THE ECONOMIC IMPACT AND APPROPRIATE MANAGEMENT OF SELECTED INVASIVE ALIEN SPECIES ON THE AFRICAN CONTINENT

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FINAL REPORT

PREPARED FOR:

Global Invasive Species Programme

PREPARED BY:

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Executive Summary

Introduction

This report provides case studies of the economic impact of five invasive alien species in different areas in Africa. The overall aim of this work was to provide detailed information to administrators and managers. The species were:

- Nile tilapia (*Oreochromis niloticus*);
- Water hyacinth (*Eichhornia crassipes*);
- The larger grain borer (*Prostephanus truncatus*);
- Parthenium weed (*Parthenium hysterophorus*); and
- Triffid weed (*Chromolaena odorata*).

This report is in two parts. The first is an overview of the case studies, intended to provide an expanded outline of the overall approach and main findings of these studies. Part 1 provides a succinct overview of the approach to economic assessment, and on the case studies, and is intended to be a readable, uncluttered account of the findings. Part 2 consists of appendices that provide the full details of the economic methods used, and the data and findings behind each of the case studies. These appendices are intended for the more technically-oriented reader, and they can serve as a resource for those seeking detailed information.

The case studies

The Nile tilapia is a fish species (endemic to the Nile River basin and West Africa), that has been widely spread across Africa. It causes the local extinction of many indigenous fish species, and changes the nature of fisheries. There are no effective means of controlling this species once introduced, therefore efforts should focus on prevention. The case study for this species focussed on its impact on the fisheries in Lake Victoria in Uganda.

Water hyacinth is an aquatic weed (introduced from South America) that invades freshwater rivers and lakes. It grows rapidly, forming expansive colonies of tall interwoven floating plants, which create impenetrable barriers and obstruct navigation. Water hyacinth can be controlled in a number of ways. These include manual or mechanical removal, floating booms to limit spread, application of herbicides (aerial spraying, or spraying from boats or from knapsack sprayers along river banks) and biological control. Biological control is important, and probably essential, for the long-term, sustainable control of water hyacinth. Five biocontrol agents are successfully used around the world. Case studies for this species included the Mossapoula River in the Central African Republic, where the species affects people whose livelihoods depend on palm wine production and fishing; and the Nseleni River in South Africa, where the species affects local fisheries, water supplies and ecotourism.

The larger grain borer is a beetle (introduced from meso-America) that is a major destructive agent in farm-stored maize and dried cassava across Africa. The control of larger grain borer focuses on reducing its numbers (and therefore its impacts) in stored grain by using insecticide mixtures or fumigants. The introduction of a biological control agent to stored grain can also reduce damage. Only one biological control agent has been introduced to Africa. The impacts of the larger grain borer can also be reduced by using modified storage and harvesting techniques. Case studies for this species included impacts on stored maize in the Mono Province of Benin, and impacts on dried cassava chips in the northern region of Ghana.

Parthenium weed is an annual herb native to tropical and subtropical America. This species impacts on stock and crop production, and is also a serious threat to environmental and human health as a result of its ability to produce chemicals that cause severe dermatitis, allergy and toxicity in humans (with corresponding reductions in quality of life and productivity) and in animals. Crop losses are caused primarily through allelopathic effects and direct competition. Control operations should focus on preventing spread, the eradication of small, isolated populations, and by means of biological control. Biological control is particularly attractive as a long-term control, as it is inexpensive, self-sustaining and permanent. Several effective biological control agents are already available and can be introduced and released with a minimum of additional research required. The case study for this species focused on its predicted impacts on both small-scale and commercial farmers in the Mpumalanga Province, South Africa.

Triffid weed is a tall, bushy, scrambling shrub introduced to Africa from central America and the Caribbean. It impacts negatively on agricultural practices and on biodiversity. Despite its wide range of negative impacts, the status of triffid weed can be controversial in African agriculture. In West Africa several agricultural systems make use of triffid weed. The control options available for triffid weed include mechanical, herbicidal and biological control. Each of these options has certain benefits and certain drawbacks. The most cost-effective approach is an integrated management approach where all of the control options are used in the most appropriate manner. Case studies for this species included impacts on tourism and game sales in the Hluhluwe/Imfolozi Park in South Africa, and impacts on livestock production in adjacent agricultural areas.

Economic methods

The economic methods used in these studies were aimed at establishing the costs of invasions, and the costs of control options. The studies used **cost-benefit analysis**, an economic decision-support tool that is designed to compare the total economic benefits (or avoided costs) to society of control with the economic costs of implementing that control. In all the analyses attempts were made to estimate the total economic values of the resources impacted upon by the invasive species on a per-unit-area or per-capita basis. This required that the direct and indirect *use values* and *non-use values* be determined using tax-free shadow prices (where the shadow prices represent the opportunity cost of the resources to society being affected). This, however, was often not possible due to data and time constraints and this is acknowledged in the text and the implications discusse. The analysis involved evaluating the economic impact of the invasive species over 30 years without and with control, and allowed for a range of control options and scenarios to be investigated where the implementation date, the effectiveness of control and the damage functions were allowed to change. The economic model also allowed for an evaluation of the profitability of investing in control. This evaluation was based on the benefit:cost-ratio criterion. Finally, it needs to be emphasised that, in all cases, average values (temporal and spatial) were used in the analyses even though it is acknowledged that the impacts and control of an infestation vary over time and space.

Results of the economic analyses

The introduction of **Nile tilapia** to Lake Victoria increased the total economic returns to the Kenyan fisheries along Lake Victoria by 2 - 12%. The Nile tilapia's contribution to the total catch from Lake Victoria is, however relatively small compared with that from Nile perch and dagaa, and since Nile tilapia is the primary cause of the local extinction of indigenous *Oreochromis* species it is questionable whether its introduction is justified.

In the Central African Republic, biological control of **water hyacinth** will improve the total economic returns from palm wine collection and gill net fishing by between 4, 2 and 1%, depending on whether it was introduced immediately or postponed for 5 or 15 years, respectively. The control had a negative impact on spear fishing, but this accounted for a relatively small proportion (8%) of the total economic returns. The benefit-cost ratios for immediate control, and control postponed for 5 years or 15 years were 5, 5.6 and 5.2 respectively. On the Nseleni River in South Africa, the estimated annual losses in income due to water hyacinth invasions amounted to US$58 195, and this decreased to US$7 000 with the immediate implementation of an integrated-control programme. The cost of the programme was US$ 48 000, yielding a benefit: cost ratio of 31:1 for the immediate implementation of control.

In Benin, clear economic incentives exist for farmers to store their harvested grain, despite the risk of larger grain borer attack. The benefit: cost ratio for immediate improved storage was 3.6, while that associated with improved storage and biocontrol was 15.6. In Ghana, the immediate implementation of biocontrol increased the total economic return to the region and its farmers by 11% (from US$507 860 to US$564 179), which equates to an increase of US$6 per farmer per year. However, benefit: cost ratios were less than unity (0.44 for the immediate implementation of control and 0.39 for delayed control). These low returns are unsurprising considering that cassava is not a cash crop and is grown primarily for food security.

In the Mpumalanga case study, it was shown that if parthenium weed were allowed to spread without control, returns to small-scale farmers would decline between 26 and 41%, while commercial farmer's annual total economic returns would decline by between US$38 818 and US$60 957. Investing in control, however, became profitable (benefit: cost ratio $\geq$ 1) for small-scale farmers only when the effectiveness of control reached 50%. In the case of commercial farmers, a relatively similar pattern was found, where control was only economically feasible when its effectiveness reached 95%, irrespective of the level of damage. If the damage caused by parthenium increased by 30% above its average, however, a control effectiveness of only 80% gave positive returns. Benefit: cost ratios were relatively small (i.e., close to unity), and ranged from 0.16 (with 10% control effectiveness and little damage expected), to 5.37 (with 95% control effectiveness and a large degree of damage expected). In view of this uncertainty, it would be necessary to develop a clear understanding of the damage and effectiveness of control before undertaking a control programme.

In the Hluhluwe/Imfolozi Game Reserve in South Africa, the present value of triffid weed control operations varied from US $2 million for a 4 000 ha infestation, to US$12 million for 28 000 ha and US$24 million for 57 000 ha. This provides an indication of the net present value of additional economic returns (i.e., those that would not accrue to a reserve that became fully infested by triffid weed) that would be required to be provided from all sources in the reserve to justify the expense of the control programme. In the Ntambanana district in KwaZulu-Natal, South Africa, the introduction of a mechanical control programme saw these annual returns from cattle sales increase by between 7 and 34%, depending on the area of the initial invasion. All three invasion-size scenarios delivered cost: benefit ratios of 3.1, 1.9 and 1.7 respectively.

Conclusions

Our studies have highlighted some of the difficulties that face researchers when they attempt to estimate the costs of invasive species and the benefits of control. It is difficult to quantify impacts or to estimate the rates of spread and densification of species invasions. Quantifying the impacts of alien invasions on biodiversity in economic terms is an especially difficult task. It would rather be illuminating to consider the cumulative effects of the steady replacement of a large number of indigenous species by a small number of invasive alien species over time, and not simply take each case study on its own – the latter approach seldom provides an adequate reflection of impacts. However, even with limited data available, and other constraints, it appears (from our and other studies) that control of invasive species will deliver positive benefits, and that control operations, if carried out effectively, will be worth the effort.

Part 1: Overview of Case Studies

1. INTRODUCTION

1.1 Background and objectives

The invasion of ecosystems by alien species is a large and growing threat to the delivery of ecosystem services (Drake *et al*. 1989). Invasive alien species are a product of the ongoing and increasing human re-distribution of species to support agriculture, forestry, mariculture, horticulture and recreation, as well as a by-product of accidental introductions. They include disease organisms, agricultural weeds, and insect pests. These species are known to erode natural capital, compromise ecosystem stability, and threaten economic productivity. The problem is growing in severity and geographic extent as global trade and travel accelerate, and as human-mediated disturbance, global changes in climate and biogeochemical cycling, and increased dissemination of propagules makes ecosystems more susceptible to invasion by alien species (Le Maitre *et al*. 2004). Besides their impacts on agriculture, forestry and human health, biological invasions are also widely recognised as the second-largest global threat (after direct habitat destruction) to biodiversity (Mooney and Hobbs 2000). Thousands of alien species from other parts of the world have been (and continue to be) introduced to Africa, both intentionally for a range of economic and ornamental purposes, and accidentally. Those that become invasive often bring considerable costs to the economy and the environment.

The Global Invasive Species Programme, with funding from the World Bank, commissioned a range of case studies aimed at establishing the economic impact of selected invasive alien species within different areas in Africa. The overall aim of this work was to provide detailed information to administrators and managers. This information should allow them to make informed decisions about investments in programmes aimed at reducing the risk of introducing invasive species to new areas, as well as those seeking to reduce the impacts of existing infestations. The CSIR, in collaboration with four additional experts, was appointed to carry out detailed case studies assessing the economic impacts of five invasive alien species of importance in Africa.

1.2 Terms of reference

This work was required to address a number of case studies of the impacts and management of selected invasive alien species in Africa. We were asked to select between four and seven invasive alien species for study, with a balance between plant and animal invasive species, and a good geographic spread of case studies. Case studies were required to include a study of *Chromolaena odorata* in Southern Africa, but otherwise the choice of case studies was not strictly prescribed.

The case studies were required to cover the following aspects:

- A brief description of the biology of the invasive species, history of introduction in the country or region of study and its invasive potential;
- The current distribution and density of the invasive species within the target country or region and the likely future rate of spread into other areas susceptible to invasion;
- An assessment of the full range of impacts of the invasive species on total economic value expressed as a per unit value; where appropriate distinguish between degrees of infestation, and/or between different conditions;
- The range of management approaches available, with their cost and effect on spread and impacts of the selected species. The different management options to be examined should include:

  i) The cost of doing nothing and letting the invasive species spread unchecked;

  ii) The cost of eradication of the invasive species;

  iii) The cost of controlling the invasive species using biological control, physical control, chemical control and combinations of these (integrated control);

  iv) An analysis of the likelihood of success of each of these approaches to achieve a stated objective to restrict the spread of the invasive species and limit the impact; and

  v) A cost-benefit analysis of the different management approaches.

- The identification of countries in Africa with similar habitats that may be impacted by each selected invasive species.
- The preparation of:

  i) A list of invasive species similar to the subject species that may enter the country or region;

  ii) The pathways by which these species are likely to enter the country;

  iii) The appropriate prevention strategies to limit movement of species along these pathways; and

  iv) The costs of these prevention strategies versus their benefits.

