectives, the less formal the project analysis method employed will be. What is evident from this literature is that political context and related objectives have an important influence on the type of decisions made and endeavours supported (Pinto & Pinto, 2007). This in turn has an effect on the sort of activities considered valuable, and to what degree this value extends. In terms of the Weeds Division, an appreciation of the political context surrounding environmental management and economic development is useful for understanding the investment decisions that have been made to date and those that are likely

to pervade in the future. This appreciation should shed light on why until now there has been limited support for biocontrol research, and how best this type of research could be promoted to increase support in the future.

In the following two subsections, the various costs and benefits that could arise through research work are further explored. This is done to help in the identification of relevant costs and benefits that arise through the Weeds Division's work.

2.2.1 Analysing the costs of research

As noted earlier, when conducting a valuation exercise it is important to get an accurate estimation of all the costs involved in a project. This should include all activities related to the work that impose a cost, directly or indirectly, on the economy (Wessels *et al*, 1998 and Reed *et al*, 2012). In this case, the project or work under consideration is the research of the PPRI Weeds Division, and as such, all costs involved in carrying out this research must be included and considered as part of the analysis.

Examining some of the specific aspects that need to be taken into account when valuing research, Wander *et al* (2004) and Deloitte (2011) listed a number of possible costs to keep in mind. These include:

- The cost of researcher's salaries,
- The cost of field work including items such as transportation,
- The opportunity cost of not doing research on some other topic,
- The environmental costs imposed by the research in, for example, the collection of data,
- The potential effect that the new research could have on other sectors of the economy if adopted, for example, the cost of changing production techniques in terms of job losses and capital expenses,
- Infrastructural costs associated with carrying out the research and
- The cost of implementing the research, for example, the cost of extension programmes.

These are all costs that need to be considered when conducting a valuation of the work of the Weeds Division. Further, it is also possible that there are other costs that must be added to the analysis that have yet to be identified. These will have to be accounted for accordingly.

2.2.2 Analysing the benefits of research

The study now moves to understand the range of benefits that might accrue as a result of research. It must be noted that many of the benefits set out in this section have already been mentioned in section 2.1, but are repeated here for the sake of continuity of argument.

To begin with, Salter and Martin (2001) noted that doing research provides numerous benefits to the economy and society. This was supported by Vang *et al* (2007), who found that research institutes have become one of the major drivers of economic growth. Again the literature provides substantial support for conducting research. This point was expressly asserted by Vink (2000), who recorded that current literature provides strong economic evidence in support of conducting research. It is explained that through researching a particular topic or area, technological change is fostered resulting in improved techniques of production and resource usage. This in turn leads to a decrease in the cost and effort required to complete a task thereby releasing some resources for use elsewhere. What is seen is an improvement in cost efficiency and productivity, which Wiebe *et al* (2001) stated as the main task for any research; identifying a technique that maximises productivity using limited resources thereby allowing for improved efficiency of economic activities.

Overall, the main benefits of conducting research were found to be increased productivity and cost efficiency (Ramaila *et al*, 2011). The improvements in productivity and cost efficiency are fuelled by technological change and improved resource usage (Salter & Martin, 2001), which are both dependent on research, extension and human capital development (Vang *et al,* 2007). Improved cost efficiency and productivity are therefore two of the major benefits that should be considered when analysing the impact of the PPRI Weeds Division. If the work of the Institute produces either or both of these then already there would be significant support for conducting such work.

Having considered the main benefits of improved cost efficiency and productivity, it is now useful to consider some of the other benefits that result from doing research. Studies such as those conducted by Martin *et al* (1996), Ashiem and Coenen (2005), Vang *et al* (2007) and Cohen *et al* (2002) identified a range of benefits that arise though conducting publicly funded research. These go beyond the production of new information and include:

- An increase in the quantity of useful knowledge available (Martin *et al,* 1996),

- The training of researchers who can continue into a wide range of fields after receiving a solid grounding in the scientific method (Vang *et al,* 2007),

- The formulation of improved scientific instruments and methodologies, which can be used to analyse various situations (Cohen *et al,* 2002),

- The creation of networks of people and information that stimulates interaction between different groups and fosters improved policy and decision making (Hollingsworth, 2000),

- The improvement in problem solving capacities of society as a whole (Cohen *et al,* 2002) and

- The formation of firms that take advantage of new knowledge to provide an innovative good or service (Martin *et al,* 1996).

Related to this last point, Ashiem and Coenen (2005) remarked that the creation of new business opportunities through research leads to increases in employment opportunities and the scope for further improvements in knowledge. Supporting this point, Vang *et al* (2007) noted a trend amongst firms located in areas with high levels of research and development to be more successful than firms outside these areas. This points to a direct positive benefit for businesses where the ability to innovate and remain successful is supported by proximity to innovating industries. Cohen *et al* (2002) reinforced this trend, noting, however, that there often exists a delay of up to 20 years between research being conducted and the benefits of the work becoming manifest. This last point is one that should be kept in mind when considering the work of the Weeds Division, since a return on investment into biocontrol is often only expected to occur within such a time frame (Henderson, 2013).

Thus far, two major aspects of research valuation have been investigated, these being the associated costs and benefits of the work and their influence on value. Identifying these aspects helps in the decision of which method of valuation is most suitable, since a better understanding has been achieved of the relevant and available information. In a valuation analysis, it is essential to include all costs that are incurred as a result of the work, whether direct or indirect, and should also include an investigation into any externalities that may arise (Salter & Martin, 2001). The same can be said of the benefits. These aspects must therefore be considered in terms of the valuation of the work of the PPRI Weeds Research Division. Failure to properly explore these areas will result in an analysis that is incomplete and does not fully convey the value of the work done. It is now appropriate to explore the idea of research spillovers and the influence these have on value (Akcigit *et al*, 2014).

2.3 Research Spillovers

The role of spillovers in the Weeds Division research framework is important to consider since these can have a significant influence on the value of the Division's work. The following section briefly examines a few of the impacts associated with research spillovers, as well as why investigating these is worthwhile.

Evenson (2001) considered the idea of spillover as referring to a situation where research conducted in one area is applied to another. Such variation in area could refer to differences in geographical location or field of research. Depending on the nature of the two areas and the specific research conducted these differences can promote or hinder the application of research conducted elsewhere (Dumont & Meeusen, 2000). Research spillovers are therefore broadly considered as externalities that can either impose a positive or negative value.

With regards the usefulness of spillover information, Gray and Malla (2007) suggested that having a research framework that promotes the use of spillover information from different research bodies makes it possible to increase productivity. This increase in productivity is due to an increase in the pool of knowledge used in producing the goods in question. New ways of producing the goods in a more cost effective manner can be identified and subsequently

implemented, thereby increasing productivity without paying for it. Moving to the agricultural sector, Bantilan *et al* (2003) stated that it is important for agricultural research institutes to harness and apply research spillovers. Research often targets specific conditions or environments and can therefore be applied to similar conditions elsewhere in the world. For example, groundnut varieties developed for India have successfully been introduced and cultivated in Swaziland, Malawi and Rwanda. What was noticed is that by developing good spillover capturing mechanisms; an organisation can decrease the cost of developing new technologies (Dumont & Meeusen, 2000). It is therefore important to investigate the ability of the Weeds Division to adopt spillover knowledge. This will indicate its effectiveness as a research body in terms of the improvement of practices based on knowledge learnt in other sectors or locations.

Research spillovers are taken as important drivers of growth that allow for improved productivity without increased cost. By having well-developed mechanisms to adopt spillover information, the PPRI Weeds Division can improve its research output without an increase in costs, making it a more efficient and cost effective research organisation (Gray & Malla, 2007). For example, the identification of control agents by foreign biological control research authorities could be used to decrease costs in identifying suitable control agents for local conditions. Alternatively, work done by the Division could be adopted by similar institutes elsewhere in the world, decreasing their cost of research.

Thus far, the chapter has considered the value of conducting research and aspects to consider when valuing such work. The literature has shown that there is strong economic support for carrying out research since doing so leads to improvements in cost efficiency and productivity of activities (Ramaila *et al*, 2011). It has also been found that high levels of research have positive spin offs for firms, which are able to create new economic opportunities by using the increase in available knowledge (Martin *et al,* 1996). Research institutes are supported as integral to the development of human capital and scientific methodologies as well as increases in the availability of useful knowledge (Vang *et al,* 2007). These three factors all support economic growth and are therefore of extreme value to any society. Improvements in knowledge and scientific method also support improved decision-making and policy formation (Hollingsworth, 2000). These factors both lead to an improved socio-economic

environment that takes better heed of prevailing conditions and its people. By supporting the work of such institutes, a state will benefit from improved capacity functioning as well as increased economic performance (Vink, 2000).

2.4 Impact of Agricultural Research in Southern Africa

Having investigated the research arena at a broad scale, some consideration is now given to the agricultural research that has been conducted in South and Southern Africa. Papers that have examined the economic impact of this work are considered to provide a sound picture of the local research valuation context. A number of useful pointers are taken from these works to guide the valuation of the ARC PPRI Weeds Research Division. Whilst these papers provided good insight and direction for this study, none have dealt with all of the same issues that have arisen here.

Regarding the value of agricultural research, and specifically the work of the ARC, Thirtle *et al* (1998), conducted an analysis of the economic impact of the Agricultural Research Council (ARC). Their study concluded that the rate of return to research conducted by the Council was high, meaning that users of this information experienced improvements in their production performance. The return to investment in research was calculated as between 60% and 65%. Considering this, and that the Weeds Division is a unit of the ARC, it could be expected that a positive rate of return on the work of the Division exists. Khatri *et al* (1996) remarked that the majority of benefits realised through domestic agricultural research are concentrated in the field crop and horticultural sectors. Since the PPRI Weeds Research Division could be regarded as falling within the horticultural sector, due to its research into plant control, the literature therefore further supports the Division as producing a range of positive benefits for the South African economy.

In terms of the effect of agricultural research on consumers, Wiebe *et al* (2001) found that too little investment into agricultural research has a negative impact on food prices, productivity growth and food security. This is because increases in agricultural output are unable to keep pace with increasing demand for food. The consequence is an undersupply of

food that causes prices to rise and food resources to be unevenly distributed. Ramaila *et al* (2011) backed this idea with the finding that South African research and extension services act as a constraint on agricultural productivity due to their limited nature. This points to a need for well-structured and directed research and extension. Although the work of the Weeds Division does not directly impact on food production or security, it does illustrate how research impacts on prices. This is an important aspect to consider with regards to IAP management as cost is becoming a more significant issue and therefore research to decrease cost is increasingly relevant. Relating to productivity improvements through research, Khatri *et al* (1996) used a profit function approach to obtain data on sources of productivity change in domestic agriculture. When this is combined with Vink's (2000) work in deriving the marginal internal rate of return realised through extension services, strong support for conducting publicly funded research emerges. The value of conducting research for the sake of improved productivity and cost efficiency is therefore promoted, again providing an indication that the work of the Weeds Division is valuable.

Despite the usefulness of agricultural research, Jayne *et al* (1994) found that research had little impact on the smallholder sector of Zimbabwean agriculture. In comparison, Wiebe *et al* (2001) found that the Zimbabwean commercial sector experienced a rate of return on investment into research of around 40%. From this it was concluded that the disparity was due to the poor availability of infrastructure in the smallholder sector, and that in order for research to have a significant impact on agriculture the complementary investment into infrastructure, both physical and institutional, needs to be in place. If this is not the case then input, output and credit markets are unlikely to function efficiently and certain sectors will be unable to properly implement the new technologies made available through research (Wiebe *et al,* 2001). Again, this finding relates to the usefulness of agricultural research, pointing to the need for well-developed infrastructure and implementation procedures. In terms of the work of the PPRI Weeds Division, it could be concluded that research into biological control of invasive plants should be accompanied by mechanisms that can effectively implement the work. Should these mechanisms not exist, or be poorly developed, then the research becomes less useful.

It was noted by Thirtle *et al* (1998) that South Africa has effective mechanisms for capturing research or technological spillovers that may arise from foreign sources in the agricultural sector. Liebenberg and Pardey (2011) noted that the incorporation of research spillovers into agricultural practices has been a central feature of South African agricultural research policy for overcoming various production problems. The ability of the Weeds Division to incorporate these spillovers, and convey them to the biocontrol community, is therefore highlighted as an area of importance.

Thus far, it has been established that investment into research is economically valuable. The literature supports doing this kind of work for a number of reasons, provided above (Wiebe *et al,* 2001, Ramaila *et al*, 2011 and Vang *et al,* 2007), and finds it economically beneficial to invest in such activities to improve productivity and cost efficiency. Looking further, the value of developing strong spillover capturing mechanisms was been noted by Bantilan *et al* (2003) as important for any institution. This is useful for keeping pace with trends in the global arena and ensuring the use of research is maximised. The South African agricultural research sector has also been examined to establish what the local context is in terms of research use and valuation. The literature showed that agricultural research in South Africa leads to improved productivity and cost efficiency (Thirtle *et al,* 1998) and is therefore of high value. Well-developed mechanisms to capture and implement this research, however, are essential. With insufficient infrastructure and support, the usefulness of research decreases as people either do not have access to the material or do not know how or have the ability to implement the research.

In terms of valuing the work of the PPRI Weeds Research Division, the need to first properly identify all costs and benefits related to the work has repeatedly been highlighted. It is important to consider how the Institute captures and incorporates spillover research from external organisations in order to decrease the cost of carrying out their own work. In conjunction with this, it will be useful to consider the use of PPRI research by external organisations, as this will give an indication of the total usefulness of their work beyond the borders of South Africa. In the context of agricultural research in South Africa, it would appear from the available literature that such work is generally of high value and that a similar conclusion can be drawn for the PPRI Weeds Division.

Now the study moves to investigate various methods of economic valuation that are available. This is done to gain a full understanding of the different options that exist for valuing the work of the Weeds Division.

2.5 Analysing Economic Value

In the sections that follow, various methods of identifying and measuring economic value are investigated. This is needed to determine which method is most suitable for conducting the assessment of the PPRI Weeds Division. The study moves to investigate a variety of methods that can be used when carrying out an economic valuation. Specific attention is given to methods that are used for the valuation of non-market goods.

2.5.1 Methods of analysis

There is a variety of ways to complete an analysis of the economic impact of research. The following portion of the chapter provides a review of a number of these methods. To begin with, the three broad methods of econometric studies, surveys and case studies suggested by Salter and Martin (2001) are considered. *Ex ante* and *ex post* analysis options are then investigated, as described by Evenson (2001). The economic surplus (ES) method is then reviewed, focussing on papers by Hassan and Shideed (2003) and Wander *et al* (2004). Lastly, the total factor productivity (TFP) method is explored (Kiani *et al*, 2008). These methods are given as examples of ways in which economic valuations have been conducted to date, and inform the choice of method for the valuation of the Weeds Division's work.

In deciding the approach to take when conducting an economic valuation, a choice exists between three broad methods of analysis. These were identified by Salter and Martin (2001) as econometric studies, which attempt to make economic measurements using mathematics and statistics (Gujarati & Porter, 2009); surveys, which make use of insights of users and producers of information or technology to draw economic conclusions (Fowler, 2009); and case studies, which combine econometrics and surveys to conduct economic analysis (Freeman, 1984). Each of these approaches are briefly investigated here, and their relevance to this study of the Weeds Division considered.

According to Salter and Martin (2001), econometric studies try to model a situation based on large-scale patterns that can be identified by producing an aggregated picture of the relation between samples. Gujarati and Porter (2009) stated that econometrics is essentially a means of economic measurement, where mathematics, statistics and economic theory converge to explain economic phenomena. Wander *et al* (2004) maintained that econometric modelling could be used to estimate the marginal productivity of research. To do this, the production function, cost function and total factor productivity are used to estimate the change in productivity that results from an investment into research. By using such an approach, one is able to estimate the rate of return to research. The results, however, can be misleading as they often involve unrealistic assumptions about the nature of innovation and change (Verspagen, 1993). Nelson (1998) noted that it is difficult to trace properly the benefits of research throughout the innovation and commercialisation process, therefore the use of assumptions is made, which can result in misleading findings.

Salter and Martin (2001) listed the second broad model of economic valuation as the use of surveys. Fowler (2009) stated that surveys could be used to analyse the extent to which research is a source of innovation by asking pertinent questions of the users and compilers of the research. This allows the answers to be gained as to how different groups use this information. Surveys are however limited by bias that may exist amongst respondents based on their affiliation with the research and their knowledge of other sectors (Arundel *et al,* 1995).

The last methodological approach noted by Salter and Martin (2001) are case studies. These seem to be the best tool for analysing the source of specific technologies and their innovation process (Brewer & Hunter, 2006). Case studies use a combined approach by drawing on support from both econometric studies and surveys (Freeman, 1984). This allows for better estimation of the rate of return to research. The use of an econometric model overcomes many of the limitations of surveys, such as the problem of biased respondents, while the use of a survey allows for a less misleading model than is generated by a purely econometric schema. Using a survey also results in the need for fewer assumptions regarding the nature of innovation, since information regarding this can be collected from respondents (Yin, 2003).

In the case of the PPRI Weeds Division, the use of a case study appears to be the most appropriate option for conducting an economic valuation. Such a study would include some basic econometric modelling, alongside the use of survey information. The econometric modelling could be comprised of a cost efficiency analysis, as suggested by Gittinger (1995), while a review of available literature and data, combined with researcher interaction, could form the basis of a survey (Yin, 2003 and Nesser, 2013).

Having investigated the three broad approaches to economic valuation as set out by Salter and Martin (2001), it is now appropriate to explore a variety of specific methods that can be used when doing such a study. Through reviewing the following methods, it will be determined which is most suitable for completing this impact study on the ARC PPRI Weeds Research Division.

Looking first at the option of conducting an economic analysis either before or after an intervention, Evenson (2001) described two methods that can be pursued. The first is *ex ante* analysis, which takes place before the change is made. The second is *ex post* analysis, which is carried out only once the change has been made. These different forms of analysis can most effectively be used when combined, as they allow for an evaluation of the economic situation before and after a change has been made. Taking this approach ensures the conclusions drawn about the impact of research are more accurate (Oehmke *et al*, 1991). For the purpose of this study, a combined approach will be taken. *Ex ante* analysis will be used to consider the potential savings in control costs that will be realised if biological control is implemented in the future (Van Wilgen & De Lange, 2011). *Ex post* analysis on the other hand will be used to gain a deeper insight into savings already achieved through the use of biological control. In the instance of the *ex post* analysis, the case of biological control of invasive *Acacia* species will be considered (Impson *et al*, 2011).

Moving now to consider a mathematical approach to valuation, Hassan and Shideed (2003) used the economic surplus (ES) model to estimate the benefits of agricultural research into improvements in barley germplasm (Evenson, 2001). This model estimated the annual cost benefit flows of research into a specific commodity and required: data of average yield of new varieties, adoption path of new research, change in production cost due to adoption of new

variety, producer prices for commodity, and demand and supply elasticity's. The model is represented by equation (1).

$$\Delta ES = P_t Q_t k_t (1 + 0.5 k_t \varepsilon) \qquad (1)$$

Where P_t is the commodity price in year t, Q_t is quantity of commodity produced in year t, k_t is the supply shift in year t as a proportion of the initial price, and ε is supply price elasticity. K is measured as

$$k = \frac{g}{e A_t} \qquad (2)$$

Where g is the ratio of new to old output yields (yield improvement ratio), and A_t is the proportion of area that has been placed under the new variety (Hassan and Shideed, 2003).

This model gives the impact on production that a change in technology has by comparing the circumstances before and after the change has occurred. Essentially, the ES model is a form of *ex ante*, *ex post* analysis, where the situation both before and after the implementation of a technology or innovation is considered.

Wander *et al* (2004) employed the economic surplus method to measure the aggregate social benefits of agricultural research. The model measured the benefits of research by conducting an *ex ante* and *ex post* comparison for the adoption of a new technology. An estimate of the return on investment was obtained by determining the consumer and producer surpluses that arose due to a technological change based on prior research (Naylor, 2000). The process is carried out in two stages. Stage one estimates the gain achieved because of the adoption of the new technology. These gains can include increases in productivity, increases in quality or decreases in cost. The second stage is to determine the costs of generating and adopting the new technology. The difference between this gain and cost gives the net benefit of the adoption of the new technology: the economic surplus (ES) (Maredia *et al*, 2000). Boulding (1945), however, made the point that it is difficult to apply the ES model to any long run scenario due to the prevalence of uncertainty and its effects on the inferences drawn from the model. This point must therefore be kept in mind if the ES model is to be used. Considering

that the study of the Weeds Research Division takes a long term perspective, given the long-term nature of biological control (Cohen *et al*, 2002), it would appear that the ES method is not appropriate for this study.

Another approach to valuation was suggested by Kiani *et al* (2008), who used the Tornqvist-Theil index method for total factor productivity (TFP). This method was employed to estimate the relation between research and productivity in Pakistan's agricultural crop sector. The Tornqvist-Thiel index is a price or quantity index and type of total factor productivity measurement that uses a weighted average of prices in calculating TFP (Kiani *et al*, 2008). The total factor productivity method determines the level of output that is not accounted for by the inputs used in the production procedure (Comin, 2006). The TFP measure therefore provides an indication of how effectively and efficiently resources are being used in a process. Ali and Iqbal (2005) noted that TFP essentially produces a marker for the level of technology employed in the production process, and hence the amount of research that has been conducted in that area. Total factor productivity can therefore be used as a measure of the long run technological change that occurs. Crafts (1998) observed that technological change is closely related to the level of research conducted, since research drives such change. The higher the TFP measure, the more productively resources are being used and hence the higher the level of technology and research employed (Felipe, 2007). The results of Kiani *et al's* (2008) work on TFP indicated that investment into research significantly increases productivity. Although this method is particularly useful for considering the effect of research, it is, however, a price index, and as such is not particularly useful for the study at hand. Since the work of the PPRI Weeds Division produces non-market public goods, it is necessary to employ a method that can account for these non-market benefits. It is therefore necessary now to consider options for non-market valuation in greater depth. The section that follows provides a review of various non-market valuation techniques to determine the appropriate method for this study.

2.6 Non-market methods of analysis

Thus far, the methods discussed have been mainly relevant to research that has a market value. The following section reviews various mainstream approaches to non-market valuation, specifically looking for a method that is suitable to the case of the Weeds Division. The total economic value (TEV) approach used by Turpie and Heydenrych (2000) is first examined. Ulimwengu and Sanyal's (2011) discussion on willingness to pay (WTP) is then investigated, briefly considering both direct and indirect models with stated or revealed preferences. An assessment of the contingent valuation method (CVM) as described by Loomis *et al* (1996) is then given. Gittinger's (1995) cost efficiency analysis is studied as an option for valuation that is suitable for the comparison of two techniques used to achieve the same task. Lastly, a brief input by Andres (2009) concerning the number of publications produced by an institute is taken into account. The section ends with a brief overview of the methods considered throughout the chapter, as well as identification of the method to be used in this study.

2.6.1 Total economic value

In assessing the economic value of the fynbos biome, Turpie and Heydenrych (2000) organised the value created through its existence into the various components of total economic value (TEV). Under this analysis, total economic value was divided into the four following categories or types of value (Naylor, 2000):

- Use value: understood to reflect the value individuals place on direct use of a natural resource. For example the value of using a pristine area to hike (Naylor, 2000),

- Non-use value: described as the value that individuals place on resources they will never use. For example, the value of knowing the Cape Fold Mountains are free of invaders, even though you will never go there.
  - A component of non-use value is that of bequest value, or the value that individuals place on the preservation of a resource for use by future generations (Champ *et al*, 2003).

- Indirect use value: the value placed on ecosystem services that provide useful outputs to humans. For example the value of air purification carried out by plants (Turpie & Heydenrych, 2000) and

- Option value: the value individuals place on a resource they may use in the future, but that they are not using currently. For example, the value of having the option of visiting a pristine wilderness area (Turpie & Heydenrych, 2000).

The work of the Weeds Division could produce any of these forms of value, depending on the aspect and person in question. Using this method would therefore require an in-depth investigation into the various users and specific impacts of the work.

2.6.2 Willingness to pay

An alternative option for non-market valuation is to use the willingness to pay approach (WTP) to determine the value individuals place on public goods. Mishra (2012) noted that willingness to pay for the conservation and availability of public goods is a suitable means of conducting a valuation of such activities. The higher the willingness to pay for a good, the more that good is valued. Willingness to pay is therefore a method that should be investigated in the context of the ARC PPRI Weeds Division.