1.3 Selection of species for case studies

A number of factors influenced the final choice of species and case studies. These included the availability of expertise and data, the need to cover an appropriate distribution of case studies across Africa, and the need to include both animals and plants. After consultation, it was decided to focus our studies on five species (one aquatic plant species, two terrestrial plant species, one fish species, and one insect species). The following species and areas were selected as case studies:

- Nile tilapia (*Oreochromis niloticus*), a fish species (endemic to the Nile River basin and West Africa) that has become widespread across Africa, and that causes the local extinction of many indigenous fish species. The case study for this species focussed on its impact on the fisheries in Lake Victoria in Kenya.
- Water hyacinth (*Eichhornia crassipes*), an aquatic weed, introduced from South America that invades freshwater rivers and lakes. Case studies for this species included the Mossapoula River in the Central African Republic, where the species affects people whose livelihoods depend on palm wine production and fishing; and the Nseleni River in South Africa, where the species affects local fisheries, water supplies and ecotourism.
- The larger grain borer (*Prostephanus truncatus*), a beetle introduced from meso-America that is a major destructive agent in farm-stored maize and dried cassava across Africa. Case studies for this species included impacts on stored maize in the Mono Province of Benin, and impacts on dried cassava chips in the northern region of Ghana.
- Parthenium weed (*Parthenium hysterophorus*), an annual much-branched herb native to tropical and subtropical America. This species impacts on livestock and crop production, and is also a serious threat to environmental and human health as a result of its ability to produce chemicals that cause severe dermatitis, allergy and toxicity in humans and animals. The case study for this species focused on its predicted impacts on both small-scale and commercial farmers in the Mpumalanga Province, South Africa.
- Triffid weed (*Chromolaena odorata*), a tall, bushy, scrambling shrub introduced to Africa from Central America and the Caribbean. It impacts negatively on agricultural practices and on biodiversity. Case studies for this species included impacts on tourism and game sales in the Hluhluwe/Imfolozi Park in South Africa, and impacts on livestock production in an adjacent agricultural area.

1.4 Report structure

This report is in two parts. The first is an overview of the case studies, intended to provide an expanded outline of the overall approach and main findings of these studies. Part 1 is based on the development of an approach to the economic assessment, and on the case studies, and is intended to be a readable, uncluttered account of the findings. For this reason, it does not contain detailed references, and these can be found in the appendices in Part 2, which provide the full details of the economic methods used, and the data and findings behind each of the case studies. These appendices are intended for the more technically-oriented reader, and they can serve as a resource for those seeking detailed information.

In the first part, the introduction is followed by an account (Section 2) of the introduction and spread of the species in Africa, and an assessment of areas at risk of invasion in the future. The known impacts of the species are summarised, and the available control options and their effectiveness are reviewed. In cases where the invasive species also confers some benefits, these are also outlined. Section 3 covers the methods used, where the general approach to the economic analyses is explained, and the procedures for each of the case studies are outlined. Section 4 provides a summary of the main findings of the economic impacts for each of the case studies. The final sections cover the economic impacts expressed per unit area, the costs of control, similar species, and costs and strategies for prevention, and conclusions for each of the case studies. A final section, “concluding remarks”, gives some of the key findings of this research.

2. INVASIONS AND THEIR IMPACTS

2.1 Nile tilapia

2.1.1 Introduction, spread and areas at risk

The Nile tilapia (*Oreochromis niloticus*) is predominantly a shallow water species, occurring naturally in many rivers of North and West Africa. Nile tilapia and other African tilapiine fish species have been spread throughout Africa and the world for aquacultural purposes. Their popularity has resulted in their being called “Aquatic Chicken” by the World Fish Center, an organisation that promotes tilapiine aquaculture worldwide. The species was introduced to Lake Victoria in the 1950s, and has since been spread widely in eastern and southern Africa. It now occurs as far south as the Limpopo system in South Africa.

Figure 1: Specimen of Nile tilapia from Kafue flats, Zambia, where it has been introduced

Despite its widespread distribution, several freshwater ecosystems in tropical and sub-tropical Africa are still free of Nile tilapia but are at serious risk of invasion. Lake Malawi is particularly vulnerable. The lake hosts at least four endemic *Oreochromis* species, three of which (*O. karongae*, *O. lidole* and *O. squamipinnis*) form a highly valued species flock collectively known as chambo. These species formed the mainstay of the commercial fisheries in the lake for many decades, but the fishery collapsed in the early 1990s as a result of increased fishing effort with small-meshed nets, many of which directly targeted immature chambo. Measures are currently being considered to restore this fishery, but the experience with other *Oreochromis* species in Africa suggests that chambo will be eliminated if placed in direct competition with *O. niloticus*. In addition to chambo, Lake Malawi is home to up to 1 000 other endemic haplochromine cichlid fish species which would be at risk. These species support important fisheries and are a major tourist attraction. Other river systems throughout tropical and sub-tropical Africa are vulnerable to invasion by Nile tilapia, including the Cunene and other west flowing rivers in

Angola, where increased development is envisaged in the future. If aquaculture is promoted, there is likely to be pressure to use Nile tilapia. The Cunene River, however, contains *O. andersonii*, a species with equivalent growth potential to Nile tilapia and with superior culinary qualities.

2.1.2 Impacts and benefits arising from invasion

Invasion of freshwater ecosystems by Nile tilapia results in localised species extinctions among indigenous fishes. If the fish gets into a river or lake system in Africa, provided the water temperature doesn't get below 12ºC, it displaces any indigenous *Oreochromis* and many haplochromine cichlid species. The time scale depends on the size of the system, the number and size of each introduction of the fish, and the existence of obstacles to free movement. For example, the extinction of *O. esculentus* took 30 years in Lake Victoria, while the replacement of *O. mortimeri* took only 10 years in the smaller Lake Kariba. The impacts of Nile tilapia, as reported in the literature, are summarised in Table 1.

Table 1: A summary of the impacts of Nile tilapia on fisheries and the environment as reported in the literature and from expert observations. The references for this information and more detailed explanations are presented in Appendix 3.

LAND-USE TYPE	IMPACT	COUNTRY
Fisheries		
Fish catch	50% decline in total biomass catch	Nicaragua
	Increases tilapiine and cichlid catch by between 15 and 25%	Lake Victoria, Kenya
	Effect of *O. niloticus* on catch is difficult to assess due to presence of Nile perch[1]	Entire Lake Victoria
	The catch increased but represents a return to the catch levels before the Nile tilapia invasion and prior over-harvesting	Tanzania
Environment		
Endangerment and extinction of species in freshwater systems	Decline of endangered Moapa dace (*Moapa coriacea*) and Moapa white river springfish (*Crenichthys baileyi moapae*)	Nevada & Arizona, USA
	31% of native fishes are considered at risk or already extinct	Mexico
	80% decline in native cichlids[2]	Nicaragua
	Drastic decline of native fish [3]	in Madagascar
	Aust. lungfish *Neoceratodus fosteri*, recently declared 'vulnerable'[4]	Australia
	O. esculentus extinct	Lake Victoria (entirety)
	O. esculentus & O. variabilis extinct	Lake Victoria, Tanzania

[1] *There has been a change in catch from O. esculentus & O. variabilis (2 endemic tilapiines) and a species flock of several hundred haplochromine cichlid species to Nile perch, Nile tilapia, and a small pelagic cyprinid (Rastrineobola argentea).*

[2] *Caused by three tilapiine species: O. aureus, O. mossambicus and O. niloticus*

[3] *Caused by three tilapiine species: O. macrochir, O. niloticus and O. mossambicus*

[4] *Caused by a single tilapiine species O. mossambicus*

Nile tilapia invasions have had a considerable impact on fish production, as the species has superior growth rates and greater breeding success when compared to other tilapine species. The replacement of indigenous species with Nile tilapia changes the quality of the fish caught (Nile tilapias are generally regarded as being of inferior quality to the species they replace and therefore command a lower price). In Lake Victoria, for example, the introduction of Nile tilapias has increased the overall fish catch from the lake (albeit with fish of a different, possible lower, quality). The Nile tilapia is apparently much more capable of withstanding fishing pressure than was the species that it replaced (*O. esculentus*) in Lake Victoria. In Lake Chicamba in Moçambique, the invasion by Nile tilapia appears to have added to the catch per unit effort of the gillnet fishery.

2.1.3 Control options and their effectiveness

Once the Nile tilapia has been introduced to any river system that offers suitable habitat, control is impractical. The only effective means of limiting the impact of this species would be to prevent its introduction to new freshwater habitats. There are a limited number of systems that could still be invaded (see Section 2.1.1). The Orange/Vaal system, for instance, is too cold in winter for successful invasion. In tropical and sub-tropical Africa, action is needed to impose controls on the movements of this and other non-indigenous species. Where the fish exists in main river channels or only in the lower reaches of rivers, every effort must be taken to prevent the species being moved into isolated dams and tributaries where barriers prevent natural spread. This may help to conserve pockets of indigenous fauna.

2.2 Water hyacinth

2.2.1 Introduction, spread and areas at risk

Water hyacinth is a free-floating aquatic weed that can form dense mats on open water bodies. Its introduction to new sites is usually a result of deliberate release in the new area. Once introduced, it can spread rapidly under optimal conditions, especially in water bodies polluted by nitrogen and phosphorus fertilizers, as is the case in many dams. Its abundance can fluctuate over time, as it is often flushed out of water systems by floods, only to cover them again when conditions improve.

Water hyacinth was first recorded in Africa in the early 1900s, in South Africa in 1910 and in Egypt shortly thereafter. The exact mode of introduction is uncertain, but it is thought that the plants were handed out as gifts during a Trade Fair in St Louis in 1904 and were thus spread throughout the world. Since the early 1900s water hyacinth has spread widely throughout Africa and is now recorded from 23 countries on the continent.

Figure 2: Water hyacinth, Eichhornia crassipes (Drawn by Rita Weber)

Climatic suitability modelling suggests that, with the exception of the drier areas of the continent (Sahara and Kalahari deserts), water hyacinth would be able to infest most of the continent (Figure 3). The fact that it does not occur in all countries in Africa is more due to it not having been recorded or not having spread there rather than it not being able to establish.

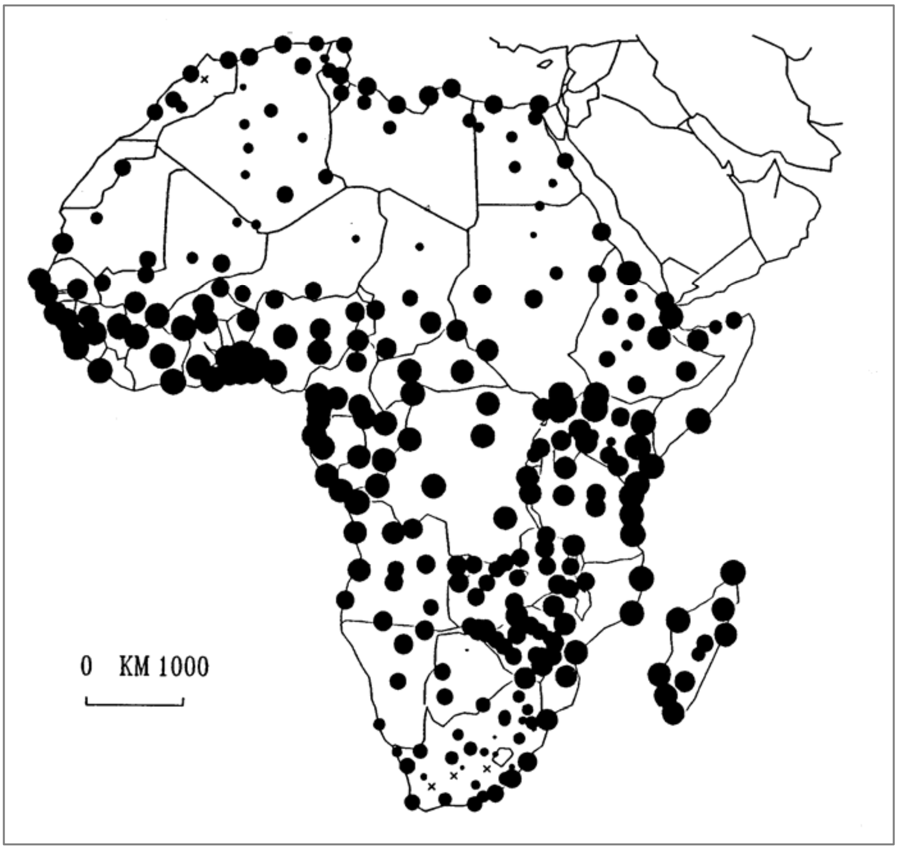

Figure 3: The relative suitability of the climate of selected localities in Africa for persistence of water hyacinth, given that a suitable water body is present. The size of the dots is proportional to the favourableness of the climate.

2.2.2 Impacts and benefits arising from invasion

Water hyacinth grows rapidly, forming expansive colonies of interwoven floating plants. As its doubling time can be as little as one week, it blankets large bodies of water soon after it invades, creating impenetrable barriers and obstructing navigation. Floating mats block drainage, causing flooding or preventing subsidence of floodwaters. Large rafts accumulate where water channels narrow, sometimes causing bridges to collapse. Water hyacinth hinders irrigation by impeding water flow, by clogging irrigation pumps, and by interfering with weirs. Multimillion-dollar flood control and water supply projects, which require decades to construct, can be rendered useless by water hyacinth infestations. Infestations also block access to recreational areas and decrease waterfront property values, often impacting the economies of communities that depend upon fishing and water sports for revenue.

Other impacts include a negative effect on the quality and quantity of potable water, increased water loss due to evapo-transpiration, the depletion of oxygen in aquatic communities, ultimately affecting fisheries, and negative effects on biodiversity. Water hyacinth thus impacts all aspects of water resource utilization including fisheries, transport, hydropower generation and the quantity and quality of potable water. It also threatens the production of electricity through hydropower generation throughout Africa. For example, water hyacinth covered some 20 000 ha of Lake Victoria in 1988. The lake basin supports some 25 million people and has an estimated worth of some US$ 4 billion annually, with fishing benefiting the livelihood of at least 500 000 people and having a potential sustainable fishery export value of US$ 288 million. Water hyacinth severely threatened the economic activities on the lake and the development of the region. Examples of the impacts of water hyacinth reported in the literature are summarised in Table 2.