Ulimwengu and Sanyal (2011) stated that to value a non-market good, it is necessary to determine an estimate of willingness to pay (WTP) for that good, although as Naylor (2000) noted, this often proves challenging. An estimate of WTP can be determined by investigating individual's behaviour, responses to surveys or people's willingness to pay for related goods. Various methods are available for analysing economic value using a WTP analysis of people's preferences. These can broadly be categorised as either direct or indirect methods that identify revealed or stated preferences of individuals (Smith, 1993). Each of the options mentioned are now briefly considered.

A direct stated preference is one that is determined using a survey or questionnaire, and is used in cases where the value an individual places on something is not directly observable (Haab & McConnell, 2002). For example, a survey could be used to illicit an individual's willingness to pay for the preservation of indigenous biodiversity. Cummings *et al* (1986) noted that the contingent valuation method (discussed later) is suitable for determining an individual's direct stated preferences. This method aims to determine the relative value of an

environment by asking respondents what price they would pay to prevent a change to, or preserve, the environment (Ulimwengu & Sanyal, 2011).

A direct revealed preference is one that is observable through an individual's actual choices. Based on the choices a person makes, it is possible to determine the value they place on various resources (Barde & Pearce, 1991). For example, in determining the value of the natural environment, the cost of an invasion on a farmer's livestock productivity can be determined. Naylor (2000) noted that market prices and simulated markets could be used in this regard.

Moving now to indirect models of valuation, Birol *et al* (2006) noted that an indirect stated preference model is used when a project has several options each with various attributes. This means indirect stated preferences are used when there is a project that can be completed in a variety of ways, with each having its own impacts (Holmes & Adamowicz, 2003). For example, the control of invasive alien plants could be posed to individuals as having various means of implementation. The first option is that only conventional control is used, creating 1000 jobs at a cost of R12 million. The second option is that only biological control is used, creating 100 jobs at a cost of R1 million. The third option is that a combination of conventional and biological control is used, creating 500 jobs at a cost of R5 million. The last option is that no control is done, with no job creation or immediate control costs. This is an example of conjoint analysis, which is similar to contingent valuation, except that it asks respondents to choose between various real world options as opposed to stating their willingness to pay for various options. Alternative methods that can be used for this type of analysis are choice experiments and contingent ranking (Champ *et al*, 2003). However, since the use of indirect stated preferences does not properly deal with the valuation of a particular research institute, as is needed in the case of the Weeds Research Division, these alternative measures are not discussed further.

The final category of benefit estimation involves the use of indirect revealed preference methods (Ulimwengu & Sanyal, 2011). Such methods draw on actual behaviour to infer the value that is placed on a certain resource. For example, the amount people are willing to pay for land that is infested by invasive alien plants, as compared to the price they will pay for

land that is free from invaders. This comparison allows for the relative value of invaded and uninvaded land to be determined, and hence an estimation can be made as to the impact of IAP invasions (Barde & Pearce, 1991). Methods that are used to determine indirect revealed preferences are the travel cost, hedonic property value (given in the example), hedonic wage value and avoidance expenditures (Tietenberg & Lewis, 2010). However, due to insufficient availability of local data, these options are not discussed further as they have been determined to be unsuitable for the case at hand.

2.6.3 Contingent valuation

Having considered the broad aspects of economic valuation using willingness to pay, a brief analysis of the contingent valuation model (CVM) is now given. The CVM has been a widely used technique of valuation in environmental economics (Hoyos & Mariel, 2010), and as such, could be considered as a means of valuing the work of the PPRI Weeds Division. The contingent valuation method (CVM) is a stated preference method that is used to determine the value of a good for which no value is directly observable. It achieves this by using a survey to determine a respondent's willingness to pay for the good in question (Carlsson & Martinsson, 2001). The CVM can be applied to a variety of situations for goods with option, existence, bequest and recreational values, and is ideal for the estimation of the value of environmental resources (Loomis *et al,* 1996). According to Loomis *et al* (1996), the CVM can be applied to estimate a person's willingness to pay to use or protect a particular natural resource or environment. This is done by creating a survey depicting a simulated market on which the respondents base their replies. Loomis *et al* (1996) noted that for any CVM survey to be effective it should be clear about the resource being valued, how the research is being financed, and what format the survey will take.

This method is, however, not without its shortcomings. For a start, Hoyos and Mariel (2010) remarked that the CVM is open to a number of critiques if not properly structured and conducted, and could result in misleading results due to bias amongst respondents. For example, Harrison (2001) stated that a survey presenting a respondent with two choices in a hypothetical situation is unlikely to elicit truthful responses from the individuals in question, since they have no incentive to behave truthfully or otherwise. The answer they give has no

real bearing on their situation and hence there is no reason for them to respond honestly. If the CVM were therefore to be used for this study, a survey would need to be developed that overcomes or accounts for the various biases that may arise. For example, it would be necessary to develop a survey that asks questions that require a response based on actual experience or knowledge, thereby circumventing the problem of hypothetical bias (discussed below). A total of five possible types of bias have been identified: strategic, information, starting point, hypothetical, and a discrepancy between willingness to pay and willingness to accept, which could skew the findings of the CVM.

- Strategic bias: Venkatachalam (2004) noted that this occurs when a respondent tries to influence a specific outcome through the answers they provide.

- Information bias: occurs when a respondent is required to value something they have little experience with (Venkatachalam, 2004).

- Starting point bias: described by Prince (1989) as arising when a respondent is asked to provide an answer based on a predetermined range of options. The range of possible options can affect the answers given.

- Hypothetical bias: occurs when a respondent is confronted with a hypothetical situation as opposed to an actual one (Champ *et al*, 2003). Under such circumstances, the respondent may provide answers that are ill-considered, since they have no bearing on the current situation.

- Discrepancy: Hanemann (1991) identified differences between the willingness to pay and willingness to accept measures of value. The tendency of respondents was to provide much higher values when asked their willingness to accept a loss, as compared to their willingness to pay for an improvement. People are less willing to pay for an improvement and require a higher payoff for a loss (Horowitz & McConnell, 2002).

Overall, Hoyos and Mariel (2010) stated that when using the contingent valuation method, it is necessary to develop a survey that eliminates or at least reduces possible biases to an acceptable level to ensure the findings are coherent. Harrison (2001), in concluding his analysis of the CVM guidelines presented by the National Oceanic and Atmospheric Administration (NOAA), stated that it is imperative for all researchers to be well informed about the limitations and design issues of the research they are conducting. With a proper

understanding of these issues, the researchers are better able to avoid bias and obtain more accurate findings in their work. If a survey is to be used as part of this economic study of the Weeds Division, it must be designed to take into consideration the various biases that have been mentioned.

The methods examined thus far have presented a variety of options for tackling the valuation of the PPRI Weeds Division. From the mathematical economic surplus (ES) approach suggested by Hassan and Shideed (2003), to the more non-market oriented approaches such as the CVM (Hoyos & Mariel, 2010), each method has its advantages and disadvantages. Despite these various options having been considered, a method that is appropriate for this study has yet to be found. A suitable method would be one that is simple and provides an indication of why biological control research is valuable when compared to conventional methods for invasive plant control. If the task of IAP control is taken as necessary (this is discussed in the next chapter), then the choice exists of how best to control invasive plants. This points the study to the issue of cost and cost efficiency as a basis of valuation. For this reason, Gittinger's (1995) approach of cost efficiency analysis is now considered.

2.6.4 Cost efficiency analysis

Gittinger (1995) noted that the cost efficiency method is useful in instances where a choice must be made between different technologies that could be used in a project. Cost efficiency analysis was also suggested by Worthington (2000) as suitable when it is difficult to determine or quantify benefits of a project. In the case of this study, the project would be that of IAP management, with the choice of technique being between conventional or biological methods. When choosing which technology to use in a project, Gittinger (1995) suggested the least cost approach, which bases the technology choice on the option that imposes the lowest cost. It would appear that the cost efficiency method would be suitable for this study. A simple cost comparison is sufficient to determine the most appropriate control method based on the cost efficiency of the various options. Gittinger (1995) maintained that while a tool such as cost efficiency analysis is a useful decision making aid for policy makers, it cannot provide the final evaluation of which option will prove best. The choice of technology to be used in

conducting an activity is embedded in a variety of circumstances and objectives (Adato *et al*, 2005). Decision makers need to take cognisance of these in order to make a balanced decision that will create the maximum benefit in the national interest. A useful insight therefore emerges for this study. While the use of an evaluation tool such as cost efficiency analysis improves the ability to make a well-informed decision or recommendation, the final decision is based on a number of other conditions as well. These conditions must be taken into consideration if a choice is to be made that maximises the net benefit of IAP control.

2.6.5 Researcher publications

As a last measure of value, Andres (2009) suggested that the number of author publications could be used as an indication of the productivity of a research institution. Toutkoushian *et al* (2002) remarked that considering this aspect of an institute's productivity provides sound insight into the value that the institute creates. As such, assessing the number of publications produced by a research institute could reflect its level of productivity. Considering this aspect of research productivity may prove useful when investigating the value of a research institute such as the PPRI Weeds Division. It will however not be a sufficient measure in itself, and would therefore need to be complemented by additional measures of value.

2.6 Synopsis

The aim of this chapter was to provide an overview of whether investment into research is valuable, and if so, how such value can be measured. The approach of a literature review was used to address these main topics, and provided insight into various methods of value analysis. The chapter began by investigating whether research is a valuable endeavour to pursue, in and of itself. An investigation into both international and local data was used to understand the value of agricultural research. From this analysis, it was determined that research plays an integral role in industrial development, human capital improvement, and cost saving (Wiebe *et al,* 2001, Donovan, 2011 and Vang *et al,* 2007). Investment into agricultural research was found to have a positive rate of return, and led to improvements in productivity when implemented (Thirtle *et al,* 1998). The concept of research spillovers was also considered, as these have been found to result in higher rates of return to research if

efficiently captured and implemented (Salter & Martin, 2001). The study then moved to consider how the value of research can be assessed. Various methods of valuation were considered in reference to this study of the PPRI Weeds Division (Salter & Martin, 2001, Hassan & Shideed, 2003 and Kiani *et al,* 2008). From this, it was determined that a method of non-market valuation was needed, since the work of the Division produces non-market public goods. Having investigated a range of non-market valuation techniques (Turpie & Heydenrych, 2000 and Tietenberg & Lewis, 2010), it was determined that Gittinger's (1995) cost efficiency analysis would appear to be the most appropriate method of valuing the work of the Weeds Division. A further analysis of the chosen method is given in the method section of this study.

The chapter that follows provides an overview of the problem of invasive alien plants (IAPs), specifically in the South African context. Means of IAP control are then investigated, with specific attention given to the role of biological control.

Thus far, the study has investigated whether investment into research is worthwhile, and how the value of such research can be determined. The analysis now moves to explore what invasive alien plants (IAPs) are and their impact on the economy and environment, and therefore assumes a more scientific nature. The aim of the chapter is to gain a full understanding of why IAPs are a problem for which a sustainable solution needs to be found. Establishing a good sense of this aspect will shed light on the value of the Weeds Research Division's work on biological control. Various papers that investigate the impact of IAPs are considered, including papers based on the South African context. The study then moves to highlight the management strategies available. These strategies include chemical, mechanical and biological methods of control (Working for Water, 2013). The specific role of biological control is then considered as a means of sustainable long-term IAP management. An investigation of this practical aspect of the study will determine whether biological control research is a viable option for IAP management. If biological control is found to be useful in IAP management, then determining the value of the related research by the Weeds Division is made easier.

3.1 What are Invasive Alien Plants?

Joubert (2009) described invasive alien species as organisms that have been introduced into an environment outside their natural habitat, and have been able to establish themselves and spread without human assistance. Most importantly, Strayer *et al* (2006) stated that these species have the potential to inflict harm on the invaded environment and economy. Invasive species can therefore be understood as organisms that have become established in an environment in which they are not endemic, with a potential to inflict damage on the native fauna, flora and economy. A major factor that aids an IAP invasion is that no natural predators exist for these species in the environment they are affecting (Joubert, 2009) and therefore no natural population balance is achieved as in a natural equilibrium. IAP populations are not

kept in check by naturally occurring predators and are therefore able to spread rapidly without the pressure of predation (Turpie, 2004).

Moving to understand invasive alien plants in particular, Turpie and Heydenrych (2000) noted that successful invasive alien plants (IAPs) are species that have established themselves in new environments and produce large amounts of seed at frequent intervals. IAPs gain a foothold either by exploiting available niches or taking advantage of disturbances in an environment (Hobbs, 2000). An available niche, for example, could be a lack of tree species in a largely shrub dominated area. A disturbance, on the other hand, could come from overgrazing, fire or clearing (Turpie & Heydenrych, 2000). In environments that have no available niches, or are not subject to disturbances, invasive plants struggle to establish. If an IAP is however able to become established in a new environment, the plant soon begins to produce seed that is easily dispersed over large areas. The ability to produce and distribute seeds over a large area enables invasive species to spread rapidly. The example of invasive *Acacia* species such as *Acacia longifolia* (long-leaved wattle) and *Acacia salinga* (Port Jackson willow) (Impson *et al*, 2011), which are dealt with in the data chapter, provide a useful illustration of this invasive characteristic. It was noted by Impson *et al* (2011) that invasive Australian *Acacia's* produce vast amounts of very resistant seed that does well in poor soils and is easily dispersed. Many other invasive plant species display similar characteristics, for example, *Chromolaena odorata* (Zachariades *et al,* 2011) and *Campuloclinium macrocephalum* (pompom weed) (McConnachie *et al*, 2011).

Establishing this will aid in determining whether investment into biological control research is valuable. If IAPs pose a risk or cost to the South African economy and environment then the need for control strategies is supported. Based on this need, a comparison can then be made between the various available control strategies to determine the role of each. Since this study is focussed on biological control research, the role of biocontrol will be the centre of the analysis.

3.2 Why invasive alien plants are a problem

Van Wilgen *et al* (2001) noted that since the early 1600s, thousands of varieties of foreign plant species have been introduced to South Africa. These were introduced for varying purposes including timber, food production, land stabilisation, hedging and ornamental usage (Joubert, 2009). Some of the introduced species are unable to persist under South African conditions, however, some have been naturalised and are able to survive and at times thrive without tending. Van Wilgen *et al* (2001) stated that since invasive alien plants (IAPs) can survive and reproduce under local conditions, they are also able to spread without human intervention. Of the plant species that have been naturalised, about 340 have become established and are now considered as invasive in South Africa (Moran *et al*, 2011). Using various mapping techniques, such as SAPIA (Southern African Plant Invaders Atlas) (Henderson, 2011) and subsequent modelling of collected data, it has been estimated that over 10 million hectares of pristine South African environment has been invaded and affected by IAPs (Le Maitre *et al*, 2000). This is equivalent to 8.2% of total land area of South Africa (121 909 000 ha) (SouthAfrica.info, 2014). The scale of the IAP problem is therefore large and requires a well-structured management strategy that takes into consideration the capacity of IAPs to spread without human assistance.

The findings of Van Wilgen *et al* (2001) supported the need for a comprehensive IAP management strategy due to the large extent of invasions. Van Wilgen *et al* (2001) additionally stated that the impacts of these invasions are not fully understood but indications are that the total costs imposed on the local economy and environment are substantial. Turpie and Heydenrych (2000) estimated that approximately 29% of land in the Western Cape has been invaded by IAPs, one of the most invaded provinces, and provides an example of the extent of the problem. When considering these two statistics in conjunction with the graphic example displaying the trend of range expansion of *Campuloclinium macrocephalum* (Figures 3.1 & 3.2) given by Henderson (2011), the increasing extent of IAP invasions over time is evident. Should no management strategy be instituted for these invasions then invading plants will continue to spread until they have reached the limit of their potential distribution.
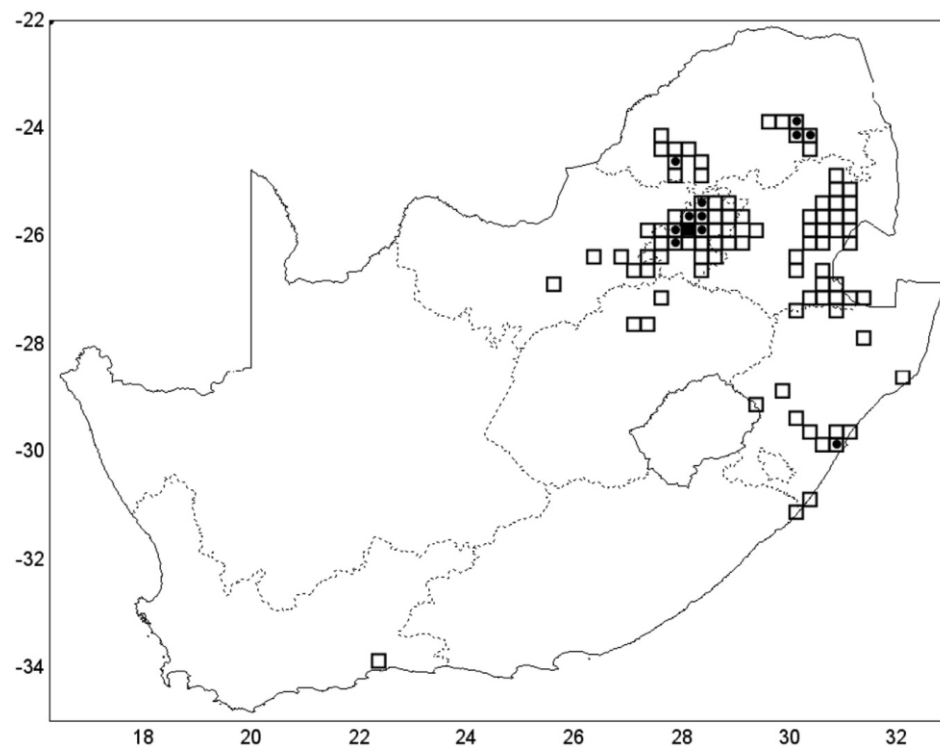
Figure 3.1: History of spread of *Campuloclinium macrocephalum*: 1960s (■), 1970s-1990s (●),

2000s (□).

(Source: Henderson, 2011).
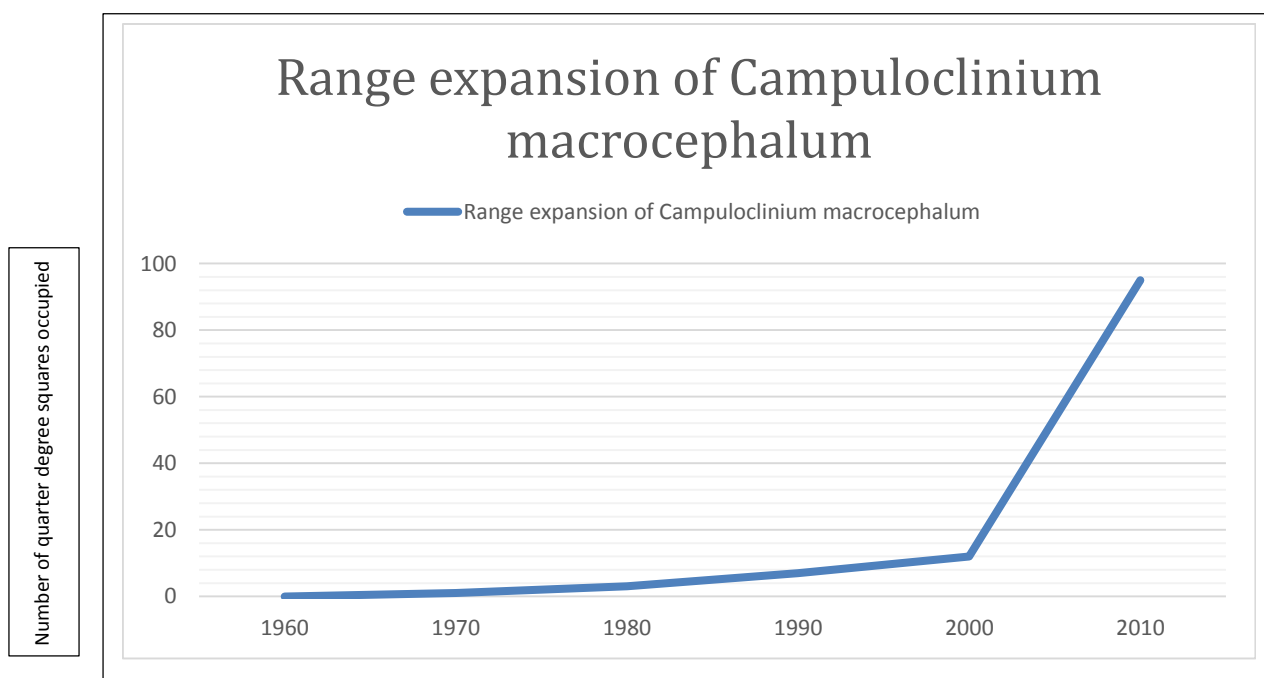
Figure 3.2: Range expansion in quarter-degree squares (QDS) occupied by *Campuloclinium macrocephalum* from 1960 to 2010.
(Source: Henderson, 2011).

From these diagrams, it is evident that the extent of IAP invasions expand over time. Having become established, the invasive plant displays a trend of rapid range expansion. The need for control strategies especially implemented at an early stage of the plants establishment is therefore promoted, as this allows for curtailment of the invasion before the plant is able to take a foothold in its full potential range (Henderson, 2011). As the range of the invasion increases, the related cost of control increases, since additional effort is required to clear the plant from new environments (Van Wilgen *et al,* 2001).

A useful tool for considering the spread of IAPs is the Southern African Plant Invader Atlas (SAPIA) (Henderson, 2011). This mapping system is suitable for investigating the extent and spread rates of invasive plants throughout the country and has been used to provide the graphic examples above. The map has been compiled using roadside surveys of the density of invader species, and has been mapped onto quarter degree squares across the country (Van Wilgen *et al*, 2001). The data from the atlas, however, is limited by financial and time resources leading to difficulties in accurately tracking the spread of IAPs and the effects of control initiatives. The effects of various control strategies on the spread of invading species is also not illustrated by this system. It remains, however, a useful tool for understanding the rate of spread of invasive plants across the country, and displays an increasing trend of invasion over time (Henderson, 2011).

Regarding the ability of IAPs to invade an environment, Hobbs (2000) stated that the rate of spread and level of distribution and density of IAPs could be alarming, and lead to full-scale invasions in a short period. This is not just a phenomenon facing South Africa, the spread of alien species is becoming an increasing problem throughout the world, as factors such as globalisation and world trade aid their distribution to environments in which they are non-native (Crowl *et al*, 2008 and Mack, 2000). Naylor (2000) noted that the spread of species across the globe poses serious risks to native fauna and flora, as well as economic potential, and mitigates the development of effective control strategies that are minimally harmful to the environment and impose the least cost on the economy. Focussing on alien plant invasions, Hobbs (2000) reported that the presence of an invasive plant species imposes negative changes on the nature of an ecosystem's functioning and integrity. Considering that South Africa has a remarkable range of biodiversity, the risks posed by IAPs are large since

many indigenous species are at risk due to the spread of these plants and the subsequent change in ecosystem dynamics (Van Wilgen *et al,* 2001).

The literature therefore supports the development of control strategies for invasive alien plants (Naylor, 2000). This need for effective control strategies was echoed by Joubert (2009), who stated that the clearing of invasive plants helps in the stabilisation of catchments, the prevention or minimisation of erosion, the prevention of a loss of biodiversity and a decrease in fire hazard. In the local context, Turpie and Heydenrych (2000) argued that from an ecological point of view there is a need for increased control of IAPs in South Africa. This is because it has taken a number of decades for society to realise the negative impacts that IAPs impose on various biomes, and in that time they have been allowed to gain a strong presence in these environments. The example of figures 3.1 and 3.2 (Henderson, 2011) provide an illustration of the spread of IAPs over time. Van Wilgen and De Lange (2011) noted that the increased need for control, however, is juxtaposed with the range of pressing socio-economic needs of the nation, which motivate for management strategies that are of minimum cost.

In relation to the control of IAPs, Turpie (2004) noted that the main challenge with invasive management is that mitigating the development of control strategies generally requires a quantitative assessment of why an intervention should be made. Support for IAP control needs to be shown as the financially sensible thing to do. In this regard, Van Wilgen *et al* (2001) stated that no standard system exists for the objective quantification of the impacts IAPs pose on the environment. This is because of the difficulties associated with the valuation of environmental goods and services, especially those that are of a non-market public good nature (Parker, 1999). Promoting the development of IAP management strategies therefore needs to make use of non-market valuation techniques to quantify both the damage that IAPs impose, and the relative value of available control methods. The quantification of the impact of IAPs and the value of the control strategy employed are further dealt with in the data chapter. A number of impact studies on IAPs are considered next to provide an outline of the extent of the financial impact these species impose. This does not amount to a total assessment of the problem, as qualitative aspects will also need to be considered in order to provide a full picture of the impacts (Economic Services Unit, 2013).

The first economic studies of the impacts of invasive alien plants on the South Africa economy were conducted in the mid 1990's. The focus of these was mainly on the effects of IAP invasions on the availability of water resources, and showed that at current levels of invasion IAPs could be using as much as 6.7% of the national annual runoff (Versfeld *et al*, 1998). These studies demonstrated that the removal or control of IAPs is an economically good choice, with the protection of water alone being worth the investment in such activities.

Despite these early attempts, very few studies have investigated the costs that IAPs impose on an economy and therefore little precise knowledge exists about how exactly this problem could best be managed (Van Wilgen *et al*, 2001). In a recent paper that investigated the costs and benefits of biological control of IAPs in South Africa, Van Wilgen and De Lange (2011) stated that IAPs are posing an ever-greater cost on the domestic economy and environment. This cost is comprised of a number of different factors including, but not limited to, negative impacts on biodiversity, ecosystem services, environmental integrity, and human environments. This is exacerbated by the increasing speed of globalisation and global trade, which has enabled the spread either intentionally or otherwise of more species across the planet (Perrings *et al*, 2010). What has been seen is that not only is the chance of new invasions increasing, but also is the need for more effective and forward looking control strategies. These strategies should ideally be developed using a combination of biological, chemical and mechanical control methods (Turpie, 2004).

Although some studies have investigated the range of impacts IAPs impose on an environment, Van Wilgen and De Lange (2011) noted that it is still difficult to calculate a comprehensive figure for the cost imposed on an economy. Indications, however, are that the costs are substantial, and easily warrant the control of these species (Van Wilgen *et al,* 2001). Examples of some studies that have attempted to identify the costs imposed include: a study on the value of a hypothetical 4 km^2 fynbos ecosystem with and without IAP invasions (Higgins *et at,* 1997); the value of water lost through invasions by IAPs (Turpie & Heydenrych, 2000); the loss of stream flow due to the presence of Black wattles (De Wit *et al*, 2001); and the benefit cost ratio for the biocontrol of red water fern (Hill, 1999). These studies suggest that the cost of controlling IAPs is increasing over time, as is the cost that their presence imposes on the economy. This therefore motivates for the development of management

practices that are minimally harmful to the environment, effective in controlling target plants and are at lowest cost to the economy (Van Wilgen *et al*, 2001).

Table 3.1 represents a summation of some of the research that has been conducted to establish the effect of IAPs on the South African economy (Van Wilgen & De Lange, 2011). These studies focussed predominantly on the effects of IAPs on water availability (Van Wilgen *et al*, 1996, Van Wilgen *et al*, 1997 and Hosking & Du Preez, 1999), biodiversity (Turpie & Heydenrych, 2000 and De Lange & Van Wilgen, 2010) and impacts on the quality of grazing available to stock farmers (Wise *et al*, 2007 and Van Wilgen *et al*, 2008). Overall, indications are that the presence of IAPs cause substantial losses to the availability and quality of environmental resources and economic opportunities, which, in turn, have significant negative economic implications. Van Wilgen *et al* (1996) described one of the most notable impacts of invasions as being the cost of ensuring water supply, through either clearing IAPs from catchment areas or building new dams to compensate for the loss to IAPs. The cost of clearing invasive plants, however, was found to be only a fraction of the cost of constructing new dams (Van Wilgen *et al*, 1996). Another major impact was on the economic value of pristine areas as compared to invaded areas, with pristine areas being up to 16 times more economically valuable than those invaded (Higgins *et al*, 1997). This large variation in value is attributed to the economic importance of improved water management, wildflower harvesting, tourism and genetic biodiversity that is associated with pristine areas as compared to invaded areas. The message from these studies is overwhelmingly clear: the economic costs associated with allowing the invasion of pristine areas by IAPs far outweigh the economic savings achieved by ensuring these areas remain invader free.

In terms of the impact of IAPs on biodiversity, limited research has been conducted in this area, especially work that considers the cost of invasions on South African biodiversity (Van Wilgen & De Lange, 2011). This is largely due to the difficulties experienced when trying to quantify such an aspect of the economy: firstly, how does one place a value on a pubic good that is not tradable on the market, and secondly, how does one know the exact impacts of such an invasion on a system that is not yet fully understood (Mack, 2000). The ability to grasp the vast network of interactions and dependencies that occur in a natural environment is yet limited, therefore the ability to identify the range of impacts that an IAP invasion has on an

area's diversity is restricted to the basic level of scientific knowledge (McGeoch *et al*, 2002). This is a major reason in support of controlling plant invasions as there is still a substantial amount of research that needs to be conducted before a proper understanding of the full extent of species and their interactions is attained (Nesser, 2013). Mack (2000) remarked that in understanding this aspect of the environment, we are likely to find innumerable opportunities for improved economic performance in the future – not only in terms of the harvesting of indigenous species for use in medical sciences, but also about the necessity of strong biodiversity in ensuring long-term economic resilience to external influences.

From a legislative perspective, South Africa has developed specific regulations for the protection of riparian zones and biodiversity. These are the National Environmental Management Act (107/1998), and the National Environmental Management: Biodiversity Act (10/2004) (Department of Environmental Affairs, 1998 and Department of Environmental Affairs, 2004). This legislation centres on the preservation of the natural environment and biodiversity, with special emphasis on riparian zones for ensuring the continued provision of water resources. IAPs threaten riparian zones and, in fact, often specifically target them (Turpie & Heydenrych, 2000) as they are rich in nutrients and water and are often disturbed through flooding and human activity. According to Hobbs (2000), five of the country's most problematic IAP species target riparian zones, leaving little room for wastage and making wise water management practices imperative. Binns *et al* (2001) supported this by noting that the majority of water resources in South Africa have already been allocated or used in some way. The need for an effective IAP management strategy is therefore promoted as supporting the preservation of South Africa's limited water resources. In this regard, the legislation mentioned above specifically speaks to the protection of riparian and other pristine zones from invasion by IAPs. A legal backing for the control of IAPs therefore exists (Department of Environmental Affairs, 2004).

Table 3.1: South African studies that have attempted to quantify the economic costs of environmental impacts arising from invasions by alien plants (R7 = about US$1). (Van Wilgen & De Lange, 2011).

Aspect of cost quantified	Magnitude	Source
Comparison of the cost of delivering water through either clearing invasive alien plants, or developing new bulk water supply schemes.	Clearing at 14% of the cost of water supply schemes (0.002 *vs* 0.012 US$ per m3, respectively)	Van Wilgen *et al*, 1996
Comparison of the value of a hypothetical 4 km^2 mountain fynbos ecosystem where alien plants were either controlled or allowed to invade. Valuation based on water production, wildflower harvest, hiker visitation, ecotourism, endemic species and genetic storage.	Value was US$3 million (with no management of alien plants), and US$50 million (with effective management of alien plants). This could be achieved by spending a fraction of total value on clearing programmes.	Higgins *et al*, 1997
Comparison of costs associated with the construction of dams either whose catchment areas were allowed to become invaded, or alternately where invasive alien plant control projects were established. .	Delivery of water from schemes with and without the management of alien plants was R0.57 and R0.59 per kl, respectively, indicating the cost-effective nature of alien plant management.	Van Wilgen *et al,* 1997
Estimation of the economic benefit that would arise from control of invasive alien plants in invaded watersheds.	Clearing yields benefit:cost ratios of between 6:1 and 12:1.	Hosking & Du Preez, 1999
Estimation of losses in ecosystem services (wildflower harvest, recreational use, and water supply) due to invasion of fynbos ecosystems on the Agulhas Plain.	Losses amount to 2.3–9.7 US$/ha for wildflowers, 1–8.3 US$/ha for recreational use, and 163 US$/ha for water.	Turpie & Heydenrych, 2000
Comparison of the costs and benefits derived at a national level from *Acacia mearnsii* De Wild. (Mimosaceae), a plantation tree species that is also invasive.	Cultivation without control yielded a benefit:cost ratio of 0.4:1. Continued cultivation with clearing, or with a combination of clearing and biological control of seeds yielded benefit:cost ratios between 2.4:1 and 7.5:1.	De Wit *et al*, 2001
Estimation of the extent of invasion, impacts of these invasions on water resources, and estimated costs to clear four South African catchments, both at current levels, and potential future levels of invasion.	Between 2–54% of the four catchments had been invaded to some degree. The corresponding reductions in the natural river flows attributed to these invasions were between 7.2–22.1%. If the invasions were not controlled they could potentially occupy between 51–77% of the catchments, and flow reductions would increase to between 22.3–95.5%. The estimated cost of the control programmes to prevent these losses under current invasions would be between 4.1–13.2 million US$. Should the catchments become fully invaded before control operations were started, costs would rise to between 11.1–278.0 million US$.	Le Maitre *et al*, 2002
Assessment of the *Working for Water* Programme's economic feasibility of the Eastern Cape Province.	Assessment suggested that clearing of invasive alien plants was not efficient (benefit:cost ratio <1). Changes in key assumptions, for example a lower discount rate, would result in a positive benefit:cost ratio.	Hosking & Du Preez, 2004
Assessment of the effects of invasion by *Parthenium hysterophorus* L. (Asteraceae) on commercial stock farmers in Mpumalanga.	Spread without control led to declines in returns to small-scale farmers of between 26–41%, while commercial farmer's annual total economic returns would decline by between 38 818–60 957 US$.	Wise *et al*, 2007
Estimation of the current and potential future impact of invasive alien plants on water, grazing and biodiversity in five terrestrial biomes in South Africa.	Current estimated losses were R5.8 billion for water, R300 million for grazing, and R400 million for other biodiversity-related values	Van Wilgen *et al,* 2008 and De Lange & Van Wilgen, 2010

3.3 Controlling Invasive Alien Plants

The Conservation of Agricultural Resources Act (Department of Agriculture, Forestry and Fisheries, 1983) stipulates that it is the duty and legal responsibility of land users to control and prevent the spread of category one, two and three invasive plant species. These three categories include the various invasive alien plants according to their level of invasiveness and threat posed to the local environment. The South African National Biodiversity Institute (SANBI, 2014) described each category and the related responsibility of landowners concerning the presence of these plants on a property. Category one plants such as the Long-leaved wattle (*Acacia longifolia*) and Madeira vine (*Anredera cordifolia*) are considered as highly invasive, with control by land users compulsory by law. Category two plants such as Sisal (*Agave sisalana*) and Port Jackson (*Acacia Salinga)* are invasive and require permits to be possessed, bred, sold or moved. Permission is granted based on the area in question, with no permits being granted for riparian zones. Category three plants such as Bailey's wattle (*Acacia baileyana*) and Loquat (*Eriobotrya japonica*) are regulated by activity, with permission granted on an individual basis. No permits are however granted for these plants within any riparian zone (SANBI, 2014). A legal framework therefore exits that places the responsibility of controlling invasive plants on landowners. This, however, is often difficult to enforce and therefore the need for a comprehensive national management strategy still exists (Klein *et al*, 2011).

For an invasive alien plant (IAP) to invade an environment there needs to either be a vacant niche such as woody invaders (*Acacia)* exploit in generally shrubby fynbos, or the environment needs to in some way be disturbed or imbalanced to create an opportunity for the weeds to exploit such as a recently cleared area, or a lack of naturally occurring predator species (Turpie & Heydenrych, 2000). Without some sort of initial disturbance like mechanical clearing, overgrazing or erosion, IAPs generally struggle to become properly established. Hobbs (2000), however, remarked that once having established, the presence of the IAP itself causes further disturbance to an environment therefore creating further opportunity for new or more IAPs to invade. Having entered an environment, IAPs initiate a cycle of environmental degradation and biodiversity loss. This is exacerbated by a lack of naturally occurring predator species that would otherwise aid in regulating the plants population and spread (Joubert,

2009). Hill and Greathead (2000) suggested that to combat such opportunistic organisms requires a solution that restores a natural balance to the environment and does not cause further disturbance and therefore creates further opportunity for invasion.

Le Maitre *et al* (2002) argued that in light of the available literature regarding the range of negative impacts and rate of spread of IAPs, a failure to clear and effectively control these species now will result in an exponential increase in the clearing and control costs in the future. With an already limited budget (Plant Protection Research Institute, 2012) and a range of other pressing social needs, a solution needs to be found that is able to deal with this problem at least cost and high effectiveness. Regarding the need for ongoing management, Joubert (2009) stated that should the control of IAPs in South Africa be delayed or hampered, the cost of control in the next 20 years could be expected to increase to over 20 times that currently experienced.

Three methods of IAP control exist: mechanical, chemical and biological (Joubert, 2009). Each of these methods are discussed with conclusions as to the most appropriate method, or combination of methods, in the following section.

3.3.1 Mechanical

Mechanical methods of IAP control involve the felling, clearing or burning of invaded areas with labour using machinery and hand tools. This form of control is labour intensive as it requires a large number of operators who continuously remove invading species from affected areas (Working for Water, 2013). Mechanical control can, however, often be damaging to the environment and produce more opportunities for invasion. Joubert (2009) noted that when clearing weed species the surrounding vegetation and soil is disturbed, creating an opportunity for more invasive seeds to germinate and therefore cause higher levels of infestation.

In discussion of the various means of IAP control available, Hill (1999) stated that mechanical methods of control are generally suitable for smaller areas due to its labour intensive nature. Even when used only in small areas this form of IAP management still requires concerted

effort to achieve success. It is also noted that once an area has been cleared using this technique the opportunity for plants to re-establish themselves is high, meaning that new invasions soon arise therefore requiring renewed clearing efforts.

3.3.2 Chemical

Joubert (2009) described the chemical control of IAPs as entailing the application of herbicides to invading plants or invaded areas. This form of control is therefore labour intensive as an entire area must be meticulously treated with the chosen poison. Well-trained personnel are required to administer chemicals to ensure safety in application (Hill, 1999). Unintended environmental pollution or degradation may arise using this method since some herbicides are not specific to the target IAP and may therefore negatively affect indigenous species. As Hill (1999) observed, the use of chemical control methods poses the danger associated with chemical spray drift, which can be extremely harmful to surrounding vegetation and waterways.

From a cost perspective, chemical methods of IAP management often prove to be highly expensive, especially in the long run (Joubert, 2009). Hill (1999) observed that chemical control imposes a high cost due to the need for follow-up treatments in sprayed areas to ensure that invaders do not re-establish and therefore cause new or continued invasions. There is also the possibility that some plants, especially smaller ones, will be missed during application, leaving them to continue growing and therefore act as a nucleus from where the IAP can spread (Turpie & Heydenrych, 2000).

3.3.3 Biological

The biological control of invasive alien plants involves the introduction of plant-feeding insects, mites or plant pathogens that naturally target the IAP in question to reduce the target weeds' fitness and invasiveness, therefore leading to declining populations and rate of spread (Van Wilgen & De Lange, 2011). Joubert (2009: 219) stated that "Biological control as a means of containing an invasive alien infestation is simple in theory: Go back to the invaders native country and find organisms that curb its growth and reproduction". The control of plants can be achieved using insects, parasites, fungus or bacteria that naturally predate on the target

plant (Hill & Greathead, 2000). Depending on the effectiveness of biological agents, this form of IAP control can have either complete, partial or no impact on the target species.

There are some wider concerns that need to be taken into account when considering biological control as a management tool for IAPs. To begin with there are the moral and ecological considerations of introducing another foreign species into an already invaded environment (White & Newton Cross, 2000). Concerns exist as to the long-term impact that such an introduction might have on the local environment (Van Wilgen *et al,* 2001). This concern is addressed below, with evidence illustrating that there have been no negative long-term side effects experienced as a result of the release of control agents (Joubert, 2009). A further concern is who is responsible for the final decision of whether to release an agent for control or not (White & Newton Cross, 2000). This issue is also dealt with below through reference given to relevant regulation.

Van Wilgen and De Lange (2011) stated that to ensure the introduction of a biological control agent does not have unexpected and damaging impacts on the indigenous flora and fauna, stringent host specificity testing must first be conducted. Moran *et al* (2005) described host specificity as the characteristic of a control agent to target only the invasive plant in question, therefore, posing no threat of feeding or attack on indigenous or other important species such as commercial crops. This is done to understand properly the full range of impacts that an agent would have on the native environment. To achieve this understanding requires thorough research and testing, and must be carried out under strict quarantine conditions to prevent an agent escaping before its host specificity has been established (Louda *et al*, 2003). As Joubert (2009) noted, the concern exists that the introduction of a biological control agent into an already destabilised environment could lead to a further invasion, which has additional detrimental impacts on the native flora or fauna. If, for example, an agent is introduced that does not specifically target the host plant, then it is possible that the agent could attack certain indigenous species and cause problems equivalent to or greater than those experienced as a result of the target plant. Concerning this, Louda *et al* (2003) noted that target or host specificity is one of the main areas of focus when identifying suitable control agents. Researchers must conduct stringent host specificity testing on all potential

control agents to ensure that they will only target the invader in question and not any indigenous species.

In the South African context, Klein *et al* (2011) stated that host specificity tests are conducted to comply with the strict requirements imposed by the Department of Agriculture, Forestry and Fisheries (DAFF) and the Department of Environmental Affairs (DEA), which regulate the importation, quarantine and release of foreign species for control purposes. Sandham *et al* (2010) remarked that these regulations have been developed to ensure only agents that are proven safe for release and that will cause minimal damage to indigenous species are allowed for use in the control of invasive alien plants. Locally, it is the responsibility of the ARC PPRI Weeds Research Division to conduct this host specificity testing (Plant Protection Research Institute, 2005). It was noted by Joubert (2009) that, to date, no unanticipated effects of biological control agents have been experienced in South Africa for the control of IAPs. This, however, is not the case with generalist species that have been introduced by other groups in the past, such as fish and mammals. Klein (2011) asserted that the fastidiousness of weed biocontrol researchers in South Africa has ensured released agents are strictly host specific.

An important assumption is that investment into biological control research and the work of the PPRI Weeds Research Division are considered synonymous in this study. This is because, in the South African context, all but one of the released IAP control agents were researched and funded by the PPRI Weeds Division (Klein, 2014). The single exception was that of *Lantana camara*, which was funded for some time by the Department of Agriculture (Klein, 2014) in the 1960's. Despite this one exception, additional research has been conducted by the Weeds Division into *Lantana* since then. This is because the research funded by the Department of Agriculture did not result in control of this invasive plant species. Klein (2014) noted that additional research into biological control of IAPs has been conducted through various academic institutions, mainly Rhodes University and the University of Cape Town, but these projects were all funded by the PPRI. As such, any reference to biological control research in the South African context refers to work done by the ARC PPRI Weeds Division. This assumption is then extended to allow a comparison to be drawn between biological control research, and biological control. Since the majority of costs associated with biological control are incurred through the preceding research (Van Wilgen & De Lange, 2011), this study

assumes that biological control represents a good proxy for biological control research. Although there will be variations between actual expenditures between the two, the relation between them is so close that for the purpose of analysis, the use of such a proxy does not materially impact on the outcome of the study.

3.4 What is the best option for IAP control?

Van Wilgen and De Lange (2011) observed that the debate about which control option is the most appropriate in the South African context is one that involves a trade-off between the creation of a large number of jobs though conventional control methods, versus the long term cost saving achieved through implementation of biological control research.

In a country with an unemployment rate of 25.5% (Statistics South Africa. 2014), the argument for the use of public works programmes such as Working for Water (WfW) to create large amounts of employment opportunities is strong (McQueen *et al*, 2001). More than 20 000 jobs per annum have been created through WfW since 1995 (Working for Water, 2013). The majority of these have been targeted at the marginalised and individuals with low skill levels. The programme has social upliftment as one of its main drivers, with targets of creating 18 000 jobs per year for previously unemployed people (60% for women and 20% for youth) and compulsory training for all staff including HIV/AIDS awareness. Employment creation is therefore at the centre of this initiative, which is the possible reason for the continued political and financial support it has received.

In terms of the value realised through public works programmes, Subbarao *et al* (1997) remarked that investment into these types of projects is a useful tool for carrying out countercyclical interventions. It was further noted that such programmes have been used throughout the world with success in aiding consumption smoothing for poor households. Adato *et al* (2005) supported this with the finding that participation in public works programmes has a positive effect on labour and employment, particularly in terms of opportunities for women. Subbarao *et al* (1997), however, concluded that while such interventions are useful as temporary safety nets for the social challenges of unemployment

and poverty, these should not be viewed as permanent or sustainable solutions to said issues. McCord (2006) provided endorsement for this view by noting that available literature suggests that investment into public works programmes does not present long-term solutions for transformative social protection. Rather, this sort of investment is useful for smoothing consumption of poor households during cyclical or structural dips.

Regarding the strategy for IAP management, Moran *et al* (2005) stated that biological control is an important tool for dealing with IAP invasions, especially considering the long-term threat that these pose to the South African environment, economy and society. Although the Working for Water (WfW) programme is able to use conventional methods to create a large number of employment opportunities in the current period, these jobs could largely prove unsustainable in the long run given the many other social, environmental and economic constraints experienced in this country (Zimmermann *et al*, 2004). If funding were to be shifted away from the WfW programme, the invasive nature of IAPs would soon undo all the work that has already been put into gaining control over these species (Van Wilgen *et al,* 2001). With no funding, salaries cannot be paid meaning people cannot be employed and IAPs cannot be cleared. Invasive plants would therefore be left without natural predators or other forms of control, and could quickly spread and infest large tracts of pristine land. Under such circumstances, the investment that has been made to date into conventional control of IAPs would be pointless.

Noting that clearing of IAPs is worthwhile simply to protect and conserve water resources (Van Wilgen *et al*, 2001), the argument for the use of biological control as a means of eradicating these species is promoted. This is because this form of control is cheaper than conventional methods and is more sustainable in the long run (Moran *et al*, 2005). Biological control was identified by Van Wilgen *et al* (2001) as the most cost effective means of controlling the spread of IAPs. This is because the costs involved in biological control are limited to the initial research and quarantine of potential agents, followed by the subsequent rearing, release and monitoring costs involved when a suitable agent is found (Plant Protection Research Institute, 2006). Once an agent has been established, no further costs are incurred except for possible further releases in areas where the agents cannot themselves gain access. For the rest, the agents spread by themselves and are able to respond to new

invasions of the target by increasing their own population through natural processes in response to the increased availability of food. This is compared to the cost of conventional control, which is constant over time (Joubert, 2009) and is associated with the cost of labour, training, transport, equipment and chemicals. These costs will continue to be incurred for as long as control is necessary, with costs rising over time. Considering that total eradication of IAPs is highly unlikely (Hill, 1999) and that new invasions are likely to arise through the spread of species across the globe, the cost of conventional control will increase in the future in response to increased need for management. Hobbs (2000) suggested that, over time, progressively more state funding would need to be dedicated to IAP control to prevent massive costs incurred through a loss of biodiversity, land degradation, water management and agricultural activities. White and Newton Cross (2000) stated that it is important to realise the use of biological control does not eliminate control costs, rather it significantly reduces these costs.

Joubert (2009) remarked that, as a nation, it is necessary to develop a variety of strategies for the control of invasive species. Amongst these strategies, biological control is given a high ranking as a management tool that is constantly prepared to deal with the spread of an IAP at minimal cost, and should therefore be a primary focus of the national control strategy (Van Wilgen & De Lange, 2011). What this suggests is that although biological methods should be used as the primary tool for IAP control, conventional methods should still form an integral part of the management approach. This is especially necessary in cases where no safe biological agents can be found or where biological methods are not 100% effective (White & Newton Cross, 2000). In such instances, the use of conventional control will need to be adopted to ensure that these species are not allowed to establish themselves as large-scale invaders. This suggests that while biological methods should become an increasing area of focus for IAP control, there remains an important role for conventional methods, but that this should be confined to species for which biocontrol is not possible. As such, it is still possible to reap the benefits of employment creation through the WfW programme, however, these will be more limited in nature and directed towards those species that cannot be controlled biologically.

This chapter has described invasive alien plants (IAPs) as non-native species of plant that enter an environment and take advantage of an available niche or disturbance to establish and spread, causing a loss of biodiversity and hampering the provision of ecosystem services (Joubert, 2009). The need for a well-designed management strategy that takes into consideration the persistent nature of these species has been highlighted as important for ensuring that the integrity of indigenous ecosystems is preserved (Hill, 1999). Biological control was found to be an integral component of any IAP management strategy (Higgins *et al,* 2001). It is only through the use of biological control that the issue of IAP management can be sustainably addressed (Turpie, 2004). The importance of biological control research into IAP management is therefore highlighted as essential in ensuring the control of invasive plants is done at minimum cost (Van Wilgen & De Lange, 2011). The role of the PPRI Weeds Research Division has therefore been promoted as vital in the pursuit of a national IAP management strategy. Since the Division is the main organisation granted authority to research biological control opportunities for IAPs in South Africa (Plant Protection Research Institute, 2005), the value of the Unit's work is accentuated.