Table 2: A summary of the impacts of water hyacinth on fisheries, the environment, infrastructure and human health, as reported in the literature and from expert observations. Detailed explanations and references are given in Appendix 4.

	IMPACT	COUNTRY
Agriculture & Environment		
Species richness, diversity and abundance	Significantly negatively affected	South Africa
Spear fishing	Increased catch by 113%	Central African Republic
Gill-net fishing	Decreased catch by 26%	
Palm wine collectors using river for transport	Decreased productivity by 14%	
Fish and wildlife losses	Decreased productivity of fisheries	6 SE states of USA Uganda
Infrastructure		
River weir	Washed away due to pressure from water hyacinth	Nseleni River, South Africa
1 of 5 turbines of hydro-power generation dam closed	Metal surface corroded due to build-up of sulphur dioxide under a water hyacinth mat	Kafue River, Zambia
Human health		
Malaria	Increase in vector-borne diseases	Uganda

Water hyacinth also has some positive uses. It can be processed in many ways, including: as feed for cattle, sheep and pigs; mulch and compost for crop production; fibre for paper-making, weaving baskets and mats; biological filtration; and the production of biogas (methane). Large-scale processing of water hyacinth, however, is seldom commercially viable as the plant is 96% water and harvesting is thus very expensive. It is possible, however, to make a living by processing water hyacinth on a small scale. The promotion of use for these benefits should probably be avoided, however, as no utilization programme will ever check the growth of water hyacinth, and promoting utilization will lead to the further spread of the weed as people become aware of its economic potential.

2.2.3 Control options and their effectiveness

Water hyacinth can be controlled in a number of ways (Table 3). In some cases, the removal of small amounts of water hyacinth by hand may be the only control that is necessary. Specialised machines are also available in a wide variety of sizes and with various accessories for removing water hyacinth in a number of situations. Small machines are available that are practical for limited areas, as well as large machines in combination with transport and shore conveyors for large whole-lake operations. Mechanical removal is an important method of water hyacinth management in certain circumstances because of several advantages it has over other methods: 1) immediate control can be achieved in small areas; and 2) harvesters can be used effectively in emergencies, e.g. providing temporary access for boats and the clearing of water intake pumps of hydroelectric power generators at some dams.

Table 3: The options for controlling water hyacinth, the inputs required and their effectiveness, as reported in the literature and from expert observations.

CONTROL OPTION	INPUTS	COUNTRY	EFFECTIVENESS
Mechanised control	Harvester, excavator, labour, dump site	Uganda	An excavator & harvester can clear 1 000 tonnes day^{-1}
	Cables & floating booms	Throughout its distribution	Highly effective at preventing spread
Hand-removal	Rakes, pitchforks, labour	Throughout its distribution	Effective on small dams Ineffective in larger infestations
Biological control	Neochetina eichhorniae and N. bruchi (leaf-feeding weevils)	Effective in: Lake Victoria, Papua New Guinea, Benin, Malawi and several systems in S Africa	Effective when combined
	Niphograpta albiguttalis (moth)		Most effective in thinned mats of water hyacinth
	Orthogalumna terebrantis (leaf-mining mite)	Less effective where systems are highly eutrophic and where the climate is temperate	Effective but restricted to warmer parts of Africa
	Eccritotarsus catarinensis (leaf-sucking mired)		
Herbicides control	Herbicides[1], labour, helicopter or light aircraft		Effective in small, single-purpose water systems (e.g., canals & dams)

* *Note: the references for this information and more detailed explanations are presented in Appendix 4.*

The amine and acid formulations of 2.4-D and glyphosate

The effective use of mechanical harvesters for aquatic weed control is limited, however, as the method requires a high capital outlay (harvesters can cost up to US$ 1 million). In addition to the initial cost of the machine are the high operating costs and the costs of removing water hyacinth material. Floating booms can also be used effectively to limit spread in some cases. This technique is very cost effective but it limited to use on rivers before and after they flow into lakes or dams. Floating booms have also been used successfully to prevent water hyacinth entering hydroelectric water intake pumps.

Herbicide control of water hyacinth has been practiced since the early 1900s. Application of herbicides includes aerial spraying from a helicopter, fixed wing and micro-light aircraft. High pressure motorized units mounted on boats and used in smaller infestations in navigable waters and knapsack sprayers are used along river banks in limited areas. Herbicide control of water hyacinth depends on skilled operators who maintain a long-term follow-up programme to continually control re-infestation from scattered plants and those germinating from seed. Therefore, any herbicide programme against the weed requires a commitment to an ongoing operation of unlimited duration. It is the lack of a rigorous follow-up regime that has often led to the failure of herbicide control programmes.

The negative impacts of herbicides on the environment have often been used to promote alternative control methods for water hyacinth. These negative impacts include the potential threat to human health in rural areas of the world where communities used untreated water for domestic use; the threat of herbicide residues in the aquatic ecosystem; the threat of de-oxygenation of the water column following decomposition of large mats of water hyacinth following treatment; and the general perception that herbicides are poisons. The majority of herbicides currently being used in water hyacinth control, whilst not ecologically benign, impact the environment considerably less than mats of water hyacinth. However, the concern of spray drift onto non-target vegetation is real and demands responsible use of herbicides by highly trained personnel.

Biological control is important, and probably essential, for the long-term, sustainable control of water hyacinth. Five biocontrol agents are believed to be effective in reducing water hyacinth to levels that do not cause ecological and economic injury. However, climate (cold and floods), watershed management (nutrient enrichment) and herbicide control often have a negative impact of biocontrol agents, thereby reducing their overall effectiveness. The available agents and their effectiveness are summarised in Table 3.

The biological control of water hyacinth has been extremely effective in some systems around the world, including the rapid reduction of the weed on Lake Victoria, Papua New Guinea, Benin, Malawi and several systems within South Africa. However, it has been less effective in other areas, where the systems are nutrient-enriched or where the climates are more temperate. In these systems the biological control takes longer (up to 10 years) to reduce the weed to an acceptable level, or it needs to be integrated with additional control options.

2.3 Larger grain borer

2.3.1 Introduction, spread and areas at risk

The larger grain borer is a species of beetle endemic to meso-America, where it has long been known as a pest of maize grain. It was an accidental introduction to Africa in the early 1980s, and it is now recorded from 18 African countries. It is also highly likely to have invaded other countries.

Figure 4: The larger grain borer (picture by G. Goergen)

Natural dispersal through flight is slow, and the maize trade has been responsible for its wide occurrence, mainly through movement of grain (Table 4). Since its first reported sightings in East Africa, (1981) and West Africa (1984) the larger grain borer has progressively extended its range in many countries of Africa. The introduction of the larger grain borer in Tanzania, for example, had been reported by farmers in Western Tanzania in 1980. Between 1980 and 1984 the beetle had spread into Kenya, and is also known to be present in Uganda, Rwanda, Burundi and the Democratic Republic of the Congo (Table 4). The presence of the larger grain borer in Benin was first reported in 1986, and since then has become a major pest of stored maize and dried cassava in several West African countries (Togo, Benin, Guinea-Conakry, Ghana, Burkina Faso, Nigeria, and Niger). Between 1991 and 1998, it was recorded 6 countries in southern Africa (Malawi, Zambia, Namibia, Moçambique, Zimbabwe and South Africa).

Table 4: Natural spread rates (ha yr^{-1} or meters yr^{-1}) of the larger grain borer as reported in the literature from field and laboratory experiments and estimates of the effect of human-interference through the trade in grains on spread rate. Detailed explanations of these data and references are presented in Appendix 5.

COUNTRY	SPREAD RATE	TIME
Natural spread		
Central Mexico	50 to 100m	per day
Yucatan	85 m	per day
Honduras	Over 150 m	per day
Human-interference through grain trade		
Benin (Mono province)	47 500 to 100 000 ha	per year
East Africa[1]	-	16 years
West Africa[2]	-	14 years

[1] *Including Tanzania, Kenya, Burundi, Rwanda & Uganda*

[2] *Including Togo, Benin, Guinea-Conakry, Ghana, Burkino Faso, Nigeria, Niger and Guinea-Bissau*

It is likely that this species will spread to any areas where grains are grown and stored, if it is not already there. This assumption should be adopted unless it can be shown that certain growing areas are not at risk. Recent monitoring of larger grain borer in South Africa has shown that the insect is no longer spreading southwards and prefers warmer climates than those found in the southern regions of Mpumalanga.

2.3.2 Impacts and benefits arising from invasion

The larger grain borer is a major pest of staple food commodities in Africa, especially farm-stored maize and dried cassava, where it causes large losses at farm and village level. The adults feed by tunneling through maize cobs and a typical sign of larger grain borer attack is the presence of flour. Larger losses occur when maize is stored on the cobs compared with when the maize is shelled. Reported losses range between 20 and 60%, and in severe infestations even more (Table 5).

Table 5: A summary of the impacts (% increase in losses) of larger grain borer on stored maize grain and cassava chips, as reported in the literature and from expert observations. The references for these data, and more detailed explanations behind their estimation, are presented in Appendix 5.

LAND-USE TYPE	IMPACT	COUNTRY
	30% increase in dry-weight losses of maize	Tanzania
Stored maize grain	23% increase in dry-weight losses of maize	Togo
	34%, 56% and 60 % after 3, 6 and 9 months of storage	Kenya, Tanzania, Togo
Stored cassava chips	20% increase in mean dry-weight losses	Togo

These substantial impacts on stored maize stocks have associated serious financial and economic implications for farmers and traders. When the pest attacks the grain or any other food crop, it also deposits excreta, which renders the remaining food unattractive and unpalatable for human or animal consumption. The larger grain borer is a pest species, and does not have any positive uses.

2.3.3 Control options and their effectiveness

Attempts to control the larger grain borer focus on reducing its numbers (and therefore its effects) in stored grain. The larger grain borer is highly susceptible to synthetic pyrethroids that have a relatively low toxicity to the other pests. Therefore, insecticide mixtures such as permethrin and pirimiphos methyl were developed to control the larger grain borer and other important post-harvest maize pests. In addition to insecticides, the larger grain borer is also highly susceptible to several fumigants, which can be used in large warehouses, but not normally for the disinfestation of smallholder stores (Table 6).

Table 6: The options for controlling larger grain borer, the inputs required and their effectiveness, as reported for a range of African countries in the literature and from expert observations. The references for these data, and more detailed explanations behind their estimation, are presented in Appendix 5.

CONTROL OPTION	INPUTS	COUNTRY	EFFECTIVENESS
Chemical control[1]	Permethrin and pirimiphos methyl; fumigants like phostoxin	East & West Africa	*P. truncatus* is highly susceptible to these insecticides and fumigants
Improved storage	Mud silo; Improved Ikenne Maize variety; insecticides	Benin	Decreases stored grain losses by about 40%
Biological control[2]	Teretrius nigrescens (histerid predator)	SE Kenya	80% decline in *P. truncatus* abundance over a 5-year period
		SW Benin Togo	lower infestation levels of and losses reduced by 56.4 % and losses by 47.4 % in the release cribs
		Togo	*P. truncatus* was reduced by 80% in 1st season & 73% in 2nd 34.3% reduction in losses

[1] *Stored maize must be chemically treated within the first three to four months after harvest (GTZ, undated a & b).*

[2] *The German government funded US$ 7.5 million through GTZ for the bio-control programme which was implemented in three countries: Togo, Benin, Guinea Conakry*

The introduction of a biological control agent to stored grain can also reduce damage. Only one biological control agent (the histerid predator *Teretrius nigrescens*) has been introduced to Africa (Table 6). It was first released in Togo in 1991 and subsequent releases of the predator have been carried out in Benin, Ghana, Kenya, Zambia, Guinea-Conakry, and Tanzania. Several evaluations have revealed that the use of this control agent can reduce damage significantly.

The impacts of the larger grain borer can also be reduced by using modified storage and harvesting techniques. A number of techniques can be used to lower the risk of damage to stored grain by the grain borer. These include, for example, checking for signs of damage and rejecting damaged cobs prior to storage; timely harvesting, about 3 weeks after physiological maturity; and artificially drying the maize before storing. Existing store residues should be removed and the new harvest should be treated with recommended insecticides (where these cannot be afforded, inert dusts and botanical pesticides can be used, but are less effective). A closed storage system should be used (mud silos for example) to prevent larger grain borer getting to the crop, hence the need to artificially dry the crop prior to storage.

2.4 Parthenium weed

2.4.1 Introduction, spread and areas at risk

Parthenium is an annual much-branched herb of about 0.3 to 1.5 m height, native to tropical and subtropical America. Populations of parthenium occur in north-east Africa as well as in South Africa.

(A) (B)

Figure 5: The plant (A) and flower (B) of a parthenium weed plant. Parthenium weed matures quickly and produces large quantities of seed (up to 100 000 seeds per plant. The weed can flower year round. Photos: A) Larry K. Allain and B) Colin G. Wilson.

Parthenium was first recorded in Ethiopia at the Alemaya University campus in 1968. In South Africa, although parthenium was recorded in KwaZulu-Natal as far back as 1880, it appears to have become troublesome only since the 1980’s. There may thus have been two separate introductions into South Africa with only the second becoming invasive, as was the case in Australia. Parthenium became very abundant in KwaZulu-Natal after the cyclone “Demoina” hit this region from the east in 1986 causing widespread damage and creating ideal conditions for an aggressive pioneer plant like parthenium to establish. Once established, parthenium spreads rapidly by first colonizing disturbed areas before invading natural vegetation. Parthenium weed has also recently been recorded from Zimbabwe, Moçambique, Madagascar, Mauritius, and Seychelles. It is suspected that parthenium entered Maputo harbour in Moçambique through grain seed imports, possibly also food-aid.

Judging by the history of spread of parthenium so far, it can be assumed that the chances are small that it will not also spread to other African countries with a compatible climate. Because of its innocent appearance at low densities the weed is easily overlooked during the early stages of invasion. It is only several years after establishment that parthenium becomes noticeable. It would not be surprising if the weed is already present in many African countries besides the ones mentioned above. Predictions using climatic suitability modelling indicate that the weed will establish in all tropical and sub-tropical regions of Africa with the exception of the dry Sahara/Sahel areas, the deserts of Somalia, the dry north-western parts of South Africa and the Namib (Figure 6).

Figure 6: Predicted distribution of *Parthenium hysterophorus* in Africa, using the CLIMEX prediction programme. It is predicted that the weed will establish in all tropical and sub-tropical regions of Africa, with the exception of the dry Sahara/sahel areas, the deserts of Somalia, the dry north-western parts of South Africa and the Namib.

2.4.2 Impacts and benefits arising from invasion

The impacts of parthenium are numerous and are most profound on livestock and grain cropping productivity, and on human health. Parthenium is highly toxic to domestic animals and animals avoid eating it. If eaten, however, the meat gets tainted and this causes direct economic losses. There are many reports of yield losses in numerous crops and orchards that have been invaded by parthenium (Table 7). Crop losses are caused primarily through allelopathic effects over and above its ability to compete for nutrients and moisture and these losses are often proportionally higher than expected from a similar crop weed. Another mechanism by which parthenium impacts upon crop productivity is through its ability to cover crops in pollen, which prevents seed set with resulting losses in yields of up to 40%. Many anecdotal descriptions on the impact of parthenium on biodiversity are available but no quantitative data is provided.

Table 7: A summary of the impacts of parthenium weed on agricultural productivity, human health and the environment, as reported in the literature and by experts. Detailed explanations and the references for these data are presented in Appendix 6.

LAND-USE TYPE	IMPACT	COUNTRY
Agriculture		
Sorghum	45% to 80% yield reduction	Ethiopia
	35% (from 6.5 to 4.3 t ha^{-1}) yield reduction	India
Cattle	25 to 80% yield reduction	Australia
Pasture/forage	10 to 90% yield reduction	India
Environment		
Species loss (forest gaps)	69 to 95%	India
"Total habitat change"[1]	100%	Australia
Human health[2]		
Allergies (e.g., rhinitis)	20% of population in infested area affected	Australia
	7 to 42% of population in infested area affected	India

[1] *Of grasslands, open woodland, riverbanks & flood plains*

[2] *Measured as a % of the population in the infested area*

The impacts of parthenium weed on human health are also significant. Between 10 and 40% of people living in infested areas suffer serious allergies, with corresponding reductions in quality of life and productivity (Table 7). Parthenium has led to almost epidemic incidences of allergic eczematous contact dermatitis (AECD) from contact with the plant and pollen. AECD was first reported amongst labourers in rural India in 1971, about 16 years after parthenium's arrival, and was later found in increasing numbers of city dwellers. It usually takes 2-4 years of exposure to parthenium to develop allergies but it can take up to 10 years. It also causes allergenic eczematous bronchial and contact asthma. There is no effective treatment for these allergies other than to leave the area. Medical treatment focuses on alleviating symptoms. The figures on allergies caused by parthenium are expected to be higher in Africa than in developed nations because mechanical control (hand-weeding) is likely to be the predominant control method, particularly in rural, subsistence-farming areas.

2.4.3 Control options and their effectiveness

Preventing spread: Preventing the spread or introduction of parthenium weed to new areas should be a priority in any areas that are at risk. Spread from the margins of existing infestations is difficult to control. By contrast, long-distance spread or "jump-dispersal" is due to human activities that include moving contaminated machinery, vehicles, livestock and agricultural produce. These pathways are controllable (as was shown in Australia) and may include wash-down facilities for vehicles and machinery at strategic points; mandatory inspections of produce and machinery leaving infested areas; the adoption of codes of practice by agribusinesses; the maintenance of a parthenium taskforce with trans-boundary powers and that can eradicate new incipient infestations; and the promotion of awareness and commitment (Table 8).

Eradicating small, isolated populations: It is also possible to eradicate small outbreaks of parthenium if they are identified at an early stage (as has been demonstrated in the Northern Territory and New South Wales of Australia). These outbreaks were located at boat ramps, camp grounds and roadsides and there is convincing evidence that these introductions were the result of vehicles arriving from Queensland. Recognizing incipient populations is probably one of the most crucial parts of the parthenium program in Australia, as it would be in Africa.

The control of parthenium in cultivated areas: The control of parthenium in mechanized cultivations is not a serious problem, as the weed is susceptible to many conventional herbicides widely used in crops (Table 8). It does mean one or two additional treatments per season, which could almost double the cultivation costs. The contamination of crops with parthenium seeds is a much more serious problem for subsistence and small-scale farmers. It may be necessary to introduce restrictions on farmers for selling or moving products contaminated with parthenium seeds to address this problem.

Table 8: The options for controlling the parthenium weed, the inputs required and their effectiveness, based on literature reports and expert observations in Australia, India, Ethiopia and South Africa. Detailed explanations and the references for these data are presented in Appendix 6.

Control option	Inputs	Effectiveness	Country
Mechanised control	1 to 2 additional sprays per cropping season	95%	Australia
Hand-weeding & deep ploughing	40 – 140 days[1] labour - 10 days per ha	Effective in small, isolated areas; combine within integrated approach	India Ethiopia South Africa
Biological control	*Zygogramma bicolorata* (leaf feeding beetle) and *Epiblemma strenuana* (stem galling moth)	Highly effective but influenced by weather (rainfall)	Australia
Preventing long-distance dispersal	Wash-down facilities for vehicles; mandatory inspections; adoption of codes of practice by agribusinesses	Highly effective but costly	Australia

[1] *100 plants per square meter*

Considerable indigenous farmer knowledge on parthenium management exists amongst subsistence farmers in Ethiopia and India. This includes the careful choice of more competitive crop varieties and intercropping between rows which smother crops e.g. cowpea and mung bean and others. Proper management of parthenium during fallow periods and repeated deep plowing and the choice of appropriate sowing rate and date and the selection of fertilizers are further options developed by these farmers to reduce the impact of the weed

Biological control: Biological control is particularly attractive as a long-term control, as it is inexpensive, permanent and perpetual. Several effective biological control agents are already available and can be introduced and released with a minimum of additional research required. Six potential agents have been released for biological control, mainly in Australia. The two most important species that became established are *Zygogramma bicolorata* (leaf feeding beetle) and *Epiblemma strenuana* (stem galling moth) and they have a significant impact on parthenium in Australia (Table 8). Only *Z. bicolorata* was released in India where it caused widespread defoliation, permitting local vegetation to grow again. In Australia, *E. strenuana* can exert significant control but erratic rainfall has disrupted the moth populations, reducing them to very low levels. Populations take a long time to build-up again, usually too late to have a significant impact on the weed.

The initially promising *Z. bicolorata* beetle caused severe defoliation of parthenium following release, but this was short-lived as the beetle failed to adjust to the variable rainfall. Recent reports from India suggest that the beetle can cause 99.5% decline of weed populations. However, biological control in India had a temporary set back when it was discovered that the *Z. bicolorata* beetle was feeding on sunflowers. This unnatural feeding on a non-host was artificially induced by parthenium pollen that covered sunflower leaves and which provided the cue to the insects to feed. It was shown that this was not a host switch and only a temporary behaviour for as long as parthenium was so dense. Unfortunately this incidence generated much suspicion on the merits and safety of biological control.

Chemical control: So far, no chemical herbicides are registered for the control of parthenium, but it can be classified under common crop weeds for which a long list of herbicides is registered.

2.5 Triffid weed

2.5.1 Introduction, spread and areas at risk

Triffid weed (*Chromolaena odorata*), also known as chromolaena or Siam weed, is native to the Americas, from southern Florida to northern Argentina, including the Caribbean. Triffid weed is a pioneer species where it is indigenous, but is one of the worst invading alien plant species in the humid and semi-humid tropics of the Old World. The species has been introduced separately to both western (originally to Nigeria in 1937) and southern Africa. It is thought that the invasion in West and Central Africa is secondary, via Asia, whereas that in southern Africa is primary, originating from the Caribbean. By 1960 it occupied the southern states of Nigeria from where it spread to Cameroon and southern Cote d'Ivoire. By 1965 it was established in the western and central-southern Ghana and southern and central Nigeria. By the early 1970s it was recorded from Togo, the Central Africa Republic, Gabon and Congo Brazzaville. In the 1980s it was recorded in Benin northern Democratic Republic of Congo and Sierra Leone. In the 1990s it was recorded in Liberia and northern Angola. There have also been, as yet unconfirmed, reports of it in the savannas of Uganda. In southern Africa, the weed was first introduced to Durban in the 1940s. Its mode of introduction is uncertain, but it possibly came in as seed in packing material, or as a garden ornamental. Between 1960 and 1962 the distribution stretched from Port Shepstone to Gingindlovo. By the 1970s it had spread throughout the subtropical regions of KwaZulu-Natal Province and by the 1980s was present in the Eastern Cape. It was first observed in eastern Swaziland in 1987 and Phalaborwa in 1991. Triffid weed is ranked as the fastest-spreading species after aquatic invaders.

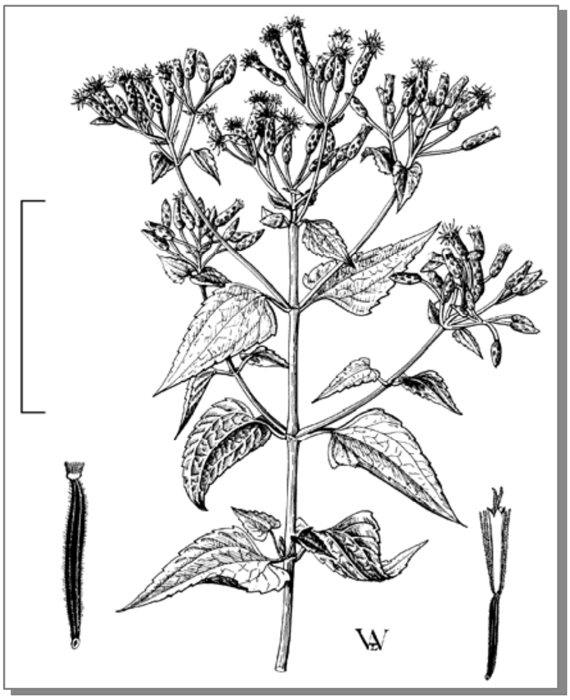

Figure 7: Triffid weed, *Chromolaena odorata*
(Drawn by A. Walters)

Infestations of triffid weed tend to be extensive in moist, frost-free vegetation types. It will probably not become an extensive problem in frost-free savanna areas of Africa that are water stressed in the growing season. It has been predicted that the species is likely to become invasive in several other southern African countries, including Moçambique, Zimbabwe, Malawi, Zambia, Tanzania, Botswana and Angola.

Triffid weed impacts on human welfare through its effects on the productivity of crop and pastoral agriculture and biodiversity (Table 9). Triffid weed has a high growth rate and reproductive output, in the form of thousands of light, wind-dispersed seeds. It has a smothering habit and allelopathic properties. It increases the intensity, range and frequency of fires, and it carries veld fires into the forest, killing forest species. Triffid weed also increases the live biomass of invaded areas and has been estimated as being responsible for the loss of 68.3 million m^3 of water per annum in South Africa, impacting significantly on groundwater flows and runoff. The foliage is reported to be toxic to livestock. In West Africa, the weed is found on food crop farms growing maize, groundnut, cowpea, plantain, rice, yam and cassava, and on industrial or cash-crop farms growing cocoa, oil, palm, coconut, coffee, rubber and sugarcane. For most crops, losses due to triffid weed range between 30 and 35%, increasing up to 40% for crops such as cocoa and coffee.

Table 9: A summary of the impacts of triffid weed on agricultural activities (crops and livestock) and on the environment, as reported by experts and in the literature. Detailed explanations and the references for these data are presented in Appendix 7.