The following chapter outlines the method used when analysing the economic value of the work of the Weeds Research Division. Chapter five then provides data for this analysis, illustrating why investment into biological control research should be promoted.

CHAPTER 4

METHOD

Thus far, it has been established that conducting research is an economically valuable activity that promotes economic development through human capital creation and cost saving (Wiebe *et al,* 2001). The work produced by the ARC PPRI Weeds Research Division has been classified as a non-market public good (Plant Protection Research Institute, 2005). Various means of economic assessment have therefore been investigated with a focus on methods of non-market valuation of public goods (Turpie & Heydenrych, 2000 and Ulimwengu & Sanyal, 2011). Furthermore, it has been established that invasive alien plants pose a threat to the South African economy and environment, creating a need for the development of sustainable control strategies (Hill, 1999). Biological control was noted as an important component of this strategy, requiring dedicated research and investment (Van Wilgen & De Lange, 2011). The work of the ARC PPRI Weeds Research Division is therefore supported from a theoretical perspective as integral to ensuring the long-term success and sustainability of IAP control (Turpie, 2004). The study now moves to determine a method for assessing the work of the Weeds Division. This method draws on the literature analysis provided in chapter's two and three and aims to establish a means of displaying the value of the work of the Division. First, an overview is given of the Monitoring and Evaluation framework that is used to structure the analysis (Economic Services Unit, 2013). Using this framework, the specific method to be employed in this study is identified. An explanation is given of why this method has been chosen as opposed to other available methods. The chapter ends by framing the inclusion of data into the method.

4.1 The Monitoring and Evaluation framework

The Monitoring and Evaluation (M&E) framework developed by the ARC Economic Services Unit (2013) has been used in this study to guide the valuation process of the PPRI Weeds Research Division. This framework sets guidelines for impact analysis of research and development work conducted through ARC projects. Since the Weeds Division is one of the projects run by the ARC, it is appropriate that this framework is used in the investigation of

the Division's value to the South African economy. To date, the framework has yet to be applied to the work of the Division.

According to the M&E framework, performance evaluation of ARC projects should be established using four broad steps (Economic Services Unit, 2013). The first is a description of the project, outlining the relevant activities, outputs, outcomes and impacts that arise through the work (Njuki *et al*, 2009). Step two establishes a set of indicators that are used to describe the activities, outputs, outcomes and impacts determined in step one. These are considered both before the project commences, as well as once it is in operation (Njuki *et al*, 2009). Step three involves the development of an evaluation model. This is done by determining the measurement tools that will be used, defining the target group or area and selecting the appropriate sample size (Anandajayasekeram *et al*, 2004). The final step is to establish a benchmark or baseline, which Soule (2008) noted is used to understand the socio-economic and environmental situation before the project has been initiated. It is understood that these steps are not mutually exclusive nor are they necessarily sequential (Economic Services Unit, 2013). Having established these basic procedures, the monitoring and evaluation of the project commences. This involves the collection and comprehension of data on identified indicators. By using this framework it is possible to understand the value of the work of the ARC in a standardised and easily interpreted manner. Each step is discussed below, with an explanation of how it is dealt with in the context of this study.

Stage one of the M&E framework entails defining the project in terms of its key area or issue that it addresses (Economic Services Unit, 2013). Njuki *et al* (2009) noted that describing a project in this way aids in problem analysis and identification of potential interventions. It is useful to be reminded that in this study, the project under consideration is the PPRI Weeds Research Division's biological control research.

Stage two of the M&E framework involves the determination of appropriate indicators. Indicators are chosen to help recognise any change that has occurred as a result of the project (Economic Services Unit, 2013). These help to determine what progress has been made through the work, especially in terms of the intended objectives, and should be clearly defined, identifiable and measurable (Njuki *et al*, 2009). In assessing the economic value of

any work, Soule (2008) remarked that it is necessary to establish a set of indicators that will be used to complete the analysis. In addition to this, the means of measuring these indicators needs to be established (International Fund and Agricultural Development, 2002). For the purposes of this study, the following indicators have been chosen to assist in the economic valuation of the PPRIs biocontrol research: cost efficiency, long-term sustainability, employment creation and skills development, and advances in scientific knowledge or capability. These indicators are considered in comparison with those for conventional control to gain an understanding of the relative value of the work of the Division. This comparison is made on the basis that biological control represents a good proxy for biological control research (Klein, 2014), as described in chapter three. The selection of indicators was made on the basis that each one provides an insight into the relative impact of biological and conventional control measures. It has been assumed that these indicators are comparable for biological and conventional control as both methods achieve the same end of IAP management. The assessment of the chosen indicators is conducted on a simple yes/no basis and is made using the literature covered in this study. Table 4.1 provides a summary of the indicators used in the study and illustrates how these indicators are measured. The table is completed in chapter five. Based on the findings of these indicators, an assessment of biological control research will be made.

Stage three of the M&E framework entails the definition of the method to be used to conduct the impact analysis (Economic Services Unit, 2013). Anandajayasekeram *et al* (2004) stated that the chosen method should be appropriate for the intervention under scrutiny and should take into consideration the availability and ability of staff, data and time involved in the project.

Table 4.1: Set of indicators and means of assessment (example).

Indicator	Means of assessment	Assessment
Cost efficiency	Does the work minimise cost of solving problem?	Yes/no
Long term sustainability	Will the work result in a sustainable solution to the problem?	
Employment creation and skills development	What is the extent and nature of employment creation opportunities produced?	
Advance in scientific knowledge or capability	Does the work produce advances in national scientific knowledge database and capabilities?	

The study now moves to consider the method that has been used in assessing the value of the PPRI Weeds Research Division. This is followed by a description of stage four of the M&E framework, where the benchmark used in the analysis is described.

4.2 Cost efficiency analysis

Due to the nature of the Weeds Research Division's work, which predominantly produces non-market type goods, it is difficult to come to an accurate valuation of the Institute's research without making a number of assumptions and estimates (Scholes & Biggs, 2005). Using available techniques of valuation, it is not currently possible to estimate the value of an indigenous forest free of invaders (Riera *et al*, 2012). The value of the Division's biological control research in terms of biodiversity and environmental protection is likewise not ascertainable using market analysis, as it is not currently possible to place a market value on such items. The method outlined here, therefore, represents an attempt to conduct a non-market valuation exercise as accurately as possible using limited data and the simplest means

available. The chosen method draws on some empirical aspects but predominantly assumes a descriptive nature. This is not the ideal option for displaying the value of the Weeds Division's biological control research but has been selected due to limitations in empirical data availability and reliability (Nesser, 2013). The study as a whole therefore assumes a more descriptive than empirical nature, drawing on a wide variety of literature surrounding the value of research and biological control to illustrate the value of the PPRI Weeds Research Division.

Given the non-market public good nature of the work of the PPRI Weeds Division (Plant Protection Research Institute, 2005), it has been decided to use the cost-efficiency analysis as suggested by Gittinger (1995) and Layard and Glaister (2012). This approach will be used to consider the cost efficiency of using either biological or conventional means of IAP control. Inferences can then be drawn about the value of the research conducted by the PPRI Weeds Division once biological control has been considered from a cost efficiency perspective. Hanley and Spash (1993) noted that the use of this method allows for a comparison and choice to be made between two or more techniques available for completing the same task. This choice is based on the technique that achieves the desired result at lowest cost (Arrow *et al*, 1996). Since both biological and conventional methods of control achieve the same end of IAP management, and because cost efficiency relates directly to economic value (Layard & Glaister, 2012), it can be concluded that this method will identify the most suitable form of IAP control. Having identified this, the value of the Weeds Division can be considered. This approach to valuation was briefly introduced in chapter two under the section 2.6 (*Non-market methods of analysis*). The method is now explained in further detail, including a description of why it has been found appropriate for this study and how it is implemented.

Considering first what is meant by cost efficiency analysis, Gittinger (1995) described this method as a means of identifying the appropriate technique to implement a project. The choice is made by considering the relative cost of each technique, with the decision based on the option that imposes lowest cost while maximising benefits (Layard & Glaister, 2012). An additional view was presented by Donahue (1980) who described economic cost analysis as the promotion of the best allocation of resources in an economy. Clearly, the concept of cost

analysis is not a new one, and has been used for decades to aid in economic and political decision-making (Arrow *et al*, 1996).

Since the basis for the valuation analysis of the Weeds Division is efficiency, it is important to ensure that a sound understanding of this concept is first established. As a broad principle, the idea of economic efficiency was described by Barr (2004) as a situation where productivity is maximised using limited resources. An important feature that is highlighted is that production, or a project, is carried out at the lowest possible unit cost (O'Sullivan & Sheffrin, 2006). The link between efficiency and cost saving is therefore highlighted, with efficient choices being those that are least expensive. An economic saving, therefore, is made as unnecessary spending is avoided whilst realising the desired outcome (Edquist, 2001).

From a decision-making perspective, Donahue (1980) noted that the understanding of economic efficiency is dependent on the goals and interests involved in a project. Since any project is situated in a specific context, there exists a variety of political, social, economic and environmental objectives and preferences that place pressure on the choice of implementation technique. Depending on the various weights assigned to each of these objectives, the choice of project will be affected in differing ways (Adato *et al*, 2005). The understanding of economic efficiency is therefore affected by the context in which a decision must be made. Killick (2004) remarked that, depending on this context, there would be a tendency to choose one project over another without as much weight given to pure economic reasoning. It is therefore imperative that decision makers are aware of these demands, and make choices that are cognisant of both these and economic thought. In the context of the PPRI Weeds Division, there are two main considerations that need to be remembered. These are the issues of job creation through conventional control (Working for Water, 2013) versus cost saving through biological control (Van Wilgen & De Lange, 2011). Each of these aspects persuades decision makers to opt for either conventional on biological control, and must therefore be considered when making a valuation assessment of either option. These considerations have been mentioned in chapter three and are again dealt with in chapters five and six.

Moving now to the actual motivation behind choosing this method for valuing the work of the ARC PPRI Weeds Research Division, two main reasons can be provided. Firstly, Van Wilgen *et al* (2001) remarked that it is inherently difficult to fully understand and quantify the benefits of biological control and the associated research. A method is therefore needed that will allow a valuation assessment to be conducted using limited empirical data regarding the benefits of biological control research. Secondly, due to the available choice between conventional and biological methods of IAP control, a method is needed that will help determine the relative value of each of these management strategies. In identifying which of these strategies is most optimal, a conclusion can then be drawn as to the value of the biological control research conducted by the Weeds Division. This may seem like a somewhat roundabout method of valuing the work of the Institute but, due to the nature of the work and limitations in data and available valuation techniques, this method has been selected as the most appropriate for illustrating why investment into the work of the Weeds Division is worthwhile. By showing that biological control is an economically efficient choice for IAP management, the supporting research will in turn be illustrated as valuable. This method of valuation will not come to a precise figure on the value of the research work but will provide an indication of whether the work is worth investing in. For some decision makers this may present a problem because of their desire for cut and dried financial figures. In the context of the PPRI Weeds Research Division's work, however, the available non-market valuation methods are yet unable to provide such figures (Riera *et al*, 2012). Instead, a descriptive approach must be pursued to illustrate why and in what ways this work is valuable. The following paragraphs provide additional reasoning for taking this descriptive cost analysis approach and explain how the method is used to display the value of the Weeds Division.

The approach of comparing the relative cost of conventional and biological control methods was chosen because this was taken as an indicator of the value of biological control research. As Hanley and Spash (1993) noted when referring to the use of cost efficiency analysis in general, if biological control is found to be more economically efficient than conventional control then the research conducted by the Weeds Division is supported as economically valuable. This is because no biological control initiatives would be possible without the associated research carried out by the Division. The value of biological control can therefore be taken as a proxy for the value of biological control research. The use of a proxy is made

because of the limitations in available empirical data concerning biological control research. Reasoning for the treatment of biological control and the associated research as analogous (Klein, 2014) was provided in chapter three.

The cost efficiency approach is further deemed suitable because both conventional and biological control measures result in the same outcome of IAP management (Dlamini, 2014), which was established in chapter three as essential for supporting the nations long-term growth potential (Turpie & Heydenrych, 2000 and Joubert, 2009). The control of IAPs can be taken as the major benefit of the work and therefore considered as equal for both techniques of control. Using the cost efficiency approach allows a valuation exercise to be conducted using limited data on the benefits of each technique because the benefits of both techniques are considered the same. Instead, the method focusses on the relative cost of each technique as the decision making aid. The cost efficiency approach therefore allows a choice to be made as to the optimal method, or technology, to be used in achieving IAP control (Worthington, 2000). Zimmermann *et al* (2004) specifically observed that the choice of IAP management strategy should be based on the relative costs of biological and conventional control methods. This was recommended due to the necessity of wise spending of limited state funds. By determining the relative cost efficiency of biological control, it is possible to illustrate the value of biological control research. This value is demonstrated through the economy-wide savings that are achieved, both currently and in the long run, by implementing the work of the PPRI Weeds Division.

In terms of how the cost efficiency analysis has actually been carried out, a simple cost comparison has been made between biological and conventional control measures. This comparison is displayed in table 4.2 where the budgeted expenses on biological research and implementation are compared with the budgeted expense on conventional control. These figures have been collected from the Working for Water (WfW) programme (Wannenburgh, 2014) and the Agricultural Research Council (Agricultural Research Council, 2014). It must again be remembered that the expenditure on biological control and comparison to conventional control has been undertaken to illustrate the relative value of biological control. Based on the finding of this analysis, conclusions are then drawn as to the value of investment into biological control research, the real crux of the study. These deductions can be made

based on the assumption that the benefits of either mode of control are the same. As such, the method of control that imposes the lowest cost will be taken as the most economically efficient.

Through the cost analysis, it will be noticed that the data for expenditures on biological control are significantly lower than on conventional measures. This reflects the current IAP control-spending paradigm and is not an initial indication of the relative success of either management technique. In order to discover the actual value of biological control research, it will be necessary to compare the data on current spending patterns with the success rates that have been achieved to date. These success rates have been determined by examining records for the number of IAP species that have been successfully controlled using biological and conventional methods respectively. These figures have been collected from the available literature (Klein, 2011), and reflect any IAP species that has been brought under either complete or substantial control using the management technique in question. Having determined the success rates of both biological and conventional control methods, a descriptive analysis is then carried out to understand the relation between investment into each form of control and the associated effect on the targeted IAPs. This means that the level of investment into biological control research will be considered in relation to the number of IAP species brought under control using this method. The same approach is taken for investment into conventional control. In the case of biological control research, consideration is given to the total number of potential control agents that were initially investigated, the number of agents actually released, and the number of IAP species subsequently brought under control. This is done to account for the number of potential agents that were investigated and never released, released but never established or established but with negligible impact on IAP populations (Klein, 2011).

To aid in easy assessment of the value of the Weeds Division's work, the cost of biological control research as a percentage of total IAP management expenditure is calculated and compared to the percentage expenditure on conventional control. These figures will then be compared to the reported success rates of the two methods of control, to understand the relative success of investment into either of these management techniques (Rao *et al*, 2012). Given the limited quantitative data regarding the success of either control strategy

(Henderson, 2013), qualitative information regarding this aspect will be used to inform the overall understanding.

Table 4.2: Cost Efficiency Comparison between Biological and Conventional Invasive Alien Plant Control (example).

Year	Biological Research Budgeted Cost (x)	Biological Implementation Budgeted Cost (y)	Total Biological Budgeted Cost (x+y)	Conventional Budget Cost (z)	Total Control Budget Cost	Biological as % Total Cost	Biological Research as % Total Cost
2013							
2014							

The impact of the PPRI Weeds Division's work on the South African economy will now be easier to determine since a deeper insight will be been gained into which control method is the most cost effective. Analysing the extent of the Division's contribution to biological control research in the larger biological control initiative in South Africa will help illustrate the value of the Division's work. To accomplish this, data has been collected and collated that depicts the number of releases of biological control agents on target weed species and the institution of origin of the background research (Klein, 2011). A picture is then provided of the overall biological control sector in South Africa, and the role of the Weeds Division in this.

4.3 Additional aspects

In addition to the cost aspect, another factor briefly considered in this study is the number of research publications produced by the PPRI Weeds Division. Andres (2009) noted that this measure points to an institution's level of productivity. It was remarked by Toutkoushian *et al* (2002) that assessing the number of publications produced by a research institute reflects the level of productivity, and hence value, of the institute. This aspect is therefore considered in the case of the PPRI Weeds Division and is used as support for the Division's value (Price,

2014). The production of publications represents a small component of the overall analysis and is therefore only considered briefly.

To analyse publication productivity of the Weeds Division, data on the number of publications, presentations and other recognised forms of information dissemination have been collected and collated (Price, 2014). From this, a picture of the amount of information produced and made publically available through the research of the Division is gained. This is used to complement descriptive data on the contribution of the Division to the greater scientific endeavour in South Africa. Although a small point of consideration, investigating the research publication productivity aids in better understanding the complex value of the work carried out by the Division.

The use of both cost efficiency analysis and the number of researcher publications produced will provide a good quantitative analysis of the economic value produced by the Weeds Research Division. This quantitative data is supported by a range of qualitative data regarding the economic impact of biological control research. This approach is taken due to the limited availability of qualitative data concerning the impact of biological control research (Henderson, 2013). Qualitative data considered includes information on the effectiveness of biological, as opposed to conventional control (Van Wilgen & De Lange, 2011), the effect of IAP invasions on economic and environmental functioning (De Lange & Van Wilgen, 2010), and the expected long-term impact of the use of biological control (Pimental *et al,* 2001). The use of biological control research in the management of invasive *Acacia* species has also been included to aid in a well-rounded analysis of the work of the Division (Impson *et al*, 2011). Including this aspect allows for examples of Weeds Division work to be considered in the study and illustrates the varied success rates achieved through the implementation of biological control research.

An additional point of consideration given in this study is of the Weeds Division's ability to produce research that is responsive to the environment in which it is situated. As Vink (2000) noted, it is important to determine how the work of an institute such as the Weeds Research Division is adapting to the ever-changing economic environment. In order to remain relevant and valuable, it is necessary to ensure that an institute focuses its work in the direction of

issues that are pertinent to local economic conditions. This work should not only be driven by the present needs of the sector but should turn its attention to what will be relevant and required in years to come. Considering the ability of the Weeds Division to be forward looking in its research therefore offers an additional aspect to the value that the institute provides to the South African economy.

4.4 Benchmark

Having described the method that will be used in this study, the next step of the Monitoring and Evaluation framework is to establish the baseline of the analysis (Economic Services Unit, 2013). This is done to understand the conditions that prevail before an intervention and includes a description of the social, environmental, economic and political situation that prevails (Baker, 2000). Data comparisons and conclusions are then made against the benchmark to understand the impact or change that has arisen due to the implementation of the intervention.

The benchmark for biological control research is established using the extent of invasion and rates of spread, as well as environmental, social and economic impacts that prevail before an agent is released. This data is then compared to the same indicators once the agents have become established, to ascertain the nature of the impact experienced (Impson *et al*, 2011). Limited quantitative data exists in this regard (Henderson, 2013) and as such, predominantly qualitative data is used and is supplemented where possible with quantitative aspects (Klein, 2011). The main aspect that has been used to determine the benchmark is the level of invasiveness associated with IAPs. This is gauged using the case of six invasive *Acacia* species for which relatively suitable data is available (Impson *et al*, 2011).

The chosen *Acacia* species have been selected in collaboration with Dr S Nesser of the PPRI Weeds Division (Nesser, 2013) for three main reasons. Firstly, the various varieties of invasive *Acacia* all pose, or have posed, a significant threat to South African environmental integrity through their invasion. Secondly, they are all varieties that have garnered significant researcher attention within the Weeds Division over the past decades and therefore present

a large amount of useful data (Zachariades, 2013). Lastly, each of the varieties has experienced a varied degree of success regarding the implementation of biological control (Impson *et al,* 2011) and therefore provided a good cross section for the success of the Weeds Division's work.

By investigating these weed species it is possible to gain a picture of the overall impact of Weeds Division work, which experiences mixed success in controlling a variety of target weeds. Six of the ten invasive *Acacia* varieties found in South Africa are considered in chapter five of this study. The six varieties investigated are *Acacia baileyana, Acacia dealbata, Acacia decurrens, Acacia longifolia, Acacia melanoxylon* and *Acacia pycnantha* (Impson *et al*, 2011)*. A baileyana* and *A decurrens* display negligible success of biological control. The success of biological control on *A dealbata* has yet to be determined. *A longifolia, A melanoxylon* and *A pycnantha* on the other hand, all display substantial degrees of success from biological control (Impson *et al*, 2011). The success of biological control for each of these species is used to inform both the overall value of biological control research and the relative success of biological as opposed to conventional control.

This chapter has provided an explanation of the method to be used in this study. Due to limitations in data and the available techniques for assessing the value of public research, a number of approaches have been drawn together to provide a full perspective of the value created through the work of the PPRI Weeds Research Division (Gittinger, 1995, Andres, 2009 and Vink, 2000). The method used would be considered unconventional by many, especially regarding the use of cost efficiency analysis to assess the value of biological control. It, however, must again be highlighted that the value of biological control has been taken as a proxy for the value of the supporting research, which is the real focus of this study. This approach was taken to overcome limitations in data availability regarding the value of biological control research. While the cost efficiency analysis speaks to the choice between two techniques for completing a project, the real appeal of this method lies in its ability to overcome limitations in data availability regarding the benefits of an endeavour (Layard & Glaister, 2012). By assessing the value of biological control, combined with various qualitative aspects regarding the value of research, this study has attempted to develop an

understandable method for illustrating the value of the work conducted by the ARC PPRI Weeds Research Division. The method used is not aimed at arriving at a precise figure for the value of the work. Instead, it is used as a descriptive tool to illustrate whether the work is indeed valuable and if so, what this value is comprised of.

Chapter five begins with an analysis of data regarding the negative impacts experienced as a result of invasions by invasive alien plants. Having considered the economic impact of these invasions, the chapter then continues to complete a budgetary cost comparison between biological and conventional control strategies. Using the approach of cost efficiency analysis described in this chapter (Gittinger, 1995), together with additional aspects of researcher publications proposed by Andres (2009), and the adaptability of the Weeds Research Division to a changing economic environment as suggested by Vink (2000), a conclusion will be draw as to the overall value of the Division to the South African economy. The study then continues to chapter six, where conclusions are drawn about the value of the PPRI Weeds Research Division, and recommendations for the future of IAP management and investment into biological control research in South Africa are proposed.

CHAPTER 5

ANALYSIS AND DISCUSSION

This chapter incorporates relevant data into the method set out in chapter four to assist in the valuation of the ARC PPRI Weeds Research Division's work. A qualitative assessment of the impact of IAPs is used to illustrate the effect that invasions have on the South African economy. The success of biological control in addressing this challenge is then considered to illustrate the value of biological control research. This introduces the cost efficiency analysis, which compares the cost of IAP control using biological versus conventional methods. Complementary to this is an analysis of the number of IAP species successfully controlled using biological methods. Having considered this aspect, the role of the PPRI in host specificity testing is then explored to determine the value of the Division from a scientific perspective. Case data on invasive *Acacia* species is then given to analyse the specific impact that biological control research has on IAPs. Data concerning job creation and the effect of research spillovers is also considered, as well as the number of researcher publications produced by the Division. Cost data has been collected from the Weeds Division and from the Working for Water programme. Data on the number of researcher publications produced by the Division has also been collected through the Agricultural Research Council. Qualitative data on the value of biological control research has been collected from a range of journal articles and through researcher interactions. A brief overview is given at the end of the chapter, with full conclusions and recommendations given in chapter six.

To overcome limitations in the availability of suitable data, the method employed in this study is twofold. Firstly, the quantitative aspects of cost efficiency analysis as suggested by Gittinger (1995) and Layard and Glaister (2012) and the number of research publications produced (Andres, 2009) are considered. These quantitative characteristics are complemented by a range of qualitative aspects to gain a more holistic impression of the economic value of this public research (Plant Protection Research Institute, 2005 and Henderson, 2013). Qualitative characteristics considered include the effectiveness of biological as opposed to conventional control (Van Wilgen & De Lange, 2011), the effect of IAP invasions on economic and environmental functioning (De Lange & Van Wilgen, 2010), and the expected long-term

impact of the use of biological control research (Pimental *et al,* 2001). These factors are used to consider the indicators set out in chapter four, namely the cost efficiency and sustainability of control, the creation of employment opportunities and skills development, and the advance in scientific knowledge or capability achieved through conventional versus biological control.