ACTIVITY	IMPACT	COUNTRY
Agriculture		
	Increased rice yields by 15% when used as a green manure	India
Crops	Reduces most crops yields by 30 35%	Ghana
	Yield losses of 40% for crops such as cocoa & coffee	Ghana
	Major pest in plantation crops e.g., cashews, peppers, rubber	India
Pasture & livestock	Reported to decrease pastureland for grazing	Congo
	Decreases carrying capacity by 60% (from 6 ha per Large Stock Unit to 15 ha per LSU)	Kube Yeni reserve, South Africa
Environment		
Grassland	“Affects grassland species composition”	African sub-tropical grasslands
Nile crocodile	Changes the sex ratio to a female bias	Lake St Lucia, South Africa
Evapo-transpiration	Increased evapo-transpiration (68.3 million m^3 of water yr^{-1} from condensed invaded area of 43 180 ha)	KwaZulu-Natal, South Africa
Forest	Carries fire into forests and kills forest species	
Grassland & Forests	Decreases carrying capacity and species diversity	

[1] *Of grasslands, open woodland, riverbanks & flood plains*
[2] *Measured as a % of the population in the infested area*

Despite its wide range of negative impacts, the status of triffid weed is controversial in African agriculture. In central Africa several agricultural systems are practised in which triffid weed is shown to have uses. It is the preferred fallow in shifting agriculture because it reduces the labour required for land preparation and weeding. In rangeland it is forcing cattle farmers to reduce stocking rates and to adopt more intensive management systems. In conservation it is believed to prevent soil erosion and promote the rehabilitation of climax forest in degraded areas.

2.5.2 Control options and their effectiveness

The control options available for triffid weed include mechanical, herbicidal and biological control (Table 10). Each of these options has certain benefits and certain drawbacks. The most cost-effective approach is an integrated management approach where all of the control options are used in the most appropriate manner.

Slashing and uprooting of triffid weed is labour intensive and often creates an environment for further weed invasion. These techniques are best suited to fallow cropping systems where clearing efforts can be combined with soil preparation.

South Africa and Australia are the only two countries that have investigated the registration of herbicides for triffid weed and are the two countries that have applied the highest volumes of chemicals against the weed. Some limited herbicide control, however, has been used in the Congo. By 1995, seven formulations comprising 16 products had been registered in South Africa. These include 11 foliar, two cut-stump and three soil applications. Commercial enterprises (e.g. forestry companies) employ chemical control effectively but this method may not be appropriate for the subsistence farmers in Africa.

Table 10: The options for controlling triffid weed, the inputs required and their effectiveness, from reports and expert observations in South Africa and Ghana.

CONTROL OPTION	INPUTS	COUNTRY	EFFECTIVENESS
Mechanical & chemical	Labour, equipment and herbicides (quantities differ between initial & follow-up clearing)	South Africa	-
Biological	*Pareucheates pseudoinsulata* (moth)	Ashanti region of Ghana	Reduced infestation from 85 to 32%
	Calycomyza flavinotum (leaf-mining fly) *Parachaetes insulata* (defoliating moth)	South Africa	Established; no quantitative data on effectiveness

The biological control programme was initiated against triffid weed in 1988. To date two agents, the leaf-mining fly (*Calycomyza flavinotum*) and the defoliating moth, (*Parachaetes insulate*) have established in South Africa (Table 10). Several other agents are currently being screened in quarantine to assess their potential impact and safety. Initially the moth did not establish and this was eventually ascribed to biotype mismatching of the plant.

Further introductions of the moth from Jamaica (the source of the South African biotype of the weed) have established. The biological control programme against triffid weed is still in its early stages and quantitative post-release evaluations and pre-release evaluations on additional agents are ongoing. The biological control programme against the West African biotype of the weed has been more successful. In the Ashanti region of Ghana, the biological control programme using the moth *Pareucheates pseudoinsulata* has reduced triffid weed populations from 85% infestation to 32% infestation and indigenous herbs and grasses have recovered.

3. METHODS

3.1 Assessing the economic value of controlling invasive species

In this section the evaluation framework to assess the economic impacts and the options to control (slow, contain or reverse) the spread of five invasive species already present in Africa is presented. Conceptually the spread of an invasive alien species over an area of land (or, in the case of species such as water hyacinth, over the surface area of a body of water) can be represented as depicted in Figure 8.

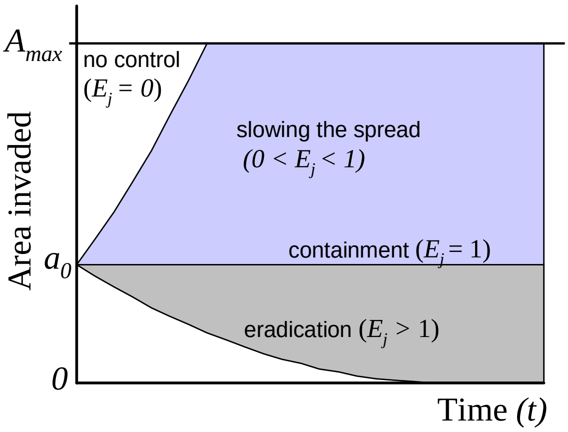

Figure 8: The trajectory of the area invaded by an invasive species under no control compared with slowing down, containing and eradicating the invasive species.

In the absence of control, the area occupied by an invasive species is assumed to increase at a rate defined by the maximum rate of spread of the species *s* (ha yr^{-1}). This rate of spread can be reduced below *s* by implementing control measures and the magnitude of this reduction in spread rate is determined by the effectiveness (E_j) of the control option '*j*' and is measured as a fraction of the spread rate. The range of possibilities is illustrated in Figure 8. The effectiveness of control depends on many factors including, but not limited to: the intensity of control, the stage of the invasion (density and area), topography, and the type of invasive species.

When no control is undertaken ($E_j = 0$) the area invaded increases at the rate *s* until the entire area at risk (A_{max}) is invaded. Partial control ($0 < E_j < 1$) can slow the spread and, although the entire area at risk will eventually be invaded, delaying this means that the benefits from the uninvaded area are obtained for a longer period and so the option has value. Slowing the spread also enhances the possibility of making eradication feasible if new technologies become available in the future (Cacho *et al.*, 2006). Total containment of the invasion ($E_j = 1$) is illustrated by a horizontal line (Figure 8), where the area invaded remains constant indefinitely. Finally, eradication is illustrated by the negatively-sloped curve ($E_j > 1$) meaning that the invasive species will eventually be eliminated.

The optimal control strategy depends on the relative magnitude of the social net benefits of the invasive species and the costs of controlling the invasive species. Therefore, the optimal level of control can only be determined by means of an economic evaluation of all benefits and costs associated with the presence and control of the invasive species compared with it's the base case of not undertaking any control measures at all.

Associated with the presence and spread of an invasive species are many costs and benefits experienced by both producers and consumers. The benefits from invasive species are, however, generally much smaller than the costs, but in some cases, particularly rural poor communities, the benefits have been found to be large. The effects of invasive species are imposed on both producers and consumers through the changes they bring about by out-competing other species. In extreme invasive species-affected situations, land-users may need to adopt entirely new production systems or completely rehabilitate the ecosystem. These impacts have direct economic implications; some of which increase the costs of production and others reduce the value of the good or service.

Given that there are benefits from reducing these negative effects of invasive species and that costs are incurred in obtaining these benefits (including forgone benefits derived from the invasive species), from an economic perspective there is an optimal level of invasive species-associated losses and invasive species control[1].

Environmental economics provides the appropriate theory and has a suite of tools available to assist decision- and policy-makers weigh up these trade-offs to ensure scarce resources are allocated efficiently between competing demands and in so doing contributes to maximising social well-being. The two main economic decision-support tools available that are particularly suited to assessing the benefits and/or costs of alternative options to control or not to control invasive species are the cost-benefit analysis (CBA) and the cost-effectiveness analysis (CEA) techniques.

Cost-effectiveness Analysis is used as an economic decision-support tool to determine the least-cost way of achieving a predetermined physical or environmental goal. It can also be used to identify and evaluate a means of maximising an environmental or physical benefit for a given economic cost. In other words, CEA contributes to choosing between levels of invasive species-induced losses (production and health) and expenditures on control, with the objective of minimising total cost.

Cost-benefit Analysis is an economic decision-support tool that is designed to show whether or not the total benefits to society of a project, policy or programme, measured in economic terms, outweigh the costs of implementing that project, policy or programme. In other words, the decision criterion is the present value of Net Social Benefits. Applying this to invasive species, CBA provides the framework to determine and weigh up the net benefits of control versus no control to maximise society's well-being. This is the most widely accepted technique for determining and comparing the economic viability of projects/policies as it is explicit in its dealings with the use (direct and indirect) and non-use benefits and costs derived from invasive species and their control.

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[1] And, in cases where the benefits from invasive species are greater than the costs this may include scenarios where it is optimal to leave the invasive species to spread uncontrolled.

The theory underlying each of these techniques is described in detail in Appendix 1. The CBA technique only is adopted in this study and was implemented using the framework described in the flow diagram depicted in Figure 9.

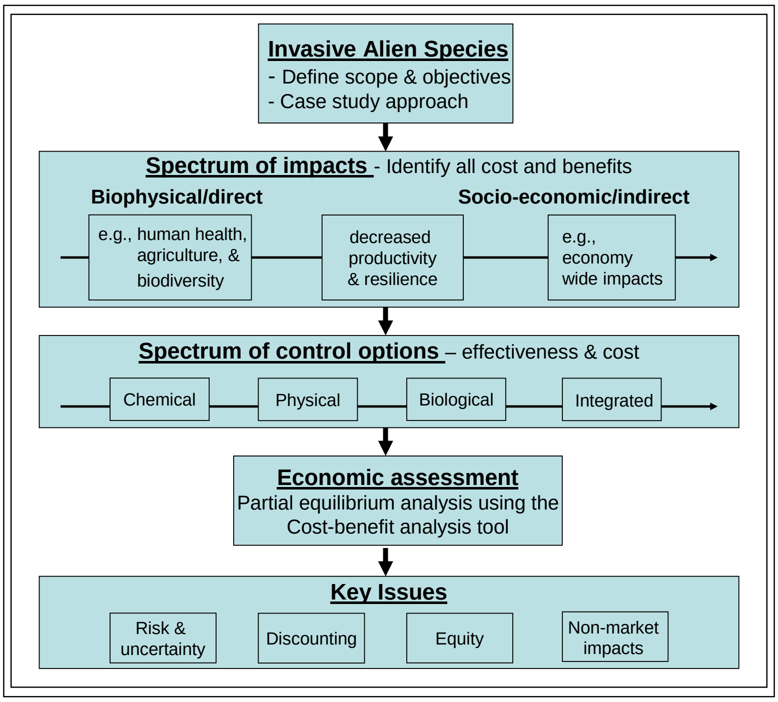

Figure 9: The major elements of a framework for costing the impacts of invasive species and invasive species control.

The economic model underlying the CBA and used to account for the flow of benefits and costs and to estimate the present value of the Net Social Benefit of control versus no control under various spread rates and control options is presented in algebraic form in Appendix 2. It is important to emphasise that the economic model presented in Appendix 2 is a generic model that uses the Total Economic Value criterion to estimate Net Social Benefit and that it is a dynamic model that accounts for changes in spread rate, and the varying degrees of effectiveness of control.

The Total Economic Value (TEV) is defined as the sum of the “actual use value” the “option value” and the “existence value” of resources. All attempts at estimating of TEV are estimated on a per unit basis (e.g., per hectare) and an ‘invaded TEV’ and ‘uninvaded TEV’ value for each resource type (land or water) is calculated, which is then multiplied by the total invaded and uninvaded areas of each resource, respectively. The TEV concept and its calculation are described below.

3.1.1 Estimating Total Economic Values (TEV)

An environment confers benefits on users, and those who, while not using it directly, derive pleasure/happiness (utility) from knowing that it is there. The 'use' benefits are derived by two types of consumer: 1) individuals who make actual use of the environment such as farmers, fishermen, recreationists, and polluters, and 2) individuals in either present or future populations that are potential users of the environment. The benefits derived in the former type of user are from their '*actual use values*' and in the latter case from their '*option values*'. Option values are defined and measured by economists as: "a *willingness to pay* for the preservation of an environment against some probability that the individual will make use of it at a later date" (Pearce *et al.,* 1989). A third type of benefit derived from the environment is the satisfaction and/or knowledge that the quality or existence of the environment is maintained and is available to others, even if not directly experienced or used by the individuals themselves. This is called its "*existence value*". When valuing the environment, it is essential that all of these values be included so as to reflect its 'true' value to society. In environmental economics this is achieved using the Total Economic Value (TEV), which is the sum of all three values:

$$TEV = Use\ value\ +\ Non\text{-}use\ value \qquad (1)$$

The per hectare TEV is estimated as best possible within time and data constraints, for an uninvaded area and for an invaded area in the case study region and then multiplied by the total area in order to estimate the Net Social Benefit to the area. TEV (the values and quantities used to estimate it) is made a function of the spread and density of the invasive species, under control and no control, and Net Social Benefit is evaluated over an appropriate time horizon to determine the PV of the various control options available.

3.1.2 The decision rule

The general model presented above was used to estimate the Net Social Benefit of all available scenarios and control options for each invasive species by modifying it to the particular characteristics of each invasive species, their impacts and the physical and socio-economic environments. In other words, case studies will differ both in the number and magnitude of goods and services provided from the ecosystem concerned, and in the number of control options available to deal with the species in that particular environment. The estimates of Net Social Benefits were then compared to determine the optimal control strategy using the decision rule:

> "*If the net social benefits from not controlling the invasive species are less than those from controlling the invasive species spread (including the costs of control, C_j), then control option j should be adopted, otherwise not*".

This can be represented algebraically as:

If	$NSB_{j=0} \leq NSB_{j>0} - C_{j>0}$	adopt control option $j > 0$	*(2)*
If	$NSB_{j=0} \geq NSB_{j>0} - C_{j>0}$	allow species to spread (i.e., $j = 0$)	*(3)*

where NSB_j is the Net Social Benefit, calculated using equation 1.4 and C_j is calculated using equation 1.14, in Appendix 2.

Relating this decision rule to the conceptual framework described above; when no control is undertaken (i.e., $j = 0$) the contribution to NSB_0 from the uninvaded area is given by the shaded area (a_0 v A_{max}) in Figure 10 and the contribution to NSB_0 from the invaded area is given by the shaded area (0 a_0 v w) in Figure 10. If control is implemented ($j > 0$) and eradication, for example, is possible then the contribution to $NSB_{j>0}$ from the uninvaded area is given by the shaded area (a_0 x z A_{max}) and $NSB_{j>0}$ from the uninvaded area is given by the shaded area (a_0 x 0). The same approach applies when calculating the Net Social Benefit from containing, slowing or reversing the spread of an invasive species.

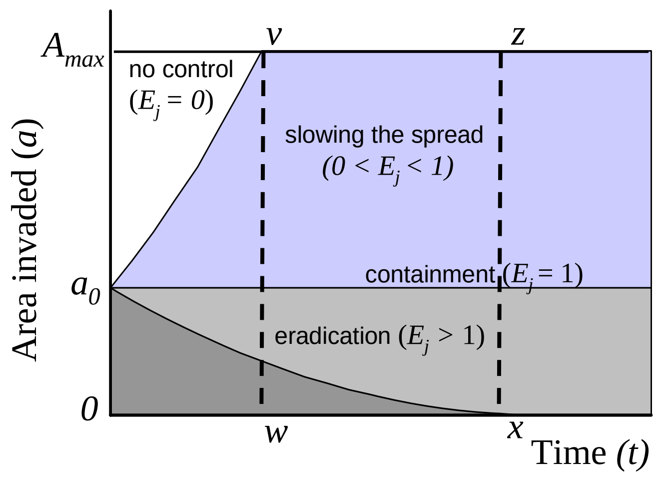

Figure 10: The relationship between the trajectory of the spread of the invasive alien species and its impact on the present value of Net Social Benefits.

3.2 Approach to case studies

3.2.1 Nile tilapia

The economic analysis of the impacts of the Nile tilapia in Lake Victoria focused on the Kenyan fisheries only. The approach to the economic analysis was determined and constrained by the characteristics of Nile tilapia as an invasive species and the limited options available for controlling it. For example, the economic analysis did not evaluate the *control* of Nile tilapia because none exists. Also, the physical impacts of economic significance are limited to the local extinction of indigenous *Oreochromis* species, and its ability to increase and sustain the total annual catch.

The impact of the local extinction of indigenous *Oreochromis* is impossible to value in monetary terms and is therefore only included qualitatively in the discussion; however, the rapid decline in catch of indigenous species over time has negative economic effects in the form of losses of choices and preferences and is included in the economic analysis by means of the premium paid for indigenous fish. The economic benefit of larger catch sizes comes in the form of increased revenues to fishermen. The economic analysis simply compared the annual total economic returns to fisheries in the presence of Nile tilapia at three rates of increase (15%, 35% and 50%) in the proportion of catch made up of Nile tilapia, to those that existed before invasions.

3.2.2 Water hyacinth

Case study 1: Mossapoula River in the Central African Republic: The Mossapoula River is a tributary to the Sangha River in the Dzanga-Sangha Reserve, which is in turn a tributary to the Congo River in the south-western part of the Central African Republic. A section of the Mossapoula River is regularly used by the local community for economic activities such as transport, fishing and accessing palm wine. The presence of water hyacinth in this area was first recorded in 1996, by which stage it was already well established, particularly in the middle-section of the river, where it is able to cover 100% of the water body during the dry season. The degree to which these infestations affected people's ability to pursue net-based fishing, spearfishing and palm wine collecting was estimated by means of a questionnaire survey. The economic evaluation focused on determining whether the economic benefits of controlling the water hyacinth exceed the costs of implementing a biological control programme or not, in terms of the economic benefits derived from the above three activities. These were then compared within a cost-benefit analysis (CBA) framework to determine whether control was cost effective, and whether or not it should be applied immediately, or delayed for either 5 or 15 years.

Case study 2: Nseleni River in South Africa: The Nseleni River is in the northern KwaZulu-Natal province in South Africa. Water hyacinth was first recorded on the Nseleni River and Lake Nsezi in 1982, and over the next few years it came to threaten many aspects of the functioning of the socio-economic systems in the area including: 1) local communities who are dependent on the river for fish protein and irrigation; 2) the general public who rely on the road bridge over the river, which is in danger of being destroyed if large mats of water hyacinth build up against it; 3) the Richards Bay Minerals company who abstract water from the river; and 4) the Mhlatuze Water treatment plant which sources its water from this river. A programme of integrated control has been in place in the area for many years, and good data were available on control costs and the effectiveness of control.

The economic analysis was limited to estimating the costs currently being experienced by the community and tourists due to the presence of water hyacinth. The costs were estimated in terms of the direct costs to the water users and the lost benefits that would normally have been received from the direct-use of the river and lake system but which are no longer available because of water hyacinth. The main beneficiaries in the area were: 1) large raw-water extractors including Richards Bay Minerals and the local water utility; 2) local fishermen; 3) irrigation farmers and 4) recreational users, particularly birdwatchers.

Cost-benefit analysis was used to compare the costs of control, or no control, with the levels of benefits derived. Four scenarios were evaluated: a base-case scenario representing the current levels of the invasion, and three control scenarios. In the base-case scenario the invasive species was left uncontrolled and therefore covered the entire river and lake. The control scenarios included the immediate implementation of a control programme, or the delayed implementation of control for 5 or 15 years respectively.

3.2.3 Larger grain borer

Case study 1: Maize storage in the Mono Province of Benin: The economic analysis of the impacts of larger grain borer in Benin focussed on maize only. The analysis evaluated whether it would be optimal for farmers to store their harvested maize to receive a higher price while bearing the risk of losing part of the harvest to grain borers, or to sell the harvest immediately at a lower price and avoid potential losses. In the former case, where farmers store their maize to add value, three storage options were evaluated. These options were ‘typical storage’ without any pre-and post-harvest handling; improved storage techniques; and improved storage techniques plus biological control. Three scenarios for improved storage, and improved storage and biocontrol were also investigated, whereby their dates of implementation were varied from immediate, to being delayed for 5 or 15 years.

Case study 2: Impacts on dried cassava in the Northern Province of Ghana: This analysis focused on cassava only. In this case there is no price incentive to store cassava, as the crop is not a cash crop, but increasing population pressure and food demands have necessitated that the traditional practice of storing the root crop underground be abandoned to free the land for other productive uses (i.e., the opportunity cost of storing cassava in the ground has become too large). The analysis examined the relatively newly adopted practice of storing cassava chips aboveground, with and without biocontrol. Again, three scenarios were investigated in which control was either implemented immediately or delayed for 5 or 15 years.

3.2.4 Parthenium weed

The economic consequences of parthenium weed were analysed at two sites in the Mpumalanga Province of South Africa. The analysis included both small-scale farming (subsistence farmers) and commercial farming areas, with a focus on the former, as the effectiveness of control, and the economic consequences of parthenium on commercial agriculture are relatively well known. The main agricultural activities investigated included maize, cattle, Soya-beans and vegetable crops. Listed market prices for both small-scale and commercial farming products were used in the analysis, and the predicted impacts of the weed on human health, and on productivity, were also considered. The costs of control were based on hand-weeding in the case of small-scale farmers, and on chemical control in the case of commercial farmers. The economic implications of implementing control were investigated for immediate implementation, or delayed implementation for 5 or 15 years.

3.2.5 Triffid weed

Case study 1: The Hluhluwe/Imfolozi Reserve in South Africa: The Hluhluwe/Imfolozi Reserve is an important nature reserve and tourist attraction in the South African province of KwaZulu-Natal. The main economic benefits derived from this area are based on tourism, and on the sale of captured game animals including the rare black rhino. Triffid weed was first identified in Hluhluwe/Imfolozi Reserve in the early 1970s. Control projects initiated in earnest in 2004 have experienced some success in controlling the weed over the past three years. The size of the Hluhluwe/Imfolozi Reserve is about 96 000 hectares, with a triffid weed invasion level of about 50% of the park (with infestation levels ranging from < 5% to > 75%). However, a lack of data on tourism and animal sale income, and the absence of a demonstrated link between these factors and triffid weed infestations, precluded a rigorous economic analysis of impacts. Consequently, the economic analysis focussed on the best use of control-cost data by developing a model for comparing the costs of control under a range of invasion scenarios involving different initial invasion sizes and impacts. These results were used to estimate the minimum returns that were required to cover the costs of control. The present values of the costs of control of triffid weed were estimated over 30 years for three scenarios and two control options. The three scenarios were initial invasion sizes of 4 320, 28 512 and 57 024 ha (5, 33 and 66% of the total reserve, respectively). The first control option involved the mechanical[2] clearing of the entire invaded area over 7 years, and the second involved clearing 50% of the invasion, and containing the remainder. Finally, the relatively crude auction data were used to estimate a rough minimum value for the revenues lost due to the presence of triffid weed.

Case study 2: The Ntambanana district in KwaZulu-Natal, South Africa: The Ntambanana district is approximately 80 km from the Hluhluwe/Imfolozi Park, where traditional tribal authorities own most of the land. This study focussed on a 13 000 ha government cattle farm in the district. The potential carrying capacity is approximately six hectares per live stock unit (LSU). Since a hectare of land can produce 0.17 LSU, the potential carrying capacity of the farm is approximately 2 200 cattle. By 1995 a severe triffid weed infestation had reduced the grazing potential by 64%. We evaluated the impact of triffid weed on the production of cattle and on whether it would be feasible to introduce mechanical control of the weed. The CBA model was used to evaluate three scenarios of varying levels of invasion and two control options in the same way that was done for the Hluhluwe/Imfolozi Park.

[2] Biological control could not be estimated because to date no effective biological agent has been found and no data exist on the costs and effectiveness of such control.

4. RESULTS OF THE ECONOMIC EVALUATIONS

4.1 Nile tilapia

The study showed that the introduction of Nile tilapia to the Kenyan fisheries along Lake Victoria increased the total economic returns by between 2 and 12% (for example, assuming a pre-invasion annual catch level of 3 000 tonnes, the value of the fishery was increased from US$24 million to US$26 million). This increase equates to an average increase in total economic return to the region of between US$28 714 and US$92 179 per year or US$0.67 and US$2.14 per fisher per year. The Nile tilapia's contribution to the total catch from Lake Victoria is, however, relatively small compared with Nile perch and dagaa, and since Nile tilapia is the primary cause of the local extinction of indigenous *Oreochromis* species it is questionable whether this extremely small increase in total economic return per fisher justifies its introduction. This is in contrast with the significant economic benefits derived from the introduction of Nile perch and dagaa, which have also led to the decline in many of the indigenous fish species in the lake. The relative contributions of Nile perch, dagaa and Nile tilapia to the total catch in 2006 (estimated to be 101 000 tonnes) are 35%, 51% and 11%, respectively and their relative contribution to the total value of this catch (estimated to be US$75 million) are 60%, 24% and 12%, respectively (O. Mkumbo, pers. comm., 2006).

As fisheries are highly variable, and there are several unknowns, we tested the sensitivity of our analysis to variations in catch size; spread rate; and price of fish. The introduction of Nile tilapia has a positive economic impact on the fishery (between 7 and 37%), for all values of the variables tested, when the average price of indigenous *Oreochromis* species is low. However, when this price reaches US$ 1.3 kg^{-1}, Nile tilapia actually has a negative economic impact (between 0.1 and 0.7%) over the 30 years investigated if its catch, spread rate and price are low. This emphasises the desirability of future research and the likely importance of developing and introducing appropriate management and harvest regimes to African fisheries.

4.2 Water hyacinth

Case study 1: Mossapoula River in the Central African Republic: Biological control improved the total economic returns from palm wine collection and gill net fishing by between 1 and 6% and 4 and 22% respectively, depending on whether it was introduced immediately or postponed for 5 or 15 years. The control had a negative impact on spear fishing, but this accounted for a relatively small proportion (8.7%) of the total economic returns. On a per capita basis these equate to increases in returns of US$2.1 - US$7.0 per year for palm wine collectors and US$16.3 - US$103.1 per gill-net fisher per year. In contrast, water hyacinth has significant positive consequences for spear fishermen, equating to US$13.4 and US$73.3 in lost revenues due to the introduction of biological-control agents. As none of the non-market and non-use benefits of controlling water hyacinth have been included, our estimates of the benefits of control are almost certainly conservative. The benefit-cost ratios for immediate control, control postponed for 5 years and control postponed for 15 years were between 5 and 5.6. In other words, control is worth investing in because benefits increases by US$5 or more for every dollar invested in the control of water hyacinth.