5.1 Impacts of IAPs

Before the cost analysis is completed to compare the relative value of biological and conventional forms of control, it is insightful to first gain an understanding of the economic impact of IAP invasions. This section follows from section two in chapter three, which described why invasive alien plants are a problem worth controlling. Here data is added to that picture to illustrate clearly the economic implications of uncontrolled IAP invasions. It is useful to consider this aspect because it will inform the choice of whether investment into any form of IAP control is in fact needed and, in turn, the value of investment into the Weeds Division. The data in this section has been drawn from various sources that have investigated the impact of IAP invasions.

According to Van Wilgen and De Lange (2011), invasions by IAPs cause changes to the composition and functioning of ecosystems and therefore hamper the delivery and quality of ecosystem services. This occurs through the ability of invasive plants to take advantage of environments where they have no natural predators and are therefore able to outcompete indigenous species and flourish (Hobbs, 2000). Turpie (2004), however, noted that it is inherently difficult to measure properly the costs that arise because of the presence of IAPs within an environment. This is because many of these costs are not easily identifiable in the current period and will regularly only be realised later once the damage has already been done and is often irreversible (Turpie & Heydenrych, 2000). It is nonetheless extremely important to get as accurate a picture as possible of the costs that IAPs impose on society, the environment and the economy. Van Wilgen *et al* (2001) remarked that costs do arise through invasions and must be accounted for. This is necessary to establish an accurate sense of whether the target species is in fact one that will impose high costs and should therefore be controlled, or will not result in an invasion and could therefore be left without control. It

is important to remember that not all foreign species will result in an invasion; only certain species will be able to naturally establish and spread. Henderson (2011) noted that being able to identify these potential invader species, and control accordingly, will ensure that the long-term cost to the economy and environment is minimised.

In terms of actual economic estimates of the costs of invasions, Van Wilgen and De Lange (2011) projected the potential future economic impact of IAPs on the South African economy. This estimation was based on current and predicted rates of invasion and the effects thereof. From their analysis, the authors determined that over time the level of impact has amplified due to an increase in the area invaded by IAPs. For example, the current impact of IAP invasions on national grazing availability has been estimated as a decrease of 1% in the potential number of livestock that could be supported (Van Wilgen *et al*, 2008). However, should the spread of IAP species be left unabated, this loss could increase to as much as 71% of available grazing land. Although the livestock industry accounts for less than 0.5% of GDP (Department of Agriculture, Forestry and Fisheries, 2012), a decrease in the availability of grazing by this amount would have dire impacts. The effect would not only be felt by large commercial farmers, who account for about 60% of cattle in South Africa, but especially by emerging and small scale farmers who comprise about 40% of the national herd (Red Meat Producers Organisation, 2013). Van Wilgen *et al* (2008) noted that these smaller scale producers were generally unable to change production techniques as the availability of grazing decreases and would therefore be forced out of the industry.

In another study completed by De Lange and Van Wilgen (2010), the impacts of invasions by groups of IAP species was expressed in monetary terms. This valuation was completed by considering the net present value (NPV) of weed control (specifically biological control) and using this to determine the associated benefit cost ratios. These ratios were calculated by comparing the cost of control to the benefits that were realised through implementation of these practices. The benefits considered were the ecosystem services that were protected from harm by IAPs using biological control. What this study found was that the yearly estimated losses experienced as a result of IAP invasions amounted to approximately 0.3% of the country's GDP, or about R6.5 billion (in 2009). In addition, the authors estimated that should no control of IAPs have been conducted to date, this cost would have risen to

approximately R41.7 billion per year. The cost of not investing in IAP control is therefore illustrated by the yearly savings realised because of current work. What can be noticed however, is that the economy still experiences a significant yearly loss because of IAP invasions. De Lange and Van Wilgen (2010) remarked that these costs would largely be avoidable if a comprehensive IAP control strategy was implemented. The current losses were calculated as R5.8 billion per year for water, R400 million per year for biodiversity, and R300 million per year for grazing. It can be determined that through current control initiatives, approximately R35 billion in costs to ecosystem services are saved per year. However, a substantial cost is still imposed through IAP invasions, which warrants the improvement of current control techniques.

IAPs also impose a range of impacts on indigenous biomes for which some have had impact studies completed. Of these, a few are notable and are mentioned here. Van Wilgen *et al* (2001) stated that studies have shown the value of the fynbos biome to have decreased by at least R72 billion because of IAP invasions in this region. Heydenrych (1999), likewise, estimated the environmental cost imposed by IAPs on the Agulhas Plain to equal about R20 billion. Considering the impact of a single invasive species, Hill (1999) assessed the cost imposed on riparian zones by red water fern alone approximated R350 million. The studies all illustrate that the costs IAPs impose on the South African economy and environment are substantial and will increase should management steps not be taken now to address this problem. In terms of control, Van Wilgen *et al* (2001) estimated it would cost about R10.2 billion to clear all IAPs at 2001 levels of invasion.

The main impacts that IAP invasions impose are decreasing availability and quality of water resources (Van Wilgen *et al*, 2008), negatively impacting on local biodiversity (Turpie & Heydenrych, 2000), increasing fire intensity and regularity (D'Antonio, 2000), decreasing the availability of grazing for livestock (Van Wilgen *et al,* 2008) and posing health risks to humans and animals (Wise *et al*, 2007). While there exist a large amount of data analysing these effects (Van Wilgen and De Lange, 2011), this study will not consider them in further detail since doing so will not directly influence on the valuation of the Weeds Division's work. What is important to note is that all of these studies recommend the development and

implementation of sustainable control strategies that include biological control (Joubert, 2009).

The data reviewed thus far indicates the impacts that IAP invasions have on the South African environment and economy are significant (Van Wilgen & De Lange, 2011). Avoiding or minimising these costs therefore requires a well-considered management strategy that deals with the invasion problem at the lowest long-term cost. The development of an integrated strategy maximising the use of biological control is therefore supported (De Lange & Van Wilgen, 2010). Taking this approach would achieve the desired result of IAP control thereby protecting the nation's valuable environment and inducing economic savings. To achieve such an integrated approach, however, requires thorough research into potential control agents, illustrating the essential nature of the PPRI Weeds Division's work. The study now moves to consider the value of biological control of IAPs in more depth.

5.2 Success of Biocontrol

This section provides a range of qualitative and quantitative findings regarding the impact of biological control research. Again, it must be remembered that in the context of this study the value of biological control and the associated research are considered as synonymous since all supporting research conducted into this field is carried out by one organisation, the PPRI Weeds Research Division. The following section includes the cost efficiency analysis that compares the biological and conventional means of IAP control to aid in determining the value of biocontrol research.

In terms of historical economic valuations of biological control, Hill and Greathead (2000) noted that early investigations were predominantly carried out by biologists and as such were largely limited in nature. The first major investigation by an economist was by DeBach (1964) who conducted a valuation study of biological control in California. He concluded that over the period 1923-1959, the net savings realised through the implementation of five successful biocontrol projects amounted to $115 million, after an initial research investment of only $4.3

million. This immediately pointed to a high rate of return on investment into biological control research, illustrating the value of this activity (Tisdell & Auld, 1990).

Relating to the global success of implementing biological control research, Julien and White (1997) noted that of 729 released agents 64% became established permanently, while 28% of the agents were able to achieve complete control of the target weed. Hill and Greathead (2000) meanwhile remarked that of 179 biocontrol projects they reviewed, 39% proved successful, with 48% the 101 targeted weeds brought under complete control. Global evidence therefore supports conducting biological control research. Although work into this field only result in a portion of the target IAP species being brought under complete control, Hill and Greathead (2000) argued that the value of this alone motivates for further support for the industry.

Between 1997 and 2000, approximately R30 million had been spent on biocontrol research in South Africa, mainly provided by the WfW programme to the Weeds Research Division. Van Wilgen and Van Wyk (1999) observed that the indications are that this outlay yielded unprecedented returns on investment. This represents the average level of investment provided to the Division over its three year budgetary cycle (Price, 2013). This relatively small investment into biocontrol research is in comparison to the yearly investment of about R750 million directed towards conventional control through the WfW programme (Wannenburgh, 2014). It must again be remembered that in the South African context, biological control research carried out for any IAP species is conducted by the PPRI Weeds Research Division (Klein, 2011).

The use of biological control for IAP management has already yielded significant cost savings to the local economy. For example, Nesser (2013) remarked that subsidies for Jointed Cactus herbicide were provided for many years to farmers affected by this species of IAP. This subsidy cost in excess of R120 million over a 40 year period. Since the introduction of a biocontrol agent researched by the Weeds Division, there has been a decrease in this expense by about 85%. Another example is that of Port Jackson willow, which has invaded about 1.8 million hectares of South Africa. Van Wilgen *et al* (2001) noted that since the introduction of biocontrol agents for this weed the need for conventional control has been eliminated,

yielding a return on investment of R800 for every R1 invested in researching suitable control agents. This research was conducted by the PPRI Weeds Division and illustrates that investment into biological control research produces large benefits.

Considering the relative value of investment into conventional and biological control respectively, Van Wilgen *et al* (2001) estimated the cost of controlling all local invasions using each option. The total cost of bringing IAPs under control in South Africa using conventional means only was estimated to be approximately R12 billion, or R600 million per year for the next 20 years. With the use of biological control however, the total cost of control is estimated to decrease to a total of R4 billion, or R200 million per year (Van Wilgen *et al*, 2001). This presents a massive saving of state funds that could then be used elsewhere to create meaningful employment and training opportunities for unskilled or semiskilled labour. Such investment could be in education and healthcare, or creating productive public works programmes where options for decreased spending do not exist. Pursuing biological methods to control IAPs therefore presents a much more manageable expenditure option for a developing country with a range of other social, environmental and economic challenges. Pimental *et al* (2001) noted that an investment into biological control research in the current period would produce large dividends over the long-term. This is because it will no longer be necessary to carry out continuous control using conventional methods that impose a sustained cost to the economy. An interesting question to consider in this regard is what the long-term cost implications would be if biological control were not used to combat IAP invasions. Although not given in this study, such an aspect would highlight the value of biological methods for keeping long-term control costs to a minimum (White & Newton Cross, 2000). Overall, however, implementing the research work of the Weeds Division leads to massive savings in the total cost of controlling IAP invasions.

To date, there have been two main studies conducted that analysed the economic aspects of the biological control research carried out against invasive alien plants in South Africa. The first was a paper by Van Wilgen *et al* (2004), and involved a comparative analysis of the costs of biological control research for six different weed species and their effects (benefits) on water, biodiversity, ecosystem services and land values. The second is a paper by De Lange and Van Wilgen (2010), which investigated the cost of biological control research conducted

for four plant groups and the associated benefits to water management, grazing capacity and biodiversity. Both of the papers calculated the present value (PV) of the research conducted and used cost data available from the relevant research institutes. Van Wilgen and De Lange (2011), however, noted that the two are not directly comparable since the base years used in the analysis are 2000 and 2008 respectively. Variations in valuation may therefore occur as a result of changes in real price levels over this period. The papers nonetheless provide interesting insight into general trends regarding the value of biological control research over time. Both papers clearly illustrate high benefit cost ratios for conducting research into all of the various species investigated (De Lange & Van Wilgen, 2010). Most notable similarities include very high benefit cost ratios for invasive cactus species (including *Opuntia* or cactus pear species) and woody *Acacia* species. A similar approach to analysis was used in both papers, having used cost data relating to locating, importation, screening and release of various control agents, as well as post release monitoring and a selection of implementation costs. These papers did not, however, consider the cost of mass hatching and rearing of the control agents as this is carried out by the Working for Water (WfW) programme. Van Wilgen and De Lange (2011) remarked that from these, as well as the other two studies included in table 5.1, there clearly exists strong economic support for carrying out the biological control research of the Weeds Division. This support is specifically due to the high benefit cost ratios and positive long-term impacts that biological control has on water management, ecosystem services, biodiversity, grazing and land value.

Table 5.1 provides a summary of the two papers discussed above (approaches one and three), as well as two other papers that have been conducted to investigate the economic aspects of biological control research in comparison to conventional control methods (Van Wilgen & De Lange, 2011). What is interesting to note from these two additional papers is the support they give to conducting biological control research as opposed to continued conventional control. Both papers found that biological control is more cost effective than conventional control measures. Given South Africa's range of social needs and limited state budget, Zimmermann *et al* (2004) indicated that cost effectiveness is an extremely important aspect to consider in any decision making process. Based on cost analysis alone there appears to be more support for increased biological control research than continued conventional control (Van Wilgen &

De Lange, 2011). This aspect, however, is considered in more detail in the cost efficiency analysis conducted in this chapter.

Returning briefly to the contents of table 5.1; although the benefit cost ratio realised in approach two is relatively small compared to those realised in approaches one and three, it must be remembered that these studies were investigating separate aspects relating to the research. Hence the findings do not provide weaker support for conducting biological control research. The point to be made is that all four studies provide positive evidence in support of investment into this field. These studies all display highly favourable rates of return of investment into biological control and therefore the associated research. Further support is therefore gained for the work of the PPRI Weeds Research Division.

Table 5.1: Outcomes of studies of the economic benefits of biological control of alien invasive plants in South Africa.
(Van Wilgen & De Lange, 2011)

Approach	Invasive alien plant species or group	Benefit cost ratio	Source
1) Comparison of costs of biological control research on six weed species to benefits gained through the protection of water resources, biodiversity-based ecosystem services, and the market value of land	*Opuntia aurantiaca* Lindl. (Cactaceae) *Sesbania punicea* (Cav.) Benth. (Fabaceae) *Lantana camara* L. (Verbenaceae) *Acacia longifolia* (Andr.) Willd. (Mimosaceae) *Acacia pycnantha* Benth. (Mimosaceae) *Hakea sericea* Schrad. & J.C.Wendl. (Proteaceae)	709:1 8:1 22:1 104:1 665:1 251:1	Van Wilgen *et al,* 2004
2) Comparison of costs of biological control research for red water fern to benefits gained through avoiding the need for ongoing mechanical and chemical control	*Azolla filiculoides* Lam. (Azollaceae)	2.5:1 initially, rising to 15:1 within 10 years	McConnachie *et al,* 2003
3) Comparison of costs of biological control research on 'functional groups' of weeds to benefits gained through the protection of water resources, grazing resources and biodiversity.	Fire-adapted trees: *Pinus* (Pinaceae), and *Hakea* species (Proteaceae) Perennial invasive Australian trees: *Acacia* species (Mimosaceae); *Leptospermum laevigatum* (Gaertn.) F.Muell. (Myrtaceae); and *Paraserianthes lophantha* (Willd.) Nielsen (Mimosaceae) Invasive succulents: *Opuntia* species, *Cereus* species and *Harrisia martinii* (Labour.) Britton & Rose (Cactaceae) Subtropical shrubs: *Lantana camara* (Verbenaceae); *Chromolaena odorata* (L.) R.M.King & H.Rob. (Asteraceae); and *Caesalpinia decapetala* (Roth) Alston (Fabaceae)	81:1 3726:1 2731:1 50:1	De Lange & Van Wilgen, 2010
4) Comparison of costs of biological and herbicide control	*Eichhornia crassipes* (C.Mart.) Solms (Pontederiaceae)	Biological control found to be more cost-effective than chemical control	Van Wyk & Van Wilgen, 2002

It is important to note that while IAPs do impose considerable costs on the economy, some of these species also provide a range of benefits that can be exploited (Van Wilgen *et al*, 2001). The majority of these benefits are realised by rural communities who use invaders, especially woody varieties, for timber, fuel wood and livestock feed. It is for this reason that the biological control of certain woody species, for example Black wattle, has not been fully investigated until now (Impson *et al*, 2011). However, Nesser (2013) commented that there is an increasing awareness that even those IAP species that provide some sort of benefit still need to be controlled. This ensures that these species are not allowed to spread unabated as the costs that they impose on the environment and society outweigh the benefits they produce for specific groups.

From a commercial perspective, the forestry and timber industry contributes significantly to the domestic economy. A recent study by the CSIR (CSIR, 2011) found that the sector contributed approximately R12.2 billion to the South African economy annually, which amounted to about 1.2% of the national GDP. It is therefore necessary to ensure that biological control does not negatively affect this sector by causing damage to the growth potential of commercial tree species such as pines and eucalyptus (Van Wilgen *et al,* 2001). The CSIR (2011) further noted that if biocontrol were to negatively influence this industry then the downstream effects on employment opportunities and income generation could be dire, especially impacting the rural poor. In light of this danger, there is a need for well-focussed biological control research ensuring that only agents that do not hamper the growth of commercial species are released. Instead, biocontrol for commercial species with an invasive nature should focus on decreasing the reproductive ability of these species. Doing so would allow natural growth but inhibit reproduction and therefore spread (Nesser, 2013). In this regard, Henderson (2011) commented that the early detection of invasive species would be helpful. This would allow control strategies to be developed that prevent IAPs from spreading and therefore prevent invasions from occurring. Instead, such species would only be able to grow in designated propagation areas where proper management can be exercised.

This chapter has thus far displayed the need for the effective management of invasive alien plants (Hosking & Du Preez, 1999). The presence of these species impose a range of negative impacts on both the environment and economy that can be avoided if effective control strategies are implemented (Turpie & Heydenrych, 2000). Furthermore, biological control has emerged from the examined qualitative data as an extremely valuable research endeavour (Van Wilgen & De Lange, 2011). Investment into this activity is therefore supported, as it results in long-term control cost savings, and the preservation of biodiversity (Pimental *et al,* 2001). Considering this existing qualitative data, the study now moves to provide an insight into the value of biological control research using the quantitative approach of cost efficiency analyses (as set out in chapter four).

5.3 Cost efficiency analysis

Having assessed an assortment of qualitative data regarding the effects of invasive alien plants, the study now provides the cost efficiency analysis identified in chapter four. This analysis compares the relative investment into biological control research and implementation with the cost of conventional control. The relative budgets of biological control and conventional control of IAPs are used to inform this section. The data has been sourced from budgets of the Agricultural Research Council (Agricultural Research Council, 2014) and the Working for Water programme (Wannenburgh, 2014). Table 5.2 provides the analysis of the relative investment into biological control as opposed to conventional control. Comparing these aspects allows a conclusion to be drawn as to the value of biological control research and, hence, the value of the work of the PPRI Weeds Research Division.

Table 5.2: Cost Efficiency Comparison between Biological and Conventional Invasive Alien Plant Control (All figures in 2014 Rands).

Period	Biological Research Budgeted Cost (x)	Biological Implementation Budgeted Cost (y)	Total Biological Budgeted Cost (x + y) = a	Conventional Budget Cost (z)	Total Control Budget Cost (x + y + z) = b	Biological as % Total Cost (a/b)*100	Biological Research as % Total Cost (x/b)*100
1 Nov 2013 – 31 Mar 2014	**7,011,269.50**	2,860,187.15	**9,871,456.65**	282,500,000.00	292,371,456.65	**3.38%**	**2.4%**
1 Apr 2014 – 31 Mar 2015	**19,801,032.44**	6,554,023.70	**26,355,056.14**	801,982,720.00	828,337,776.14	**3.18%**	**2.4%**
1 Apr 2015 – 31 Mar 2016	**21,087,672.80**	6,695,769.37	**27,783,442.17**	807,241,160.00	835,024,602.17	**3.33%**	**2.53%**
1 Apr 2016 – 31 Mar 2017	**20,839,868.61**	7,249,945.82	**28,089,814.43**	850,832,400.00	878,922,214.43	**3.2%**	**2.37%**

*Figures are VAT inclusive

Mean Biological control as % Total Cost = 3.27%

Mean Biological Research as % Total Cost = 2.43%

The data shows that approximately 2.4% of the total budget for IAP management is spent on biological control research. From this level of expenditure, Klein (2011) stated that biological control options have been investigated for 73 species of invasive alien plants. Based on the results of host specificity research, 106 control agents have been released against 48 weed species. Of the 73 investigated species, 10 have been brought under complete control meaning that no other measures are needed to control the target plant. A further 19 species have been brought under substantial control using biological methods, meaning that minimal levels of effort are required to bring the target plant under control. Of the remaining 44 species of target weed, 14 have been negligibly impacted by the release of biological control agents, and the impact on 9 species has not yet been determined. In the case of the 9 undetermined species, either there has been no post release evaluation conducted or it is still too soon after release to conduct such an evaluation. For the remaining 21 species, no data exists regarding the impact of biological control agents on the weeds prevalence. For ease of reference, this information is tabulated below and includes the percentage of IAP species controlled at the various levels. A full list of all IAP species targeted using the biological control work of the PPRI Weeds Research Division is provided in Appendix 1.

Table 5.3: The effectiveness of biological control research.

Degree of success of biological control (BC)	Number of IAP species	Percentage of species investigated for BC
Complete	10	14%
Substantial	19	26%
Negligible	14	19%
Not determined	9	12%
No data	21	29%
Total	**73**	**100**

If it is assumed that both complete and substantial degrees of control are considered as a success in terms of IAP management then investment into this project yields a success rate of 40%. Where a success rate refers to the percentage of instances where biological control implementation has resulted in very limited to no further need for future control (Rao *et al*,

2012 and Klein, 2011). The assumption that both complete and substantial degrees of control can be considered as successful is taken as valid because under both of these circumstances the future level of investment into controlling these IAPs is very low. According to Roa *et al* (2012), a success rate of 14% and over can be considered as a valuable investment. Considering that 14% of the research of the Weeds Division has resulted in complete control and an additional 26% of the work resulted in substantial control, the investment into this work is taken as valuable. This assumption may be challenged by the point that in the cases of IAPs that have been substantially controlled, a certain degree of control is still required. However, given that the degree of conventional control required is drastically reduced and the invasiveness of the IAP significantly deceased, the ability of the biological control agent to hamper the weeds spread can be taken as successful.

In comparison to the success rates of biological control, conventional control is not associated with any long-term sustained level of IAP management (Joubert, 2009). Rather, conventional control in the current period must be accompanied by control in the future since current efforts only work to manage existing infestations, which then have a chance to re-establish. Turpie and Heydenrych (2000) noted that re-establishment occurs as a result of the large seedbeds IAPs tend to produce, meaning that although the parent plants may be cleared now, seed will germinate and re-infest an area once conventional control has been ceased. In this regard, conventional control could be considered to have a very low rate of return in the long run. The aspect that still promotes the implementation of this form of control is the large amount of employment opportunities associated with conventional control measures. This aspect is discussed further in section 5.6 of this chapter.

Biological control research has effectively controlled 29 of the 73 weeds targeted by the ARC PPRI Weeds Research Division (Klein, 2011). Based on this, it can be determined that biological control research presents substantial value to the South African economy. This is especially the case given the low long-term success rate of conventional control measures. From a cost efficiency perspective, investment into biological control represents just over 2% of the total allocated budget for IAP control. From this 2% investment, 10 species of IAP have been brought under complete control and 19 have been brought under substantial control. In both of these cases, the need for further conventional control has been drastically minimised. This represents

control of 29 of the 336 species of invasive alien plants catalogued in South Africa. Although this represents only 8.6% of IAP species having been brought under control using biological methods, it is a notable success considering the focus of the Weeds Division on only 73 of these species to date. Conventional control in contrast is not responsible for the complete control of any of the 336 IAP species present in South Africa (Klein, 2011). Considering that approximately 98% of the IAP control budget is spent on conventional measures, the value of this form of control from a cost perspective is highly questionable.

5.4 Host specificity

Having considered the cost efficiency aspect of the investment into biological control, it is also important to consider the safety aspect of this endeavour. A brief review is given here that outlines the number of biological control agents investigated and the resultant number of agents released. This is done to provide a picture of the level of scrutiny entailed in this project, as well as the relative rate of success of research from the time of initial identification to the final release of proven agents.

Moran *et al* (2005) compiled a database of the testing and introduction of biological control agents in South Africa since 1913, which was the first recorded date of release of a biological agent in the country. From that time, 271 possible biological control agents have been tested by the Weeds Division for host specificity and other impacts on the local environment. Of these, 40% were eventually deemed to have a negligible impact on the local environment, were therefore safe for release, and have been used in the control of various species of invading plant. A further 40% of the 271 test subjects were rejected as unsafe for release, due to the identification of a range of negative impacts they would have on the local environment. The remaining 20% are currently still under quarantine (Klein, 2011). This rigorous testing, which only permits the release of agents that will not negatively impact on the indigenous environment, has ensured that to date no biological control agent has been released that had any significant negative impacts on the South African environment, agriculture or economy (Moran *et al*, 2005). What is seen is that if proper testing and quarantining is carried out, the use of a biological control agent will not result in the emergence of a new invasion by the

released agent. Hill and Greathead (2000) remarked that despite the large proportion of biocontrol projects that fail, those that succeed provide a large enough savings and range of benefits to justify continuation of all projects.

5.5 Biological control research conducted by PPRI for invasive *Acacia* species

Having established invasions in every province of South Africa (Henderson, 2001), Australian *Acacia's* have proved a major problem to the nation's environmental integrity, whilst imposing a variety of high costs on the economy. The costs experienced have been partially offset by the benefits some communities or individuals are able to extract from the plants and should not be discounted. Benefits include use as fuel wood by poor communities, fodder for stock farmers, wood chipping for paper pulp and low-grade timber (Turpie & Heydenrych, 2000 and Hobbs, 2000). These benefits have thus far restricted the extent of biological control research to agents that would target the reproduction, as opposed to growth, of invasive *Acacia* species. By targeting the reproductivity of plants, researchers have been able to decrease the rate and density of spread without interfering with the human uses that had developed (Impson *et al*, 2011). Taking this approach, however, has meant that for a long period it appeared as if little to no progress had been made in the fight to control these species. Van Wilgen and De Lange (2011) commented that what is probably closer to the truth is without the implementation of biological control against the reproductivity of these species, the level of infestation would have been far greater than what has actually been experienced. With perennial species that develop large seed banks such as the Australian *Acacias*, biological control that only targets the plants reproduction means spread is however inevitable (Impson *et al*, 2009). Impson *et al* (2004) remarked that a control agent is highly unlikely to be able to control every individual in the population; therefore, at least a few plants are able to set seed successfully allowing the plant to continue to spread. Without targeting the plants growth and preventing it from reproducing, the battle against such species is likely to be lost eventually. Joubert (2009) stated that, to achieve long-term control, a more holistic approach to the biological control research for these species is needed, which focuses on eradicating the plants entirely as opposed to slowing their spread. Nesser (2013) suggested that in conjunction with this, research should be conducted

into alternative indigenous species that could replace invasive species, provide the same benefits, and therefore offer equal or greater economic value.

Impson *et al* (2011) recorded that since 1982, biological control measures have been researched and implemented against ten species of invasive *Acacia* in South Africa. These species have invaded a variety of South African ecosystems with differences in climatic and environmental conditions leading to differentiated productiveness and rates of spread. The ten species that have been focussed on to date are *Acacia baileyana* (Bailey's wattle), *Acacia cyclops* (Rooikrans), *Acacia dealbata* (Silver wattle), *Acacia decurrens* (Green wattle), *Acacia longifolia* (Long-leaved wattle), *Acacia mernsii* (Black wattle), *Acacia melanoxylon* (Blackwood), *Acacia podalyriifolia* (Pearl acacia), *Acacia pycnantha* (Golden wattle) and *Acacia salinga* (Port Jackson willow) (Impson *et al*, 2011). A further seven species of Australian *Acacia* have been identified in various locations across the country, with current efforts aimed at early mechanical and chemical control to prevent the establishment of these plants. Should these mechanical or chemical methods prove unsuccessful then biological control will be investigated to prevent invasions from occurring (Impson *et al*, 2011). It is not precisely clear how these foreign *Acacia* species ended up in South Africa; however, records from the 1820s refer to them as ornamental species in private and state gardens. Later in the century, these species were increasingly introduced and used in the rapidly expanding timber industry. Joubert (2009) recorded that as the species' importance grew; their seeds were collected and distributed across the country. This widespread propagation is largely responsible for the massive extent of current invasions, except in the case of *Acacia longifolia,* which has been able to spread without much human intervention (Macdonald, 1985). It is the ability of these invasive *Acacia* species to proliferate quickly in poor quality soil and produce massive amounts of seed, which is well dispersed and long lasting, that has given them the ability to spread into and dominate such a wide range of South African environments. Many of these *Acacia* species are fire adapted and grow well in fire prone areas such as fynbos, which are generally treeless. This allows for mass germination after burning, quickly giving rise to the establishment of dense stands of the weeds (Clark, 1998).

The biological control efforts on six species of invasive *Acacia* are considered in this study. This is done to provide an overview of the success of biological control research, as well as the type of effects of such research. The six species investigated are *Acacia baileyana* (Bailey's wattle),

Acacia dealbata (Silver wattle)*, Acacia decurrens* (Green wattle)*, Acacia longifolia* (Long-leaved wattle)*, Acacia melanoxylon* (Blackwood) and *Acacia pycnantha* (Golden wattle) (Impson *et al*, 2011)*.* The research into control agents for each of these species was conducted by the Weeds Research Division. Each species is briefly considered in the following sections.

5.5.1 Acacia baileyana (Bailey's wattle)

The seed feeding weevil *Melanterius maculatus* was first identified as a potential control agent for *A. baileyana* in 1976 (Impson *et al*, 2011). The first release of this agent against this species of IAP was conducted in 2000, and was done at a site in the North West Province. Establishment of the agent was confirmed in 2007, with further releases occurring in 2009 in the Western Cape. Due to the recent nature of these releases it is however too soon to determine the effectiveness of this agent against the target plant. Impson *et al* (2011) suggested that further releases are required for this species.

5.5.2 Acacia dealbata (Silver wattle)

The first biological control agent released against *A. dealbata* was the seed feeding weevil *Melanterius maculatus,* which was done in 1994 (Impson *et al*, 2011). The effect of this release, however, was never established. Further releases of *M. maculatus* occurred in 1998, with the establishment of the weevil confirmed in 2001 at one selected release site in the Western Cape. Since 2004, seed damage was monitored at this site and ranged between 64% and 93%, with an average of 79% of pods unfit for germination. Dennill *et al* (1999) stated that certain release sites in the Western Cape Province were mechanically cleared after the release in 1998, and as such, the effect of the agent is unestablished in these areas. This raises a concern of the uncoordinated management of IAPs between conventional and biological control, and requires a more systematic approach to the recording and monitoring of biological control release sites. The same issue is noted at six additional release sites, three in Limpopo, two in Mpumalanga and one in the Eastern Cape. All of these locations were conventionally cleared after the release of the control agent, with the effect of the release unknown. The weevil has only been confirmed as established at an additional three sites, two in Mpumalanga and one in KwaZulu-Natal. Impson *et al* (2011) noted the need for follow up evaluation at additional release sites as this has been limited in nature.

5.5.3 Acacia decurrens (Green wattle)

Since the first release of *Melanterius maculatus* (a seed feeding weevil) in 1994 against *A. decurrens,* further releases were conducted in 1997 and the early 2000's (Impson *et al*, 2011). Starting in 2004, annual monitoring has been conducted at one site in the Western Cape and found damage levels ranging between 42% and 93%, with a mean damage level of 63%. Further establishment was confirmed at a site in the North West Province; however, the establishment at the additional release sites must still be investigated. It has been recommended by Impson *et al* (2011) that further releases be conducted at as many new sites as possible.

5.5.4 Acacia longifolia (Long-leaved wattle)

Impson *et al* (2011) noted that since the introduction of *Trichilogaster acaciaelongifolia* and *Melanterius ventralis* as agents for the control of *A. longifolia*, the weed has been brought under significant control in South Africa. This is evidenced by the drop of *A. longifolia* from number five on the list of South Africa's most important or prominent weeds (Wells, 1991) to number 21. This provides a clear indication that the species no longer poses the same environmental threat as before the introduction of control agents. This change in ranking is supported by a recent aerial survey of IAPs in South Africa, which found that recordings of *A. longifolia* were too scarce to qualify surveying the species as distinct from other species. This relates the success of biological control of this species as it is no longer as widespread or dense as before introduction of the agent occurred. Instead, it is now mainly found in isolated pockets or sparse stands that do not pose a threat of densification or expansion into surrounding areas (Impson *et al,* 2011).

5.5.5 Acacia melanoxylon (Blackwood)

The seed feeding weevil *Melanterius acacia* was first introduced in 1986 to target the Blackwood, an invasive Australian hardwood used for its timber. Since the release of this agent, high levels of seed damage of the target weed have been recorded with particular effectiveness in the southern Cape region (Dennill *et al*, 1999). During the course of monitoring 17 release sites in 2002, seed damage levels of between 55% and 100% were recorded with a mean of 90.5%, illustrating the high levels of effectiveness of this agent in the control of its target. Similar monitoring in 2005, of eight of the 17 sites from 2002, recorded damage levels of on average

91% demonstrating the continued effectiveness of this control agent. Due to the significant and sustained effect that *M. acacia* has had on the productivity of *A melanoxylon*, fears of its woody species invasiveness have now diminished significantly. The high levels of seed damage inflicted by this agent have motivated for its distribution to other areas where it has yet to be established (Moran *et al,* 2011).

5.5.6 Acacia pycnantha (Golden wattle)

The bud galling wasp, *Trichilogaster signiventris,* was introduced into South Africa in 1987 to combat the spread of Golden wattle. The agent was introduced in an attempt to prevent any further invasion by the species, which was not yet well established in South Africa (Henderson, 2001). The wasp, whose galls cause decreased seeding rates, has largely been able to keep the seed production and therefore spread of the wattle in check. However, Impson *et al* (2011) highlighted that in some years plants in certain locations successfully produced seed resulting in sporadic spread. In an attempt to overcome the periodic spread *Melanterius maculates*, a seed feeding weevil was introduced in 2003 as a second control agent (Impson *et al*, 2011). Due to the recent release of the second agent, its effectiveness is yet to be established.

In the cases of *A. longifolia, A. melanoxylon* and *A. pycnantha*, indications are that the release of biological control agents has curbed the spread of these species and that they no longer pose a threat to South African habitats (Impson *et al*, 2011). Regarding *A. dealbata* and *A. decurrens*, the literature supports the finding that a moderate level of success in control has been achieved using biological methods. For the last species considered, Impson *et al* (2011) stated that due to the recent nature of the release of control agents against *A. baileyana*, the effect is yet to be established. It is found that the use of biological control achieves a varied success rate. This relates to the success of biological control research and therefore the work of the PPRI Weeds Division. Use of this work cannot be expected to result in complete control in all instances; however, the implementation of this form of control is associated with positive effects on the management of IAP species. Joubert (2009) remarked that the early initiation of biological control programmes against specific species that pose a high risk of invasion has almost certainly ensured that these will never properly establish themselves as invaders.

5.6 Job Creation

One particularly important area to consider in any valuation exercise in the South African context is that of employment. Joblessness is a perennial problem, with an unemployment rate of over 25% (Statistics South Africa, 2014); the need for job creation is therefore high on the list of national priorities. To understand the employment implications for biological control research it is necessary to come to grips with the current extent of employment opportunities within the biological control sector, which includes employment for researchers, support staff, and downstream sectors such as implementation. These figures are then compared to the equivalent statistics for conventional control methods.

In terms of biological control, the Working for Water (WfW) programme employs a total of 107 people to implement its various biological control initiatives (Sharpe, 2014). These jobs are spread over the nine provinces of South Africa, and include managers, contractors and workers. This is complemented by 38 researchers and support staff employed at the PPRI Weeds Division (Price, 2014).

Conventional control, on the other hand, is responsible for the creation of many more employment opportunities. In the 2012/2013 financial year alone, 25 404 work opportunities (or 11 063 full-time equivalent jobs) were created through the WfW programme. The majority of these positions were associated with conventional control practices. This speaks to the strong social development aim that drives the WfW. According to the Department of Environmental Affairs (Department of Environmental Affairs, 2014), the Working for Water programme is grounded in an ethos of environmental protection serving social development. In line with this intention, the WfW programme aims to create 18 000 jobs per annum focussing on previously unemployed people. Of these jobs, 60% are targeted at women, 20% for youth and at least 2% for disabled persons.

Biological control can clearly not compete with conventional control through the WfW in terms of sheer scale of employment creation. This is particularly the case with biological control research, as only 145 people are employed in this area as compared to the approximately 25 000 created through conventional control. Biological control does however offer the advantage of training researchers in sound scientific practice, adding to the national pool of scientific talent.

This is an extremely important aspect given the limited number of trained scientists available in South Africa. The addition of even just a few to the national skills base represents a major long-term benefit to the economy. The main trade off with regards employment creation in the IAP management sector therefore appears to be in terms of the job numbers from conventional control, compared to control cost savings from biological control.

5.7 Researcher Publications

According to Price (2014), since 2010 researchers from the PPRI Weeds Research Division have authored 67 journal articles that have been published in peer reviewed scientific journals. In addition to this, 53 scientific presentations were made, along with the 148 non-peer reviewed publications in the form of pamphlets, training manuals and services, client reports and other publications. This amounts to 268 instances over four years where information was disseminated by Weeds Division researchers on the role and value of biological control in IAP management.

The Weeds Division ranks at a similar level of total research output to some of the lower producing local universities such as the Central University of Technology (Department of Higher Education and Training, 2014). Although the Weeds Division does not compete with large research producing institutes like the University of Pretoria or Rhodes University, considering that the Division is such a small unit employing only a fraction of the staff of a university, it is quite impressive that its research output is in any way comparable to these institutions. From the perspective of individual researcher productivity, in 2011, one Weeds Division researcher published five journal articles, five researchers published four journal articles, two researchers published three journal articles and eight researchers published two journal articles (Price, 2014). In the same year, the Department of Botany at Rhodes University had one researcher that published six journal articles, three researchers that published three journal articles and four researchers that published two journal articles (Rhodes University, 2011). While the Division's overall research output is low in comparison to the big universities, its individual researcher productivity is comparable to that of some of the top research institutes in the country.

The number of publications and researcher productivity highlights the active role that researchers within the Division are playing in the overall scientific endeavour of South Africa. Through these works, the scientific capacity and capability of the nation is steadily bolstered, contributing to the creation of a knowledge driven developmental economy (Andres, 2009).

5.8 Research spillovers and biological control in South Africa

When analysing the impacts of biological control research on the spread of Australian *Acacia's* in South Africa, Impson *et al* (2011) noted that one of the seed feeding weevil species, *Melanterius maculates,* that was initially introduced to control *A. mearnsii* in 1993 (Dennill *et al,* 1999) was later found to target as many as six of the *Acacia* species that are problematic in the country. This means that it was only necessary to have one control agent cleared for release yet this same agent has been applied to control several species of weed. A considerable saving on research costs for the other *Acacia* species was therefore realised. Similar savings have also been achieved for a number of additional weed species researched by the Weeds Division, where research from foreign countries or organisations has been used to control locally problematic species (Nesser, 2013). An example of this is the use of the mealy bug *Hypogeococcus pungens* and stem boring beetle *Alcidion cereicola,* first identified and used in Australia, to control Queen of the Night cactus (C*ereus jamacaru)* in South Africa (Plant Protection Research Institute, 2002). The beetle *Alcidion cereicola* was further used by the Division to control the Harrisia cactus (*Harrisia martini*). Both of these control agents were provided to the Division by Australian researchers (Plant Protection Research Institute, 2002). Savings in the cost of research are often achieved when work from foreign sources is incorporated to inform the nature of local research or suggest possible control agents to consider. These cost savings can have a significant impact on the value of research conducted and support the case for biological as opposed to conventional control (Joubert, 2009). South Africa, through the PPRI Weeds Division, is currently a world leader in biological control of IAPs and is therefore unlikely to experience the same level of benefits from research spillovers as countries using locally produced research (Van Wilgen & De Lange, 2011). Local researchers do however regularly rely on American and Australian work as similar problems with IAPs are experienced in those countries. As such, strong research networks have been developed

amongst these three nations and this has aided in shared problem solving and improved research capacity and efficiency (Nesser, 2013).

Another unexpected, yet possibly lucrative, industry that has risen out of the biocontrol research of the PPRI is that of commercial cochineal production (Weeds Research Division, 2001). Traditionally, this insect has been reared in central and southern American countries such as Peru and Mexico as a source of the high value carmine dye. The Division's research into the commercial mass rearing of this species has equipped the organisation with world leading knowledge on how best to produce these insects. This knowledge is now in demand by countries that rear the insect for dye production, as their techniques have proven to be less scientific and efficient than those developed by the Division. Staff from the unit have been invited to aid the development of these industries in their countries of origin and have initiated a similar project in Namaqualand to start the commercial production of the dye in South Africa. Although no figures are yet available for the value of this industry, or the associated work by the Division, an important point is highlighted.

The competencies and capacity developed through the work of the Division may prove to be highly valuable not only domestically, but internationally as well. This point was re-iterated by Joubert (2009), who stated that although biological control agents are at times expensive and difficult to find they offer a solution to the IAP problem not only within South Africa, but also beyond its boundaries. Specific reference is given to the countries that border South Africa as these also suffer large negative impacts from the spread of invasive plant species (Mack, 2000). These countries are however largely unable to effectively deal with this challenge due to limitations of poor economic performance and human capital development. Considering the relatively developed and well-financed nature of the South African economy, as compared to the underdevelopment and financial constraints largely experienced by our neighbours, biological control offers an opportunity for increased regional cooperation and support, which positively influences the lives of rural poor. This highlights the importance of biological control research for the Southern African region as a whole, with South Africa as the leader in this regard.

Clearly, biological control research conducted in South Africa by the PPRI Weeds Division has large positive research spillovers into the rest of the region. Whilst the Working for Water programme provides employment opportunities for thousands of unskilled rural poor, this should not be seen as a long-term solution to the unemployment or IAP problems. In this regard, biological control should increasingly be used to combat invasive species, as this will allow for financial and human resources to be allocated to other areas where such a long-term sustainable solution to an environmental or social problem does not exist (Joubert, 2009).

5.9 Conclusion

This chapter has investigated a range of both qualitative and quantitative data regarding the value of biological control research and the work of the Weeds Research Division. Overall, the data shows strong support for conducting this work, illustrates that investment into this activity yields high rates of success, and ensures that the long-term cost of IAP control is minimised. Although biological control does not offer the same level of immediate social benefits in terms of employment creation, support for this initiative will ensure that the long-term cost of IAP management is minimised. This would allow for wise investment into other environmental public works programmes where a sustainable solution such as this does not exist. It should therefore not be seen as an either or scenario, where employment opportunities for unskilled labour are lost to the use of biological control. Instead, the use of biological control should be viewed as an integral solution to the problem of IAP invasions, which continue to increase in intensity and frequency. Pursuing this form of control would allow for a re-gearing of environmental public works programmes and ensure that the goal of IAP management is achieved at lowest cost. Further, it would create the opportunity for increased investment, and therefore job creation, addressing other environmental issues that cannot be managed in this way.

CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This study has set out to explore whether investment into the biological control research conducted by the ARC PPRI Weeds Research Division is a valuable activity that should be supported. The study has progressed from investigating various means of valuing research to describing why IAPs pose a challenge to the domestic economy. A method was developed for assessing the economic value of the Division's work, and was followed by the inclusion of relevant data and discussion thereof. This last chapter serves to finalise the study and provide a number of closing observations and recommendations regarding the management of invasive alien plants and the value of the Weeds Research Division.

The chapter begins with an overview of why the need for IAP control exists, from both a legislative and developmental perspective. An assessment of some cost considerations for biological and conventional control are then investigated. Included here are a few brief remarks on the pertinent issue of water usage in South Africa. Some additional recommendations for the use of the SAPIA mapping project and invasive plants that have thus far been regarded as special cases are also given. Concluding ideas regarding the changing role of the Working for Water programme are then examined and are used to recommend a possible future development path for the organisation. The study ends with a final analysis of the value of investment into biological control research conducted by the ARC PPRI Weeds Research Division. This assessment provides some concluding remarks as to why investment into the Division is important, as well as recommendations as to the scope of future research in this area. These recommendations include improved post release monitoring and improved co-ordination between conventional and biological control measures. The set of indicators set out in chapter four are also considered for both biological and conventional control. These are used to support the case for further investment into biological control and the changing role of the Working for Water programme.

Some of the recommendations provided in this chapter may be seen as irrelevant for directly illustrating the value of the Weeds Research Division. A decision was, however, taken to

incorporate such a broad spectrum of recommendations for the sector due to the intricate system of linkages between areas. No economic unit operates in isolation and, as such, considering the value of such a unit must be undertaken under the broader conditions that prevail. This point was raised in chapters two (Pinto & Pinto, 2007) and four (Adato *et al*, 2005). Each aspect considered in this chapter has been taken as having a significant degree of influence over the final analysis of the value of the Division. Omitting one or more of these aspects would result in an analysis that provides decision makers with an incomplete view of the sector and therefore the role and value of the Division in the South Africa economy.

6.1 Legislation and Development

Examining briefly the legislative support for IAP control, item 24 of the South African Bill of Rights states that all people have the "right to have the environment protected, for the benefit of present and future generations" (Constitution of the Republic of South Africa, 1996). This right includes the prevention of degradation of the natural environment. Given the long-term effects that invasive alien plants have on an environment and economy (Joubert, 2009); efforts to guarantee the sustainable control of these species are essential for securing this right. By ensuring methods of environmental management are adopted that impose least cost and maximum benefit, the ability to achieve long-term social and economic development goals is enhanced (Zimmermann *et al*, 2004). The National Environmental Management Act (107/1998), and the National Environmental Management: Biodiversity Act (10/2004) both deal with the issue of preservation of national biodiversity and natural resources. These Acts highlight the need for effective management of invasive alien plants to preserve national biodiversity and water resources, which are seen as essential for the sustained growth of the domestic economy and development of society.

Van Wilgen and De Lange (2011) stated that in terms of South African development strategy, there appears to be a gap in understanding the link between environmental integrity and socio-economic wellbeing. There is increasing evidence that good quality environmental assets are essential for pro-poor development and that without this sound environmental base any future prospects of growth are limited. Naylor (2000) noted that biological invasions have harmful

impacts on economic growth potential, poverty alleviation programmes and food security. This is because invaded areas are left infertile, inaccessible and with low productivity. Increased support for research that aims to protect our natural heritage is therefore suggested, as this will aid the continued upliftment of the poor and marginalised.

6.2 Cost considerations

In terms of the broader environmental preservation initiative in South Africa, the cost of investment into managing environmental resources is one that presents a significant expenditure of state funds (Wannenburg, 2014). Ensuring that this task is completed at lowest cost should therefore be of high priority to guarantee that scarce financial resources are used in the most efficient manner.

The approximate budgeted expenditure on conventional control exercised through the Working for Water programme for the 2014/2015 period equals about R800 million. In comparison, the total budget of the PPRI Weeds Research Division equals about R20 million for the same period (Price, 2014). Given that the research of the PPRI Weeds Division has resulted in the complete control of 10 and substantial control of 19 of the 73 targeted weed species, whereas conventional control has not been able to completely control any weed species, the case for investment into biological control is supported. Should further investment into the PPRI Weeds Division be made, the ability to control more IAP species with minimum expenditure will be achieved. Although research into this field does not result in a 100% success rate of control of researched species, it does have a substantially higher rate of complete control than conventional measures.

The case for continued and increased investment into biological control research carried out by the PPRI Weeds Research Division is therefore supported. Through further investment into this form of management, the ability to control completely more IAP species will be achieved. This means that over time fewer financial resources would need to be directed toward the conventional control of IAPs. Having achieved control, it would then be possible to direct these saved financial resources towards other environmental public works programmes. Investment

into biological control research therefore presents an opportunity to achieve a sustained economic saving in terms of IAP control costs.

6.2.1 Water

Given the water scarce nature of South Africa and the large amount of literature regarding the impact of IAPs on water resources, it is pertinent to reflect briefly on some closing remarks on the matter. To begin with, any use of this precious resource represents an imposed cost on the domestic economy (Turpie, 2004). Considering that on average 98% of South Africa's water resources are already allocated to specific activities (Gorgens & Van Wilgen, 2004), including agriculture, industry and household use, there exists a limited leeway in the ability to allow unnecessary wastage without causing some or other party to suffer a loss due to water shortages. In many instances, demand for water in South Africa already exceeds supply, which is particularly evident in arid and large urban areas where most water finds some sort of economic use. It is therefore ill advised to permit as substantial a loss of available water as is currently the case through usage by IAPs (Hosking & Du Preez, 1999). De Wit *et al* (2001) estimated the macroeconomic consequences of water loss for urban, agriculture and industrial usage in South Africa. The analysis showed that the cost of controlling IAPs is justified by the economic benefits realised through deceased water loss alone, and was supported by Van Wilgen *et al* (2001). The analysis does not consider the range of other negative impacts that these species pose to national biodiversity.

6.3 SAPIA

To establish a proper understanding of the extent and impact of the various IAP invasions in South Africa, and to aid timely future response to new invasions, it is suggested that the SAPIA II project be more extensively supported through state funding. This funding could be made available through the Working for Water programme and would aid in improving the understanding of the spread and density of invasive alien plants across the country.