Case study 2: Nseleni River in South Africa: The estimated annual losses in income due to water hyacinth invasions amounted to US$58 195 and this decreased to US$7 000 with the immediate implementation of a biocontrol programme. Postponing the biocontrol programme still reduced the losses, but the reductions were not nearly as great. The net present value of the avoided costs ranged from US$ 1.5 million for immediate implementation, to $1 million and $400 000 when implementation was delayed by 5 or 15 years respectively. The cost of biological control was US$ 48 000, yielding a benefit: cost ratio of 31:1 for the immediate implementation of control. A particularly interesting finding, however, is that the benefit cost ratio increases to 67:1 with a five-year delay. This is because of the effects of discounting, which make the large up-front costs of the biological-control programme decrease by 69% if postponed for 5 years, whereas the benefits of control only decrease by 33%.

4.3 Larger grain borer

Case study 1: Maize storage in the Mono Province of Benin: Storage of maize increased the total annual economic returns from US$ 9.6 million (when sold immediately) to US$ 14.4 million. Thus economic incentives clearly exist for farmers to store their harvested grain and risk larger grain borer attack. The economic implications of implementing an improved storage programme with or without biocontrol further increased these returns to US$ 17.6 and US$ 20.4 million, respectively. Even when control is delayed by 15 years, farmers still benefit from its implementation, but the total economic return to farmers would only increase by between 4% and 7% compared with the no control scenario. These results indicate that the control of larger grain borer by means of improved storage and biocontrol programmes is economically beneficial to the region and to individual farmers. The benefit: cost ratio for immediately implementing improved storage was 3.6, while that associated with improved storage and biocontrol was 15.6. Since these ratios are greater than unity, controlling larger grain borer is economically worthwhile.

The economic effectiveness of a control programme often depends on the magnitude of the damage caused by the invasive species, the effectiveness of the control option implemented, and the costs of implementing control. The sensitivity of the BC ratio to changes in each of these variables was investigated.

The economic return increased as the effectiveness of control increased and as the damage caused by larger grain borer increased. For example, each 10% increase in damage from 10% to 40% led to a 100%, 50% and 33% increase in the benefit: cost ratio, respectively, for both the improved storage and the biocontrol control options; each 10% increase in improved storage effectiveness from 20% to 50% leads to a 50%, 33% and 25% increase in the benefit: cost ratio, respectively; and finally each 10% increase in biocontrol effectiveness from 5% to 35% leads to a 30%, 23% and 19% increase in the benefit: cost ratio, respectively. For most combinations of damage and effectiveness, investing in the control of larger grain borer gives positive returns. It was only when the damages caused by larger grain borer were small (approximately 10%) that the economic effectiveness of control became questionable.

Case study 2: Impacts on dried cassava in the Northern Province of Ghana: The annual total economic returns from typical storage were estimated at US$507 000 for typical storage. These increased to US$564 000 and US$514 000 for the immediate or delayed implementation of biological control, respectively. The question of whether it is economically feasible to control larger grain borer is particularly relevant for cassava, which is not as profitable as other crops such as maize. The most important economic consequences of implementing control are: 1) the immediate implementation of biocontrol increases the total economic return to the region by 11% (from US$507 860 to US$564 179), which equates to an increase of US$6 per farmer per year; and 2) delaying control by 15 years improves the annual TER to farmers by only 1% (which is equivalent to only US$ 0.4 per year). In other words, biocontrol is clearly beneficial to cassava farmers if implemented immediately and delaying control has almost no positive economic effect on farmers. However, benefit: cost ratios were less than unity (0.44 for the immediate implementation of control and 0.39 for delayed control) indicating that, irrespective of the delay in its implementation, a negative return is received for each dollar invested. These low returns are unsurprising considering that cassava is not a cash crop and is grown primarily for food security reasons. It needs to be acknowledged that although the returns to the investment derived from cassava growers are less than half the amount invested there are likely to be co-benefits to biocontrol from other agricultural crops and natural vegetation in the region which are likely to make the total return on the investment positive.

4.4 Parthenium weed

The analysis showed that if parthenium spreads as it is expected to, and if no control is implemented, small-scale farmers would suffer a decline in total economic returns of between 26 and 41%, which equates to an annual loss in total economic revenues to each small-scale-farming family in the region of between US$ 87 and US$ 136 per year. Commercial farmer's annual total economic returns would decline by between US$ 38 818 and US$ 60 957.

In the case of small-scale farmers, the analysis showed that they were left slightly worse off from controlling the parthenium weed compared to not undertaking any control, for either immediate or delayed implementation. This finding was due to the assumptions that the impact of parthenium on productivity and health remains constant over time and that control only changes the area invaded and not the density of the invasion. These assumptions had to be made because very few data exist for changes in density over time and for the relationship between damage and density. If, however, more data were available on the changes in density over time and how this relates to declines in productivity, it is expected that control would realise benefits to small-scale farmers.

Commercial farmers, on the other hand, benefited substantially from implementing control. Their total economic returns increased by 49% in the case of immediate control, and by 13% when control was delayed by 15 years.

The sensitivity of benefit: cost ratios was investigated by changing 1) the effectiveness of control (varied between 10% and 50% for small-scale farmers and between 80% and 95% for commercial farmers), and 2) the damage caused by parthenium (varied by 30% on either side of the mean). In general, investing in control became profitable (BC ratio $\geq$ 1) for small-scale farmers when the effectiveness of control reached 50%, irrespective of the damage caused by parthenium. The only situation where a lower level of effectiveness was economically feasible occurred when the damage caused by parthenium was high (30% greater than expected). In the case of commercial farmers, a relatively similar pattern was found, where control was only economically feasible when its effectiveness reached 95%, irrespective of the level of damage. If the damage caused by parthenium increases by 30% above its average, however, an effectiveness of only 80% also give positive returns. Benefit: cost ratios were relatively small (i.e., close to unity), and ranged from 0.16 (with 10% control effectiveness and little damage expected), to 5.37 (with 95% control effectiveness and a large degree of damage expected). In view of this uncertainty, it would be necessary to develop a clear understanding of the damages and effectiveness of control before undertaking a control programme.

4.5 Triffid weed

Case study 1: The Hluhluwe/Imfolozi Game Reserve in South Africa: Depending on the initial size of the infestation, the present value of control operations varied from US$ 2 million (for 4 000 ha), to US$ 12 million (for 28 000 ha) and US$ 24 million (for 57 000 ha). This provides an indication of the net present value of additional economic returns (i.e., those that would not accrue to a reserve that became fully infested by triffid weed) that would be required from the productive use of all sources in the reserve to justify the expense of the control programme.

Case study 2: The Ntambanana district in KwaZulu-Natal, South Africa: The annual total economic returns from cattle sales in the presence of triffid weed infestations ranged from US$ 447 000 (for 5% invasion), to US$ 382 000 and US$ 270 000 for 33 and 66% invasions respectively. The introduction of a mechanical control programme saw these annual returns rise to US$ 509 000, US$441 000 and US$361 000, respectively. Thus irrespective of the area of the invasion when control is first commenced, there are economic benefits to its implementation (with the average net returns increasing by between 7 and 34%). Secondly, the greater the area of the initial invasion the greater the percentage improvement in average net returns. These three scenarios delivered cost: benefit ratios of 3.1, 1.9 and 1.7 respectively.

5. ECONOMIC IMPACTS EXPRESSED PER UNIT AREA OR PER CAPITA

Very few studies, if any, provide estimates of the economic impact of invasive alien species on a per capita or per unit area basis. Estimates of the economic impacts of invasive species are often expressed in terms of the total costs incurred in implementing and managing a control programme. Some studies present the impact in terms of the revenues lost due to the decreased productivity of the resource (i.e., decreased catch in fisheries, decreased yield from agricultural activities, and decreased productivity from labour) or in severe infestations where the invasive species has forced a change in land use, the opportunity/replacement cost is used. Again, these estimates are seldom given as per-unit-area or per-capita values, but are given for a region, sector, or at the national level. In this study of five invasive species, the focus was on determining (where possible) the Total Economic Value of the economic impact of each invasive species on a per-unit-area and/or per-capita basis. This was done using the available data reported in the literature and wherever possible supplemented with additional data from experts, government departments, and interviews with those affected by invasive species. For all estimates, the assumptions were made that the impacts of the invasive species, the effectiveness of control, and the benefits and costs incurred were all evenly distributed across space and the population. The results are presented on a case-study by case-study basis.

5.1 Nile tilapia

The Nile tilapia negatively impacts upon species diversity and positively impacts upon the size of catch in a fishery. The economic consequences of these biophysical impacts (both *use* and *non-use*) are both positive and negative. The economic value of the *direct-use* impacts are experienced as increases in income from fish sales and changes in the choices available to consumers (i.e., increased prices paid for the preferred indigenous tilapiine species). The economic values of the impacts of Nile tilapia on the *indirect-uses* and *non-uses* of indigenous *Oreochromis* species (i.e., benefits derived from the future possible use of biodiversity and from existence and bequest values) could not be quantified and are not included in these estimates. Consequently, the estimates presented here are conservative estimates.

The magnitude of the economic impact of Nile tilapia on the direct-uses of a fishery depends on whether the total catch increases, and whether the increase in total catch is sufficiently large to offset the lower price received for Nile tilapia. In the Kenyan fishery of Lake Victoria the economic impact of Nile tilapia, per fisher per year[3] ranges between -US$0.57 and US$3.4 depending on the pre-invasion and post-invasion catch sizes. The lower value in this range occurs when the pre- and post-invasion catches average 5 000 and 5 750 tonnes per year, respectively, and the upper value in the range occurs when the pre- and post-invasion catches average 3 000 and 8 000 tonnes per year, respectively. This range in economic impacts was found to be particularly sensitive to changes in the relative prices of indigenous tilapiines and Nile tilapia (see Appendix 3) and highlights how

[3] The nature of fish as invasive species makes it impossible to estimate the impacts of Nile tilapia on a per-unit-area basis.

marginal the economic benefits are of introducing Nile tilapia. This emphasises the importance of researching and evaluating the ecological and economic implications of introducing invasive species to new areas.

5.2 Water hyacinth

Water hyacinth negatively impacts upon aspects of water resource utilization including fisheries, transport, hydropower generation, irrigation, and the quantity and quality of potable water. The economic values of these impacts are generally reported in terms of the costs of controlling the weed, replacing the damaged infrastructure, or the lost revenue due to decreased productivity; and very few data exist on the per-unit-area or per-capita economic impacts. Other than the economic impact analyses of the direct-use impacts of water hyacinth on livelihoods undertaken in this study, De Groote *et al*. (2003) undertook a thorough economic impact assessment of water hyacinth in Benin. In that study, De Groote *et al.* (2003) estimated the per-capita economic impacts of water hyacinth in southern Benin, between 1991 and 1993, and found that: 1) the annual income to men (derived mainly from fishing) dropped from US$1984 to US$607 per person (31%); 2) the annual income to women derived from trading fish dropped from US$519 per person to US$137 (26%); and 3) the annual income to women derived from trading crops dropped from US$310 to U$193 per person (62%).

Along the Mossapoula River in the Central African Republic the per-capita economic impact of water hyacinth is both positive and negative (Table 11). The worst affected by water hyacinth are the gill-net fishers whose annual revenue decreases by $429 per year (26%) when water hyacinth is present. The per-capita economic impact on palm wine collectors is also negative, with their annual revenue decreasing by $127 per year (14%). Interestingly, spear fishers benefit from the suitable fish habitat provided by the weed, with their annual per capita revenues increasing by 113% or $351. The net effect of these economic impacts, however, is negative and if the annual per-capita cost of controlling the weed is smaller than this then control should be undertaken. In this case, compensatory payments to the spear fishermen may be required in order to effectively and efficiently control the weed.

In the Nseleni case-study, although water hyacinth could potentially impact upon three economic activities (irrigation water sales, industry water pumps, fishing, and bird tours), only fishing could be estimated on a per-capita basis (Table 11). In this case, water hyacinth has a negative impact of $158.7 per fisher per year. It is meaningless to estimate the impacts of the others on a per hectare basis therefore these impacts are not included here, but can be found in Appendix 4.

Finally, little or no data are available on the impacts of water hyacinth on biodiversity, although initial reports and observations clearly indicate the impacts are negative and are likely to be large unless controlled. Since no data were available estimates of these economic impacts could not be determined and this is highlighted as an important area for future research. There is a possibility that the water hyacinth provided a suitable environment for mosquitoes and other disease-carrying insects, which means possible negative economic impacts on human health; these too could not be quantified and were not considered.

Table 11: The per capita economic consequences (2006 US$ yr^{-1}) of the biophysical impacts on agricultural activities (% change in productivity) of water hyacinth at two sites: the Mossapoula River in the Central African Republic and the Nseleni River in South Africa.