The SAPIA II project aims to raise public awareness about invasive plant species and the variety of impacts they impose (Henderson, 2013). This assists in improved identification and recording

of the spread and effects of IAPs and their associated control initiatives. The project is broadly based on the structure used in the Southern African Bird Atlas Project 2 (Henderson, 2013), where participants make recordings of a variety of species within set periods and locations. This provides a more accurate perspective of the changing population dynamics of invading species over time, and presents an opportunity for employment creation. By supporting this project, it will be possible to understand better the trends in spread and control of invasive plant species. This trend data could potentially be used to inform the management of other forms of biological invasions, such as disease spread and control. The SAPIA data can also be used for early detection of invaders and aid in the timeous implementation of biological control. One of the main advantages of supporting this project is that the impact of biological control agents can be more easily monitored. This would help future assessments of the financial impact of biological control on IAP species.

6.4 Special cases

Invasive species that have an established economic or social value in South Africa, such as the Black wattle, should not be granted privilege against biological control (De Wit *et al*, 2001). Although they do provide some form of economic value for certain groups, the long-term environmental and economic damage that they inflict far outweighs this. To avoid properly controlling such species simply to protect the interests of a relatively small group, whilst the country as a whole is made to bear the costs they impose, presents a classic case of a negative consumption (or production) externality. In instances such as this, what would prove most valuable is for control research to be coupled with restoration or reparation research. Such research should investigate which indigenous species can suitably substitute invasive species. This would restore or even improve the economic value of once invaded areas. For example, in the case of Australian *Acacia,* biological control research aimed at their eradication could be coupled with research into suitable indigenous *Acacia* species that grew at comparable rates over similar areas and could be put to the same use. In this way, local biodiversity, and the development of industrial knowledge around these species – which increases opportunities for future economic growth – are promoted.

6.5 Changing role of Working for Water

The Working for Water (WfW) programme should continue its investment into conventional control in order to maintain the benefit of job creation for unskilled labour. Efforts of conventional control must, however, be focussed on species for which biological control currently does not exist. Concurrently, the programme should enhance its efforts into the use of biological control. This would take the form of increased investment into the research necessary to locate, test and release control agents. Providing greater support for this form of control would ensure that sustainable IAP control strategies could be developed for more species. It must be recognised that it is unlikely to find biological control agents for all invasive species (Henderson, 2013); however, maximising the potential of this method will ensure that the total long-term cost of control is decreased. The PPRI Weeds Research Division should therefore be given priority investment, as the work of this unit contributes significantly to the preservation of South African biodiversity and economic potential.

The focus on veld rehabilitation and management techniques is essential if South Africa is to reap the long-term economic benefits of a flourishing natural environment. Such a flourishing environment was noted earlier in the study as essential to the sustained improvement in socio-economic conditions (Naylor, 2000). No nation has ever experienced continued success on a base of degradation of the natural environment. All efforts to ensure the environment is protected and enhanced must therefore be pursued. In line with this, the work of the WfW must be recognised as integral in guaranteeing the environmental integrity of South Africa. Recognising the essential contribution of well-functioning and pristine environments in the development of resilient economies, the argument for a shift in focus of the WfW programme away from only IAP control and towards improved land management practices is promoted. With increased use of biological control, stakeholders in the conventional control sector can steadily be shifted towards a more holistic public works programme that focusses on total environmental rehabilitation and not just IAP management. This shift in focus is a marker of any well-functioning economic system, which promotes a constant movement towards more efficient techniques of achieving aims and away from those techniques that prove less efficient. By facilitating this process, the development of key scientific competencies is encouraged allowing for the establishment of international competiveness and economic growth. This would specifically take place within the environmental management sector and the associated

scientific fields of biotechnology and biodiversity management. These are areas of rapid growth and importance in contemporary economies (Uctu & Essop, 2012) and could position South Africa as a global leader in this regard. The key is to turn the knowledge and expertise gained through programmes such as Working for Water into tradable goods. The most obvious way of doing this would be through the sale of biotechnology inputs and management expertise.

In discussing the changing role of the Working for Water programme, there is a need to speak to the trade-off between creating large amounts of public employment through conventional control, which will be unsustainable in the long run, compared to the low long-term cost of control using biological methods (Van Wilgen & De Lange, 2011). From a cost perspective, the best option would appear to be a move towards a higher rate of incorporation of biological control supplemented by selective conventional control where biological control is either not an option or ineffective. Jobs lost in this regard can then be offset by the creation of employment opportunities in other environmental public works programmes such as land rehabilitation, land stabilisation and reforestation. These would all complement the work of IAP control, to rehabilitate natural environments and ensure resilience of the South African natural heritage. It is recommended that the WfW programme begin a process of gearing rural areas towards improved veld management practices. This should include investment into the training of education staff on veld management, and teams who focus on addressing issues in veld areas such as IAP invasions, erosion, loss of biodiversity and overgrazing. With increased investment into biological control research via the PPRI Weeds Division, it will be possible to achieve savings in financial resources otherwise used to create employment in conventional IAP control. These savings can then be directed towards other more sustainable employment opportunities such as the cultivation of indigenous plant species for use in medicine, and the sustainable harvesting of wild collected resources such as honey and aloe products. All of these efforts will aid in upward social mobility, creating greater economic opportunities for previously unskilled labour.

From a WfW administration perspective, a recommendation is that increased attention should be paid to the record keeping of the organisation. This is because implementation and monitoring data is not readily available for the relative expenditure on conventional and biological control, and neither is cost data for the control of a particular species and success of

each method. More reliable and available data would aid in improved decision making, which is likely to decrease the long-term cost of IAP control.

The literature suggested that while investment into public works programmes such as WfW is valuable at certain points in an economy's lifetime, such investment should not be seen as a lasting solution to poverty and unemployment (Subbarao *et al*, 1997). The need for such spending in a country like South Africa is likely to remain for some time. With the variety of social challenges facing the nation, the focus of current public works spending, however, may change. The possible change in public works spending patterns motivates for the increased investment into biological control research. Since the option of controlling IAPs using biological methods exists, it makes financial and long-term economic sense to increase investment into such research (Euston-Brown *et al*, 2007). Doing so would free up increasingly larger amounts of state funding for investment into other forms of state spending or public works programmes that are preferably of a productive nature. This would occur because with the increased use of biological control, progressively less conventional control would have to be carried out. From this cost perspective, indications are that biological control should be used wherever possible as doing so will minimise overall costs of IAP control and allow for the funds saved to be used for other public works programmes (Joubert, 2009).

6.6 The value of the PPRI Weeds Research Division's biological control research

One of the most notable difficulties with conducting a valuation exercise on biological entities is the extent of unknowns and imprecision (Perrings *et al*, 2000). The very nature of biological objects, particularly invasive species, creates difficulty in taking precise measurements without going to extensive effort and cost to conduct a census or audit. Depending on environmental factors including rainfall, soil type and quality, aspect, temperature and predation, one species will perform in a variety of ways within even a small area. Without full understanding in this regard, it is difficult to comprehend exactly what are the extent and impacts of an invasion. This problem is equally experienced with invasions by alien plant species. Henderson (2013) remarked that understanding population dynamics of an IAP species is difficult because of the

variance of density across the species range. This makes quantification of the impacts of biological control challenging.

Having considered the role of biological control in managing invasive *Acacia*, similar trends in effectiveness have been noted across the board of biological control research (Nesser, 2013). Some biocontrol projects are extremely successful and result in the complete control of target species while others prove largely unsuccessful. However, the benefits of this research can be concluded to outweigh the costs. This is especially the case when considering the long-term nature of the investment and the increasing value of pristine, well-functioning environments to be realised in the future. An interesting aspect that arises from the data on invasive *Acacia* species is that in many instances, one control agent is suitable for targeting a number of IAP species (Impson *et al*, 2011). This points to large possible spillovers if suitable agents are identified, with one agent contributing to the control of numerous IAP species. A full list of the IAP species targeted with biological control through the work of the PPRI Weeds Division is provided in Appendix 1. This appendix provides greater insight into the varied success of biological control.

An extremely important facet to remember when considering an investment into environmental research is the time dimension over which the subsequent payoff will be realised. True, an investment into manual control does hold a high redistributional value at that time; however, the payoff from such an investment ceases the moment the investment stops: no more money invested, no more jobs, and no more redistribution. This effect is compounded by the back-track in the progress of controlling invasive alien plants. As soon as the investment stops, the clearing stops, and the weeds can once again invade largely unabated – with the benefits achieved from clearing soon lost. Biological control research, on the other hand, continues to provide a payoff long after the investment ceases, with that payoff often only being realised years after the initial investment (Price, 2013). This delay in receiving payoff often leaves investment into biological control seemingly unappealing. The reality, however, is that an investment in the current period into biological control research will produce large positive benefits in the future. These benefits far outweigh the benefits of current spending on conventional control (Joubert, 2009). Biological control research will result in the need for lower expenditure on IAP control in the future, representing a significant economic cost saving. The need to appreciate the existence of a delay

in payoff must be recognised for biological control research to be properly supported. This is particularly the case given that in some instances a delay of up to 20 years is experienced between initial research investment and the achievement of control (Nesser, 2013).

It is important to note that although biological control methods may often not result in immediate control of target species, their role is rather to re-establish a more natural functioning of invaded areas that in time allows the re-establishment of indigenous vegetation (Nesser, 2013). Degraded land does not provide the same level of opportunities as land in its natural state. Pimental *et al* (2001) noted that this state might be slightly altered by a low degree of invasion by foreign species, however, as long as it retains its natural equilibrium it will be able to provide bountifully.

As part of a larger research area in South Africa, the Weeds Research Division holds value through its contribution to the biotechnology sector, which has been identified as one of the nation's strategic areas of future development (Uctu & Essop, 2012). Earlier in the study it was noted that South Africa is a global leader in biocontrol research, already providing a competitive advantage in the sector (Van Wilgen *et al*, 2004). Ashiem and Coenen (2005) remarked that because of globalisation, competition between nations has increased the need for development of competitive advantages in unique areas. As referred to in section 6.5, research into biological control of IAPs fosters the development of strategic scientific competencies that are increasingly in demand considering the shifting nature of world economies and society towards a more sustainable or 'green' mode of conducting business (Jordaan & Jordaan, 2010). By providing increased support for existing biological control research, a small yet established industry will be encouraged to develop further, creating improved national scientific competencies and therefore possibilities for growth. The work of the Division positions South Africa as a potential global leader in the development of biological environment and agricultural management systems. An increase in the support for biological control research will in turn support the decreased need for conventional control methods.

In terms of the use of biological control as a component in a larger IAP control strategy, Bale *et al* (2008) noted that biological weed management has the potential to be highly successful in controlling problem species but that more research into this area is needed in order to improve

effectiveness. Such research includes investigation into a variety of different predators for identified weed species. With hundreds of predators for each species of invader, much research still needs to be conducted into which of these is the best at controlling a specific weed and how predator populations can be grown to a size where they can effectively combat these. Work must also be focussed on changing the agricultural industries perception of biological control. Currently, biological control is widely viewed as an ineffective mechanism of pest management. The value of biocontrol needs to be conveyed to key individuals in order to increase the number of practitioners of this technique (Bale *et al*, 2008).

Table 6.1 provides the assessment of the indicators set out in chapter four. This table illustrates the difference between biological and conventional IAP control methods in terms of cost, sustainability, employment creation, and scientific advancement. Considering this table assists in the decision of which form of IAP control is most suitable.

Table 6.1: Set of indicators and means of assessment

Indicator	Means of assessment	Biological Control Assessment (Yes/No)	Conventional Control Assessment (Yes/No)
Cost efficiency	Does the work minimise cost of solving problem?	**Yes**	**No**
Long-term sustainability	Will the work result in a sustainable solution to the problem?	**Yes**	**No**
Employment creation and skills development	What is the extent and nature of employment creation opportunities produced?	**Limited** Mainly high-end researchers and managers. Some low skill positions for monitoring and evaluation.	**Extensive** Mainly low skill opportunities for previously unemployed. Specifically women and youth.
Advance in scientific knowledge or capability	Does the work produce advances in national scientific knowledge database and capabilities?	**Yes** Fairly extensive advances supported	**No** Limited associated research and scientific development

Based on the analysis conducted in this study, the conclusion is reached that the ARC PPRI Weeds Research Division provides substantial value to the South African economy, environment and society. A recommendation is made that investment into the Division be increased into the future to take advantage of the full range of positive benefits of biological control of IAPs. It must, however, be remembered that while in the private or market sector, dollars count, in the public or non-market sector, votes count (Baron, 1995). As such, it is essential that the public sector is made aware of the availability and benefits of biological control.

6.7 Practical implementation recommendations

Three practical recommendations for improving the effectiveness and value of the Weeds Division's work into biological control research are now provided. These are discussed, and followed by a summary of the major recommendations made by this study.

6.7.1 Improved post release monitoring of biological control agents

Monitoring the impact of a biological control agent on a target species is a challenging task (Nesser, 2013). Doing so requires continual assessment of certain sites where the agents were released, often over a period of ten or more years, to establish the impact of an agent on the target plant (Henderson, 2013). The extended duration of the monitoring is because of the lag that tends to occur between releasing an agent and the establishment of a population large enough to deal with the high rate of spread of the target weed. It is because of this time delay between release and establishment of an effective colony of agents that so many control programmes are prematurely considered as having failed. The effects of the agents are at times only noticed years later, once they have developed a large enough population to cause a significantly noticeable impact on the spread or density of the target plant. This time delay is also responsible for the limited amount of monitoring that takes place after a release is conducted, since it is often too costly in terms of time and money to carry out regular population audits. Instead, researchers need to move onto new projects due to limited funding and large workloads. The limited nature of post release data, with regards plant and agent densities and spread, means that tracking the impact of the agent on the target population with any precision is particularly challenging. Henderson (2013) remarked that the impact of the agent is often

recorded based on visual sightings and anecdotal evidence, that is, on the basis of whether the plant seems relatively more or less abundant than pre-release. This is often done by the researchers who conducted the work, but is generally not recorded as scientific data. For this reason, any valuation analysis of the impacts of biological control research on IAPs has entailed limited scientific or statistical data.

In accordance with this constraint, it is recommended that the PPRI Weeds Division conduct increased post release monitoring of control agents. This monitoring should be conducted regularly and should be recorded and made openly available. Doing so would improve the ability to identify control agents that are having a positive impact on IAP invasions. It would then also be possible to determine more accurately the monetary value of investment into biological control research. The motivation for continued investment into this activity can then be supported by reliable data and impact statistics.

Seed feeding weevils have been introduced as control agents against all ten invasive *Acacia* species in South Africa, with marked success (Impson *et al*, 2011). These agents, however, are - generally slow to disperse from release sites, so manual redistribution and monitoring is often needed to ensure their spread over large areas (Impson *et al,* 2004). This is an area where it is possible to create employment opportunities with upward mobility. Unskilled labour can be used to distribute and monitor agents in an area, thereby allowing for improved monitoring and effectiveness whilst creating employment opportunities for people to enter the environmental sector. The creation of these sorts of opportunities engenders a view of the environment as an important resource to be protected in its natural state in order to realise maximum benefit.

6.7.2 Improved co-ordination between conventional and biological control implementation

To avoid clearing of areas where biological control agents have been released, it is recommended that improved coordination between conventional and biological control efforts be established. Dennill *et al* (1999) stated that certain release sites in the Western Cape Province were mechanically cleared after the release of biocontrol agents in 1998, and as such, the effect of the agent is unestablished in these areas. This raises a concern of the uncoordinated management of IAPs between conventional and biological control, and requires a more

systematic approach to the recording and monitoring of biological control release sites (Impson *et al,* 2011). A possible tool for identifying those areas that require conventional control and those that are currently using biological control could be the SAPIA mapping tool mentioned in section 6.3. Making better use of a mapping system such as this would allow control practitioners to identify easily those areas that require conventional control and those that are currently under use as biological control sites.

6.7.3 Increased capacity and scope of Weeds Division

To ensure that the maximum benefits of biological control of IAPs are harnessed in the shortest possible time, it is recommended that the PPRI Weeds research Division receive increased financial support. This would allow the Division to upgrade and extend its facilities and increase the number of researchers employed. Doing so would enable the Division to step up the number of invasive plant species currently under research, thereby ensuring that the control of more species of IAP is achieved in a shorter time. This would result in an improved ability of the nation to manage effectively more invasive plants, leading to a decreased need for expenditure on IAP control in the long run. Supporting the Weeds Division in this way would also ensure that the problem of IAP invasions is brought under control in a shorter time, thereby imposing a lower cost on the economy and ensuring that the local environment is conserved as the base for sustained future economic growth.

6.8 Summary of recommendations

The following are the major recommendations of this study.

- Improve the post release monitoring on the impact of biological control agents,
- Improve the coordination between biological and conventional control measures,
- Improve the record keeping and data availability of the PPRI Weeds Division and Working for Water programme,
- Increase the level of investment into biological control research through the ARC PPRI,
- Improve the capacity and scope of the Weeds Division's work and
- Implement biological control measures for as many IAP species as possible.

6.9 Final Remark

Van Wilgen *et al* (2001) stated that biological control offers substantial benefits in the control of IAPs. Although there is debate regarding the trade-off between conventional and biological control methods it appears that biocontrol offers the best, most cost effective, tool for IAP management (Hill & Greathead, 2000). It is suggested that labour intensive control strategies are likely to prove unsustainable in the long run and that, should long-term management strategies not be put in place now, the problem of IAP invasion will increase in the future (Joubert, 2009). Zimmermann *et al* (2004) stated that any management programme should ensure that the cleared area does not become reinfested after control has been applied. This, however, is not the case with conventional methods of control, which require the same area to be cleared on a regular basis to prevent weeds from re-establishing. Conventional methods only target mature or adolescent plants but do not address the problem of large seed banks that develop in invaded areas. Continuous cycles of re-germination and establishment of IAPs occurs through this technique. Conventional methods should therefore be used as a strategy to control invasions that cannot be controlled using biological methods, but should not be viewed as a sufficient solution to the IAP problem (Van Wilgen & De Lange, 2011). The most viable solution appears to be the combined use of biological control wherever possible with conventional methods where not possible. Taking this approach would ensure that IAPs are successfully controlled at least cost to the South African economy, providing the opportunity for public investment into more holistic environmental public works programmes.

Zimmermann *et al* (2004) remarked that the opportunity biological control presents is that once an agent has been released and established, it will remain in the environment (and will continue to control the target weed) until the target has either been completely wiped out or properly controlled. No salaries need to be paid from year to year, all that is required is the initial investment to find, quarantine and release the agent. After that, the agent should be able to do all the work by itself, for free, *ad infinitum*. This may not apply in all instances, always, but has held so far to date (Joubert, 2009). The strength of biological methods of IAP control is therefore its self-sustaining nature (Moran *et al,* 2005). This allows financial resources to be directed away from weed control in the long run and towards other more pressing issues that need financial assistance – for example small farmer support. To identify and release an agent that will effectively control an invading species requires only a limited initial investment of human and

financial capital – at the testing stage of the control process – after that the only costs incurred are breeding, release and monitoring costs, these generally being small and short-term in nature. Conventional control methods, on the other hand, require a continual investment of high levels of human and financial capital that places unnecessary economic strain on the fiscus where a cheaper more sustainable solution exists.

If one considers what an infestation of alien plants is, then it will be realised it is a biological invasion – the same as any infection of a host by a virus. To control the virus, a solution is needed that will not only work now but that will also build resistance and protect the host from further invasion at a later date (Van Wilgen *et al*, 2014). Biological control presents this opportunity. As Moran *et al* (2005: 78) noted: "sustained, long-term suppression of most IAPs will not be possible without the intervention of biological control". Biological control offers the tool that is paid for now but from which the benefits will flow long into the future. Any plan for controlling IAPs that does not include a biological control component will prove unsustainable and expensive in the long run, as human based control will have to be continued until the invaders are completely wiped out. This will take years, and may prove impossible.

It is essential to remember that a cost to an environment or community is a cost to the economy (Naylor, 2000). This highlights the idea that the economy is broader than merely what takes place in the business sector. If considered in this way, biological control can be viewed more as acting to preserve an existing yet unaccounted for economic value than creating a new one (Hobbs, 2000). Yes, creating new economic value is highly important in today's society, however, allowing the destruction of natural capital, whether purposefully of through negligence – such as allowing the spread of IAPs – constitutes a destruction of existing value (Naylor, 2000). The value lost is exceedingly difficult to restore even if replaced by conventional business. This is a point that is difficult for many people to reconcile, given our desperate need for economic development. However, if the general perception of the natural environment as a resource to be exploited to achieve an economic end can be changed, and instead viewed as an essential base for any sustained social progress, then it is possible to create a space where millions of people can subsist and thrive. Not everyone needs to live in a city, and not all jobs need to be located there – appreciating and harnessing the value of our natural environment and the

operation of the informal sector can create a space where people can solve their own problems and develop themselves, without the need for a donation.

The work of the ARC PPRI Weeds Research Division is therefore supported as an extremely valuable activity for the South African economy, society and environment. Although there exists limited quantitative evidence to support this finding, the available literature on the effects of biological invasions, biological control, and the relationship between environmental integrity and economic prosperity all point to the research of biological control methods as an exceptionally valuable activity. The study therefore recommends that the Division receive increased financial support in order to expand its research capacity and scope. This should be complemented by improved monitoring of control agents, and coordination with conventional control measures. Concurrently, it is suggested that the Working for Water begins a shift in focus away from its role as a public works programme, and more towards environmental rehabilitation and improvement. This would support the creation of employment in a more diverse range of fields, with greater upward social mobility into the environmental sector, which can become a major area of future growth in South Africa.

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List of IAP species targeted for biological control by the ARC PPRI Weeds Research Division.
(Klein, 2015)

Target weed, region of origin, and degree of control	Natural enemy	Feeding guild	Agent status	Damage inflicted
ARACEAE				
Pistia stratiotes L. (water lettuce) South America **Complete**	*Neohydronomus affinis* Hustache (Coleoptera: Curculionidae)	Leaf and stem borer	Released 1985, Established	Extensive
ASTERACEAE				
Ageratina adenophora **(Spreng.) R.M.King & H.Rob.** (formerly in *Eupatorium*) (Crofton weed) Central America **Negligible**	*Passalora ageratinae* Crous & A.R. Wood (="*Phaeoramularia*" sp.) (anamorphic fungus; Mycosphaerellales: Mycosphaerellaceae)	Leaf spot pathogen	Released 1987, established	Moderate
	Procecidochares utilis Stone (Diptera: Tephritidae)	Stem galler	Released 1984, established	Moderate
Ageratina riparia **(Regel) R.M.King & H.Rob.** (formerly in *Eupatorium*) (mistflower) Central America **Complete**	*Entyloma ageratinae* R.W. Barreto & H.C. Evans (Entylomatales: Entylomataceae)	Leaf pathogen	Released 1989, established	Considerable
Campuloclinium macrocephalum **(Less.) DC.** [formerly in *Eupatorium*] (pompom weed) South America **Not determined**	*Puccinia eupatorii* Dietel (Pucciniales: Pucciniaceae)	Leaf rust pathogen	Not released, occurs locally; also under investigation	Unknown
Chromolaena odorata **(L.) R.M.King & H.Rob.** [formerly in *Eupatorium*] (triffid weed) North, Central & South America **Not determined**	*Calycomyza eupatorivora* Spencer (Diptera: Agromyzidae)	Leaf miner	Released 2003, established	Moderate
	Lixus aemulus Petri (Coleoptera: Curculionidae)	Stem borer	Released 2011, establishment unconfirmed	
	Pareuchaetes aurata (Butler) (Lepidoptera: Arctiidae)	Leaf feeder	Released 1990, not established	
	Pareuchaetes insulata (Walker) (Lepidoptera: Arctiidae)	Leaf feeder	Released 2001, established	Considerable
	Pareuchaetes pseudoinsulata Rego Barros (Lepidoptera: Arctiidae)	Leaf feeder	Released 1989 & 1998, not established	
Cirsium vulgare **(Savi) Ten.** (spear thistle) Europe **Negligible**	*Rhinocyllus conicus* (Froelich) (Coleoptera: Curculionidae)	Seed feeder	Released 1984-1986, established	Moderate
	Urophora stylata (Fabricius) (Diptera: Tephritidae)	Seed feeder	Released 1984-1990, not established	
Parthenium hysterophorus **L.** (parthenium) Gulf of Mexico & South America **Negligible**	*Puccinia abrupta* Dietel & Holw. var. *partheniicola* (H.S. Jacks.) Parmelee (Pucciniales: Pucciniaceae)	Leaf rust pathogen	Not released, occurs locally	Unknown
	Puccinia xanthii Schwein. var. *parthenii-hysterophorae* Seier, H.C. Evans & Á. Romero (=*P.melampodii*; Pucciniales: Pucciniaceae)	Leaf rust pathogen	Released 2010, establishment unconfirmed	Unknown
Silybum marianum **(L.) Gaertn.** (milk thistle) Mediterranean, Asia	*Rhinocyllus conicus* (Froelich) (Coleoptera: Curculionidae)	Seed feeder	Alternative host, released 1985, not established	

***Azolla filiculoides* Lam.** (red water fern) South America **Complete**	*Stenopelmus rufinasus* Gyllenhal (Coleoptera: Curculionidae)	Frond feeder	Released 1997, established	Extensive
BIGNONIACEAE				
***Macfadyena unguis-cati* (L.) A.H.Gentry** (cat's claw creeper) Central & South America **Negligible**	*Carvalhotingis hollandi* Drake (Hemiptera: Tingidae)	Leaf sucker	Released 2007, established	Unknown
	Carvalhotingis visenda Drake & Hambleton (Hemiptera: Tingidae)	Leaf sucker	Released 2007, established	Moderate
	Charidotis auroguttata Boheman (Coleoptera: Chrysomelidae: Cassidinae)	Leaf feeder	Released 1999, established	Trivial
	Hylaeogena (*Hedwigiella*) *jureceki* Obenberger (Coleoptera: Buprestidae)	Leaf miner	Released 2007, established	Unknown
	Hypocosmia pyrochroma Jones (Lepidoptera: Pyralidae)	Leaf feeder	Released 2010, establishment unconfirmed	Unknown
Tecoma stans* (L.) Juss ex Kunth var. *stans (yellow bells) North & Central America **Not determined**	*Prospodium transformans* (Ellis & Everh.) Cummins (Pucciniales: Uropyxidaceae)	Leaf rust pathogen	Released 2010, establishment unconfirmed	Unknown
CACTACEAE				
***Austrocylindropuntia subulata* (Muehlenpf.) Backeb.** (=*Opuntia exaltata* (Berger)) South America **Not determined**	*Cactoblastis cactorum* (Berg) (Lepidoptera: Pyralidae)	Cladode borer	Alternative host, established	Unknown
***Cereus jamacaru* DC. and *C. hildmannianus* K.Schum.** (queen of the night) South America **Complete**	*Hypogeococcus pungens* Granara de Willink (Hemiptera: Pseudococcidae)	Stem sucker	Alternative host, established	Extensive
	Nealcidion cereicola (Fisher) [formerly in *Alcidion*] (Coleoptera: Cerambycidae)	Stem borer	Alternative host, released 1990, established	Considerable
Cylindropuntia fulgida* (Engelm.) F.M.Knuth var. *fulgida (chain-fruit cholla) North & Central America **Complete**	*Dactylopius tomentosus* (Lamark), 'cholla' biotype (Hemiptera: Dactylopiidae)	Cladode sucker	Released 2008, established	Extensive
	Dactylopius tomentosus (Lamark), 'imbricata' biotype (Hemiptera: Dactylopiidae)	Cladode sucker	Alternative host, released 1970, established	Trivial
***Cylindropuntia imbricata* (Haw.) F.M.Knuth** (imbricate prickly pear) North & Central America **Substantial**	*Dactylopius tomentosus* (Lamark), 'imbricata' biotype (Hemiptera: Dactylopiidae)	Cladode sucker	Released 1970, established	Considerable
	Metamasius spinolae (Gyllenhal) (Coleoptera: Curculionidae)	Stem borer	Alternative host, released 1974, not established	
***Cylindropuntia leptocaulis* (DC.) F.M.Knuth** (pencil cactus) North & Central America **Complete**	*Dactylopius tomentosus* (Lamark), 'imbricata' biotype, (Hemiptera: Dactylopiidae)	Cladode sucker	Alternative host, released 1977, established	Extensive
***Harrisia bonplandii* (Pfeiff.) Britton & Rose** (= *H. balansae* (K.Schum.) N.P.Taylor & Zappi) South America **Substantial**	*Hypogeococcus pungens* Granara de Willink (Hemiptera: Pseudococcidae)	Stem sucker	Alternative host, released 2006, established	Extensive
***Harrisia martinii* (Labour.) Britton & Rose** (harrisia/ moon cactus)	*Hypogeococcus pungens* Granara de Willink (Hemiptera: Pseudococcidae)	Stem sucker	Released 1983, established	Extensive

South America **Complete**	*Nealcidion cereicola* (Fisher) [formerly in *Alcidion*] (Coleoptera: Cerambycidae)	Stem borer	Released 1990, established	Considerable
***Opuntia aurantiaca* Lindl.** (jointed cactus) South America **Substantial**	*Cactoblastis cactorum* (Berg) (Lepidoptera: Pyralidae)	Cladode borer	Alternative host, established	Moderate
	Dactylopius austrinus De Lotto (Hemiptera: Dactylopiidae)	Cladode sucker	Released 1935, established	Extensive
	Mimorista pulchellalis Dyar (Lepidoptera: Crambidae)	Cladode borer	Released 1979, not established	
	Nanaia sp. (Lepidoptera: Pyralidae)	Cladode borer	Released 1983, not established	
	Zophodia tapiacola (Dyar) [formerly in *Tucumania*] (Lepidoptera: Pyralidae)	Cladode borer	Released 1976 & 1982, not established	
***Opuntia engelmannii* Salm-Dyck ex Engelm.** (=*O. lindheimeri, O. tardospina*) (small round-leaved prickly pear) North & Central America **Substantial**	*Cactoblastis cactorum* (Berg) (Lepidoptera: Pyralidae)	Cladode borer	Alternative host, released 1938, established	Extensive
	Dactylopius opuntiae (Cockerell), 'ficus' biotype (Hemiptera: Dactylopiidae)	Cladode sucker	Alternative host, released 1938, established	Considerable
***Opuntia ficus-indica* (L.) Mill.** (mission prickly pear) Central America **Substantial**	*Cactoblastis cactorum* (Berg) (Lepidoptera: Pyralidae)	Cladode borer	Released 1933, established	Extensive
	Dactylopius opuntiae (Cockerell), 'ficus' biotype (Hemiptera: Dactylopiidae)	Cladode sucker	Released 1938, established	Extensive
	Lagocheirus funestus (Thompson) [formerly in *Archlagocheirus*] (Coleoptera: Cerambycidae)	Stem borer	Released 1943, established	Trivial
	Metamasius spinolae (Gyllenhal) (Coleoptera: Curculionidae)	Stem borer	Released 1948, established	Extensive
***Opuntia monacantha* Haw.** (smooth/ drooping prickly pear) South America **Substantial**	*Cactoblastis cactorum* (Berg) (Lepidoptera: Pyralidae)	Cladode borer	Alternative host, established	Considerable
	Dactylopius ceylonicus (Green) (Hemiptera: Dactylopiidae)	Cladode sucker	Released 1913, established	Extensive
***Opuntia salmiana* J.Parm. ex Pfeiff.** South America **Substantial**	*Cactoblastis cactorum* (Berg) (Lepidoptera: Pyralidae)	Cladode borer	Alternative host, established	Considerable
***Opuntia spinulifera* Salm-Dyck** (large round-leaved prickly pear) Central America **Not determined**	*Cactoblastis cactorum* (Berg) (Lepidoptera: Pyralidae)	Cladode borer	Alternative host, established	Unknown
***Opuntia stricta* (Haw.) Haw.** (Australian pest pear) North America & Caribbean **Substantial**	*Cactoblastis cactorum* (Berg) (Lepidoptera: Pyralidae)	Cladode borer	Alternative host, released 1980s, established	Extensive
	Dactylopius opuntiae (Cockerell), Australian ('stricta') biotype (Hemiptera: Dactylopiidae)	Cladode sucker	Released 1997, established	Extensive
***Pereskia aculeata* Mill.** (Barbados gooseberry/ pereskia) South America & Caribbean **Negligible**	*Phenrica guerini* Bechyné (Coleoptera: Chrysomelidae)	Leaf feeder	Released 1991 & 1995, established	Trivial
CLUSIACEAE				
***Hypericum perforatum* L.** (St John's wort) Europe & Asia **Complete**	*Agrilus* (*Spiragrilus*) *hyperici* (Creutzer) (Coleoptera: Buprestidae)	Root borer	Released 1974-1979, not established	
	Aplocera efformata (Guenée) (Lepidoptera: Geometridae)	Leaf feeder	Released 1983, not established	

	Aphis chloris Koch (Hemiptera: Aphididae)	Sap sucker	Released 1982, not established	
	Chrysolina hyperici (Forster) (Coleoptera: Chrysomelidae: Chrysomelinae)	Leaf feeder	Released 1960-1973, not established	
	Chrysolina quadrigemina Suffrian (Coleoptera: Chrysomelidae: Chrysomelinae)	Leaf feeder	Released 1960-1973, established	Extensive
	Zeuxidiplosis giardi (Kieffer) (Diptera: Cecidomyiidae)	Shoot-tip galler	Released 1972, established	Moderate
FABACEAE				
***Caesalpinia decapetala* (Roth) Alston** (Mauritius thorn) Asia **Negligible**	*Sulcobruchus subsuturalis* (Pic) (= *S. bakeri* Kingsolver) (Coleoptera: Chrysomelidae: Bruchinae)	Seed feeder	Released 1999, established	Trivial
***Gleditsia triacanthos* L.** (honey locust) North America **Not determined**	*Megabruchidius tonkineus* (Pic) (Coleoptera: Chrysomelidae: Bruchinae)	Seed feeder	Not released, occurs locally	Unknown
***Leucaena leucocephala* (Lam.) de Wit** (leucaena) Tropical America **Negligible**	*Acanthoscelides macrophthalmus* (Schaeffer) (Coeloptera: Chrysomelidae: Bruchinae)	Seed feeder	Released 1999, established	Trivial
***Prosopis* L. species** (mesquite/ prosopis) North & Central America **Negligible**	*Algarobius bottimeri* Kingsolver (Coleoptera: Chrysomelidae: Bruchinae)	Seed feeder	Released 1990, not established	
	Algarobius prosopis (LeConte) (Coleoptera: Chrysomelidae: Bruchinae)	Seed feeder	Released 1987, established	Considerable
	Neltumius arizonensis (Schaeffer) (Coleoptera: Chrysomelidae: Bruchinae)	Seed feeder	Released 1993, established	Unknown
***Sesbania punicea* (Cav.) Benth.** (red sesbania) South America **Complete**	*Neodiplogrammus quadrivittatus* (Olivier) (Coleoptera: Curculionidae)	Stem borer	Released 1984, established	Extensive
	Rhyssomatus marginatus Fåhraeus (Coleoptera: Curculionidae)	Seed feeder	Released 1984, established	Extensive
	Trichapion lativentre (Béguin-Billecocq) (Coleoptera: Brentidae: Apioninae)	Flowerbud feeder	Released 1970s, established, present before release	Extensive
HALORAGACEAE				
***Myriophyllum aquaticum* (Vell.) Verdc.** (parrot's feather) South America **Substantial**	*Lysathia* sp. (Coleoptera: Chrysomelidae)	Leaf feeder	Released 1994, established	Extensive
	Xanthomonas campestris (Pammel) Dawson (?) (Proteobacteria: Xanthomonadales; Xanthomonadaceae)	Bacterial wilt	Not released, occurs locally; rejected	
MIMOSACEAE				
***Acacia baileyana* F.Muell.** (Bailey's wattle) Australia **Negligible**	*Melanterius maculatus* Lea (Coleoptera: Curculionidae)	Seed feeder	Alternative host, released 2006 & 2009, established	Moderate
***Acacia cyclops* A.Cunn. ex G.Don** (red eye/ rooikrans) Australia **Substantial**	*Calonectria scoparia* Ribeiro & Matsuoka ex Peerally (Hypocreales: Nectriaceae) (anamorphic fungus: *Cylindrocladium candelabrum*)	Leaf spot pathogen	Not released, occurs locally; rejected	
	Dasineura dielsi Rübsaamen (Diptera: Cecidomyiidae)	Flower galler	Released 2002, established	Extensive
	Melanterius servulus Pascoe (Coleoptera: Curculionidae)	Seed feeder	Alternative host, released 1991 &	Considerable

			1994, established	
	Pseudolagarobasidium acaciicola Ginns (Polyporales: Phanerochaetaceae)	Die-back pathogen	Not released, occurs locally; under investigation	Unknown
***Acacia dealbata* Link** (silver wattle) Australia **Not determined**	*Melanterius maculatus* Lea (Coleoptera: Curculionidae)	Seed feeder	Alternative host, released 1994-2007, established	Moderate
***Acacia decurrens* (Wendl.) Willd.** (green wattle) Australia **Negligible**	*Melanterius maculatus* Lea (Coleoptera: Curculionidae)	Seed feeder	Alternative host, released 2001-2007, established	Moderate
***Acacia longifolia* (Andr.) Willd.** (long-leaved wattle) Australia **Substantial**	*Melanterius ventralis* Lea (Coleoptera: Curculionidae)	Seed feeder	Released 1985, established	Extensive
	Trichilogaster acaciaelongifoliae (Froggatt) (Hymenoptera: Pteromalidae)	Bud galler	Released 1982, established	Extensive
***Acacia mearnsii* De Wild.** (black wattle) Australia **Not determined**	*Ceratocystis albofundus* M.J.Wingf., De Beer & M.J.Morris (Microascales: Ceratocystidaceae)	Gummosis pathogen	Not released, occurs locally; shelved	
	Cylindrobasidium laeve (Pers.) Chamuris (Polyporales: Physalacriaceae)	Early succession wood rot pathogen, prevents coppice growth	Not released, occurs locally; developed as cut stump inoculant "Stumpout"	
	Dasineura rubiformis Kolesik (Diptera: Cecidomyiidae)	Flower galler	Present before release, established	Extensive (but still localized)
	Melanterius maculatus Lea (Coleoptera: Curculionidae)	Seed feeder	Released 1993-1996, established	Moderate
***Acacia melanoxylon* R.Br.** (Australian blackwood) Australia **Substantial**	*Melanterius acaciae* Lea (Coleoptera: Curculionidae)	Seed feeder	Released 1986, established	Extensive
***Acacia podalyriifolia* A.Cunn. ex G.Don** (pearl acacia) Australia **Not determined**	*Melanterius maculatus* Lea (Coleoptera: Curculionidae)	Seed feeder	Alternative host, released 2008, established	Unknown
***Acacia pycnantha* Benth. (**golden wattle) Australia **Substantial**	*Cylindrobasidium laeve* (Pers.) Chamuris (Polyporales: Physalacriaceae)	Early succession wood rot fungus	Alternative host; not released, occurs locally; developed as cut stump inoculant "Stumpout", but never used	
	Melanterius maculatus Lea (Coleoptera: Curculionidae)	Seed feeder	Alternative host, released 2005-2007, established	Moderate
	Trichilogaster signiventris (Girault) (Hymenoptera: Pteromalidae)	Bud galler	Released 1987 & 1992, established	Considerable / Extensive
***Acacia saligna* (Labill.) H.L.Wendl.** (Port Jackson willow) Australia **Substantial**	*Melanterius compactus* Lea (Coleoptera: Curculionidae)	Seed feeder	Released 2001 & 2003, established	Considerable
	Uromycladium tepperianum (Sacc.) McAlpine (Pucciniales: Pileolariaceae)	Gall former	Released 1987, established	Extensive
***Paraserianthes lophantha* (Willd.) Nielsen** [formerly in *Albizia*] (stink bean) Australia	*Melanterius servulus* Pascoe (Coleoptera: Curculionidae)	Seed feeder	Released 1989, established	Considerable

Substantial				
MYRTACEAE				
***Leptospermum laevigatum* (Gaertn.) F.Muell.** (Australian myrtle) Australia **Negligible**	*Aristaea thalassias* (Meyrick) [formerly in *Parectopa*] (Lepidoptera: Gracillariidae)	Leaf feeder	Released 1996, established	Considerable
	Dasineura strobila Dorchin (Diptera: Cecidomyiidae)	Bud galler	Released 1994, established, present before release	Considerable
PONTEDERIACEAE				
***Eichhornia crassipes* (C.Mart.) Solms** (water hyacinth) South America **Substantial**	*Acremonium zonatum* (Sawada) W.Gams (anamorphic fungus; Hypocreales)	Leaf pathogen	Not released, occurs locally	
	Alternaria eichhorniae Nag-Raj & Ponnappa (anamorphic fungus; Pleosporales: Pleosporaceae)	Leaf pathogen	Not released, occurs locally; shelved	
	Cercospora piaropi Tharp. (anamorphic fungus; Mycosphaerellales: Mycosphaerellaceae)	Leaf pathogen	Not released, occurs locally	
	Cercospora rodmanii Conway (anamorphic fungus; Mycosphaerellales: Mycosphaerellaceae)	Leaf pathogen	Released 1992, established	Considerable
	Cornops aquaticum (Brüner) (Orthoptera: Acrididae: Leptysminae)	Leaf feeder	Released 2011, establishment unconfirmed	
	Eccritotarsus catarinensis (Carvalho) (Hemiptera: Miridae)	Leaf sucker	Released 1996, established	Considerable
	Neochetina bruchi Hustache (Coleoptera: Curculionidae)	Stem borer	Released 1990 & 1996, established	Considerable
	Neochetina eichhorniae Warner (Coleoptera: Curculionidae)	Stem borer	Released 1974-1985, established	Considerable
	Niphograpta albiguttalis Warren (Lepidoptera: Crambidae)	Petiole borer	Released 1990, established	Considerable
	Orthogalumna terebrantis Wallwork (Acari: Sarcoptiformes: Galumnidae)	Leaf miner	Released 1989, established	Considerable
PROTEACEAE				
***Hakea gibbosa* (Sm.) Cav.** (rock hakea) Australia **Negligible**	*Aphanasium australe* (Boisduval) (Coleoptera: Cerambycidae)	Stem borer	Alternative host, released 2001, established	Unknown
	Erytenna consputa Pascoe (Coleoptera: Curculionidae)	Green-seed feeder	Alternative host, released 1975, established	Trivial
***Hakea sericea* Schrad. & J.C.Wendl.** (silky hakea) Australia **Substantial**	*Aphanasium australe* (Boisduval) (Coleoptera: Cerambycidae)	Stem borer	Released 2001, established	Unknown
	Carposina autologa Meyrick (Lepidoptera: Carposinidae)	Seed feeder	Released 1970 & 1982, established	Considerable
	Colletotrichum acutatum J.H. Simmonds f.sp. *hakeae* Lubbe, Denman, P.F. Cannon, J.Z. Groenew., Lampr. & Crous (Order Incertae sedis: Glomerellaceae)	Stem gummosis disease	Not released, occurs locally; developed as mycoherbicide "Hakatak"	
	Cydmaea binotata Lea (Coleoptera: Curculionidae)	Leaf & shoot borer	Released 1979, established	Trivial
	Dicomada rufa Blackburn (Coleoptera: Curculionidae)	Flowerbud feeder	Released 2006, established	Unknown
	Erytenna consputa Pascoe (Coleoptera: Curculionidae)	Green-seed feeder	Released 1970 & 1974, established	Extensive
SALVINIACEAE				
***Salvinia molesta* D.S.Mitch.**	*Cyrtobagous salviniae* Calder &	Stem borer	Released 1985,	Extensive

(water fern) South America **Complete**	Sands (Coleoptera: Curculionidae)		established	
SOLANACEAE				
Solanum elaeagnifolium **Cav.** (silverleaf nightshade/ satansbos) North, Central & South America **Substantial**	*Frumenta nephelomicta* (Meyrick) (Lepidoptera: Gelechiidae)	Fruit galler	Released 1979 & 1985, not established	
	Frumenta sp. (Lepidoptera: Gelechiidae)	Stem & fruit galler	Released 1989, not established	
	Leptinotarsa defecta (Stål) (Coleoptera: Chrysomelidae: Chrysomelinae)	Leaf feeder	Released 1992, established	Moderate
	Leptinotarsa texana (Schaeffer) (Coleoptera: Chrysomelidae: Chrysomelinae)	Leaf feeder	Released 1992, established	Extensive
Solanum mauritianum **Scop.** (bugweed) South America **Negligible**	*Anthonomus santacruzi* Hustache (Coleoptera: Curculionidae)	Flowerbud feeder	Released 2008, established	Unknown
	Gargaphia decoris Drake (Hemiptera: Tingidae)	Leaf sucker	Released 1999, established	Trivial
Solanum sysimbriifolium **Lam.** (wild tomato/ dense-thorned bitter apple) South America **Substantial**	*Gratiana spadicea* (Klug) (Coleoptera: Chrysomelidae: Cassidinae)	Leaf feeder	Released 1994, established	Extensive
VERBENACEAE				
Lantana camara **L.** (lantana) Central & South America **Negligible to Substantial** (depending on plant variety)	*Aceria lantanae* (Cook) (Acari: Trombidiformes: Eriophyidae)	Flower galler	Released 2007, established	Extensive, some vars. Coastal
	Alagoasa parana Samuelson (Coleoptera: Chrysomelidae: Galerucinae)	Leaf miner	Released 1985, not established	
	Autoplusia illustrata (Guenée) (Lepidoptera: Noctuidae)	Leaf feeder	Released 1978 & 1984, not established	
	Calycomyza lantanae (Frick) (Diptera: Agromyzidae)	Leaf miner	Released 1982, established	Moderate
	Coelocephalapion camarae Kissinger (Coleoptera: Brentidae: Apioninae)	Petiole galler	Released 2007, established	Unknown
	Crocidosema lantana Busck [formerly in *Epinotia*] (Lepidoptera: Tortricidae)	Flower- & receptacle miner	Released pre-1961 & 1984, established	Trivial
	Eutreta xanthochaeta Aldrich (Diptera: Tephritidae)	Shoot galler	Released 1983; not established; rejected	
	Falconia intermedia (Distant) (Hemiptera: Miridae)	Leaf sucker	Released 1999, established	Moderate, localized
	Hypena laceratalis Walker (Lepidoptera: Noctuidae)	Leaf feeder	Not released, native	Moderate
	Lantanophaga pusillidactyla (Walker) (Lepidoptera: Pterophoridae)	Flower miner	Released pre-1961, established	Trivial
	Leptobyrsa decora Drake (Hemiptera: Tingidae)	Leaf sucker	Released 1972-1984, not established	
	Longitarsus bethae Savini & Escalona (Coleoptera: Chrysomelidae: Galerucinae)	Root feeder	Released 2007, established	Unknown
	Neogalia sunia (Guenée) (Lepidoptera: Noctuidae)	Leaf feeder	Released 1962 & 1969, not established	
	Octotoma championi Baly	Leaf miner	Released 1978,	

(Coleoptera: Chrysomelidae: Cassidinae)		not established	
Octotoma scabripennis Guèrin-Mèneville (Coleoptera: Chrysomelidae: Cassidinae)	Leaf miner	Released 1971-1975, established	Considerable
Ophiomyia camarae Spencer (Diptera: Agromyzidae)	Leaf miner	Released 2001, established	Considerable
Ophiomyia lantanae (Froggatt) (Diptera: Agromyzidae)	Seed miner	Released pre-1961, established	Moderate
Orthonama ignifera (Warren) [formerly in *Leptostales*] (Lepidoptera: Geometridae)	Leaf feeder	Approved for release	
Passalora lantanae (Chupp) U.Braun & Crous var. *lantanae* [formerly in *Mycovellosiella*] (anamorphic fungus; Mycospherellales: Mycospherellaceae)	Leaf pathogen	Released 2002, not established	
Plagiohammus spinipennis (Thomson) (Coleoptera: Cerambycidae)	Stem borer	Released 1973, not established	
Salbia haemorrhoidalis (Guenée) (Lepidoptera: Crambidae)	Leaf feeder	Released 1962, established	Trivial
Teleonemia elata Drake (Hemiptera: Tingidae)	Leaf sucker	Released 1972, not established	
Teleonemia scrupulosa Stål (Hemiptera: Tingidae)	Leaf & flower sucker	Released 1972, established	Considerable
Uroplata fulvopustulata Baly (Coleoptera: Chrysomelidae: Cassidinae)	Leaf miner	Released 1978, not established	
Uroplata girardi Pic (Coleoptera: Chrysomelidae: Cassidinae)	Leaf miner	Released 1974 & 1983, established	Considerable, coastal
Uroplata lantanae Buzzi & Winder (Coleoptera: Chrysomelidae: Cassidinae)	Leaf miner	Released 1984, not established	