WATER-USE ACTIVITY	POTENTIAL REVENUE[1]	IMPACT	ECONOMIC VALUE OF IMPACT
Mossapoula River (Central African Republic)			
Palm wine collection	893	- 14%	- 128
Spear fishers	1 638	+ 113%	351
Gill-net fishers	312	- 26%	- 429
Nseleni River (South Africa)			
Line fishers	159	- 100%	- 159

[1] The prices, quantities and assumptions used to estimate these values are listed in Appendix 5

5.3 Larger grain borer

The larger grain borer negatively impacts upon stored crops, particularly maize grain and cassava chips. The borer also impacts upon trees in savannas, woodlands and forest plantations. The economic consequences of the impacts on stored food crops, in terms of changes in revenues to farmers, have been estimated using storage-loss data from field and laboratory experiments and observed quantities and prices for each crop. The economic impact on native vegetation and tree plantations could not be estimated due to a lack of data quantifying the losses of timber and the extent and consequences (on biodiversity or tourism, for example) of borer attacks on woodlands and savannas. Since no data were available on the biophysical and economic impacts on woodlands and savannas this is highlighted as an important area for future research. Finally, the costs incurred to control larger grain borer are an additional economic impact and are discussed in Section 7.

The magnitude of the economic impact of larger grain borer depends on:

1. whether farmers sell their crops immediately to avoid losses from borer attack or whether they store their crops to receive higher prices (e.g., maize) or to free up the land for other productive uses (e.g., cassava);
2. the land-use type (i.e. subsistence or cash crops, woodlands, savannas, or forest plantations); and
3. the storage infrastructure and management practices adopted.

Since data on the impacts of larger grain borer were only available for stored maize grain in Benin and stored cassava chips in Ghana, these are the only economic impacts estimated and reported (Table 12).

Table 12: The per capita economic consequences (2006 US$ yr^{-1}) of the biophysical impacts (% reduction) of larger grain borer on stored maize grain in the Mono province in Benin and on stored cassava chips in the Northern region of Ghana.

STORE OPTION	POTENTIAL REVENUE[1]	IMPACT	ECONOMIC VALUE OF IMPACT
Maize grain - Benin			
Sell immediately	368.3	5%	18.4
Typical storage	874.8	40%	349.9
Improved storage	874.8	24%	209.8
Cassava chips - Ghana			
Sell immediately	276.3	10%	27.6
Typical storage	310.8	40%	124.3

[1] *The prices, quantities and assumptions used to estimate these values are listed in Appendix 5.*

In Benin the potential economic impact of larger grain borer (i.e., without control) per farmer per year, who on average stores approximately 2 000 kg of maize grain, is only US$18.4 if the grain is sold shortly after harvest as the borer has little time to cause damage. The economic impact, however, increases to about US$350 when the grain is stored in a ‘typical’ storage structure or to US$210 when stored in an ‘improved’ structure with appropriate management practices. It is noticeable that even with the large losses caused by larger grain borer it is still economically beneficial to store the grain to receive a higher price (Table 12). These losses can be still further minimised by introducing biocontrol (see Appendix 5).

The economic impacts of larger grain borer on cassava growers in Ghana range between US$28 and US$124 per farmer per year, depending on whether it is sold immediately or not. It is noticeable that the decision to store cassava, if larger grain borer is present and no control is implemented, results in a lower return than if it is sold immediately. This, however, does not include the cost of having to purchase food in the future for subsistence.

5.4 Parthenium weed

The parthenium weed negatively impacts upon cropping and livestock activities, wildlife numbers in conservation areas and human health. The economic values of the impacts on agriculture and human health have been estimated from the revenues lost as a direct result of the parthenium-induced productivity losses[4]. This is a minimum estimate of the economic impact on these activities as medical expenses will be incurred to treat those affected and, if control is attempted, the costs of control will add to the economic impacts of the weed (presented in Section 7). Finally, little or no data are available on the impacts of parthenium on wildlife and biodiversity, although initial reports and observations in the Kruger National Park indicate the impacts are negative and are likely to be large unless controlled. Since no data were available, estimates of the economic impacts on biodiversity could not be determined and this is highlighted as an important area for future research.

[4] It is sometimes necessary to estimate the cost of replacement if the infestation of the weed is severe enough to have stopped production entirely.

The magnitude of the economic impact of parthenium depends on: whether the farmer is a small-scale or commercial farmer; whether the agricultural activities are at low or high altitudes; and the land-use type.

In Mpumalanga the potential economic impact of parthenium per-unit-area of agricultural production ranges between US$30 and US$214 ha^{-1} for small-scale farmers and between US$38 and US$229 ha^{-1} for commercial farmers (Table 13). The lower values in these ranges relate to the revenues lost due to the decrease in cattle productivity, irrespective of altitude, and the upper values in these ranges relate to vegetable crops and soy-beans, respectively and occur at low altitude.

Chippendale and Panetta, (1994) estimated the economic impact of parthenium on the cattle industry in Queensland (excluding control costs) as follows: lower weight per head of cattle (US$43 per head); extra seed for pasture establishment (US$ 958 000); extra land preparation (US$ 1 526 250); extra forage to get animals marketable (US$ 218 000); machinery (US$ 130 600); and lost production other than cattle (US$ 345 300). The total of all these costs, directly attributable to parthenium, is US$ 12.7 million. This amounts to approximately 10.7% of the total income derived from cattle in this area (Queensland). No quantitative data on actual stock losses are available from India.

Table 13: The per capita economic consequences (2006 US$ yr^{-1}) of the biophysical impacts (% change in productivity) of parthenium on agricultural activities at two sites (low altitude and high altitude) within the Mpumalanga province, South Africa.

LAND-USE TYPE	POTENTIAL REVENUE[1]	IMPACT		ECONOMIC VALUE OF IMPACT	
		Low altitude	High altitude	Low altitude	High altitude
SMALL-SCALE FARMERS					
Maize	208	55%	25%	115	52
Cattle	100	30%	30%	30	30
Other	388	55%	25%	214	97
COMMERCIAL FARMERS					
Maize	417	55%	25%	229	104
Cattle	126	30%	30%	38	38
Soya-beans	416.4	55%	25%	229.0	104.1
Planted pasture	222.4	30%	30%	66.7	66.7
Other	388.1	55%	25%	213.5	97.0

[1] *The prices, quantities and other assumptions used to estimate these values are listed in Appendix 6*

The economic impact of the parthenium weed on human health in Mpumalanga was estimated at US$13.5 yr^{-1} and US$27.1 yr^{-1} for each of the expected 15% of the small-scale and commercial farms that would be affected, respectively[5]. This is a conservative estimate as it assumes only a single worker is affected per farm, that only 3 days per year are lost due to ill-health, and that no medical costs are incurred. This is significantly lower than the AU$500 per person per year estimated for Australian workers, where it is reported that five days per person per

[5] A wage rate of R65 per day (US$9.03) is used for the worker on the commercial farm and R32.5 per day (US$4.5) is used for labour on small-scale farms.

season is the average number of days lost and the average daily wage rate is AU$100. The per capita medical costs due to parthenium in affected areas in Australia is AU$6.90.

5.5 Triffid weed

Similar to parthenium weed, triffid weed negatively impacts upon cropping and livestock activities by decreasing the carrying capacity and species diversity of ecosystems (agricultural and natural). The presence of triffid weed also has silvicultural, logistical and economic implications, particularly as it is a fire hazard (it often carries these into forests). The foliage is also reported to be toxic to livestock.

The economic consequences of the impacts on agriculture can be determined relatively easily from the revenues lost as a direct result of the weed-induced productivity losses. This often gives a minimum estimate of the economic impact as other costs are often also incurred, including the costs of attempting to control the weed (discussed in Section 7) and, if harvested material has been contaminated by triffid weed, then an additional cost is incurred in the form of a lower price or the inability to sell the harvested material. Although an estimate of the minimum economic consequences of triffid weed can be relatively easily determined, very few have been reported in the literature, particularly on a per-unit-area basis. In this report, an estimate of the per-hectare economic consequences of triffid weed on livestock production in KwaZulu-Natal was determined as US$59.3 per hectare, where it was reported that triffid weed reduced grazing potential by 64%[6].

The economic consequences of triffid weed on biodiversity and conservation have not been determined due to a lack of understanding and data on the relationship between the density (extent) of the weed, the damages it causes to wildlife and biodiversity, and the resulting affects on tourism and/or game sales. The lack of understanding and data on these relationships between density, damage and economics is highlighted as an important area for future research.

[6] Here we have assumed that the resulting decline in stocking numbers is directly and proportionally related to the decline in land productivity.

6. COSTS OF CONTROL

The costs of control are determined by the rate at which the invasive species spreads, the density and area of the infestation, the time or delay in implementation of control and the effectiveness of control. Consequently, the costs vary over both space and time. Each of the control options was evaluated in terms of its costs and effectiveness and the results of these analyses are presented in Section 4 and discussed in detail in the Appendices. The costs of control reported in the literature and by experts in the field are listed and described in this section on a per-hectare and/or annual basis. Where possible, all relevant information is given on how these values were calculated.

6.1 Nile tilapia

6.2 Water hyacinth

Water hyacinth can be controlled by: 1) manually (mechanically) removing the weed, 2) aerially or hand-spraying herbicides, 3) introducing biological agents and/or 4) adopting an integrated approach that includes all of these and aspects of nutrient control. Each of these options, along with their relative effectiveness, advantages and disadvantages, was described in detail in Section 2.2.3. The costs associated with the activities involved in the various options, as reported in the literature or observed in control programmes, are listed in Table 14.

In the cases of mechanised and chemical control, the per-hectare costs are relatively low (between $36 and $400 per ha), but the cost-effectiveness of these options depends on the size of the area and the goal of the treatment. If the area is large (> 100 ha, for example) and the goal is eradication, these options are inappropriate as they are unlikely to succeed and be cost-effective. In such cases (i.e., where eradication is the goal and the invaded area is large) biological control and integrated approaches are more likely to succeed and be cost-effective, even though the upfront costs are often large (i.e., the R&D costs alone are between $110 000 and $210 000 per year over 10 years). In other words, the observed and reported effectiveness of the latter two options relative to the former two (see Section 2.2.3), make the large upfront investments worthwhile, as indicated by the large benefit: cost ratios estimated by De Groot *et al.* (2003) for the biocontrol of water hyacinth in Benin, and McConnachie *et al.* (2003) for the biocontrol programme implemented to control the red water fern (*Azolla filiculoides*) in South Africa.

Finally, it is essential to emphasise that irrespective of how effective biocontrol is, water hyacinth will tend to re-establish if the nutrient status of the aquatic ecosystem is not also managed appropriately, which requires continuous commitment from private individuals and companies causing the eutrophication to invest in appropriate management practices and technologies that prevent excessive nutrients being discharged into the system.

Table 14: The economic costs (2006 US$) involved in the relevant aspects and activities of the four options available to control water hyacinth, taken from a range of reports in the literature and numerous experts. Detailed explanations of these data and the references are presented in Appendix 4.

CONTROL OPTION	DESCRIPTION	COST	COUNTRY
Mechanised control Successful in short-term, but expensive as follow-up operations are required (up to 20 years)	35 women are paid to remove the weed using pitchforks	$ 1.25 per day	Kunming Lake, China
	Harvester, excavator, labour, dump site	Harvester: $1 million Operating: "high" Disposal: "high"	Owen Falls Dam, Uganda
Chemical control Successful in short-term, but expensive as follow-up operations are required (up to 20 years)	Aerial application	$ 400 ha-1	South Africa
	Hand-spray application[1]	$ 36 ha^{-1}	Nseleni River (100ha), S. Africa
Biological control A cost-effective option but takes 3 to 5 years to achieve control. Generally involves release of N. eichhorniae & N. bruchi	Requires Research & Development (R&D)	R&D[2]: $109 000 yr^{-1} for 6 years	South Africa
		R&D: 10-year present value $2.09 million (1999 US$)	Southern Benin
	Rearing of beetles; equipment; labour for implementing and monitoring	Expert to site: $1 500 Expert time: $ 800 Lattice pools: $ 320 Bio agents: $1 000 Miscellaneous: $ 560 Annual: $ 12.5 ha^{-1}	Mossapoula River (100ha) Central African Republic
Integrated approach Most effective option: the correlation between nutrient status of the aquatic system & water hyacinth is managed	Spraying & manual clearing were initially used with bio-control	Establish: $6 270 ha^{-1} Recurrent[1]: $ 64 ha^{-1}	Nseleni River (410ha), South Africa

1 *Includes labour, petrol and chemicals*

2 *Excluding the contribution to salaries made by the Agricultural Research Council and various universities (estimated to be an additional 35%) and the cost of lost production of the water body while control takes effect (up to 5 years)*

6.3 Larger grain borer

There are no reports in the literature of attempting to eradicate larger grain borer because eradication is deemed to be impossible in any practical and cost-effective sense. This is primarily because the borer is able to live and multiply in natural vegetation (savannas, woodlands and forests) surrounding agricultural areas and will always re-establish in treated areas once control has ceased. Attempts to control the larger grain borer therefore focus on reducing its numbers and minimising its impact on stored grain. Three control options are practiced, normally in an integrated manner, namely chemical (insecticide) control, improved storage, and biological control. These were discussed in detail in Section 2.3. The costs associated with each option, expressed on a per-farmer basis, are summarised in Table 15.

The annual costs for chemical control and integrated storage are the sum of the expenses incurred in drying the harvested material, purchasing insecticides, labour, and interest repayments on loans to build the necessary infrastructure for drying and storing the crops. The establishment cost for improved storage is actually incurred periodically, as the storage facilities last for 15 or so years. The economic analysis of improved storage (Appendix 5) indicates that, for most scenarios and assumptions for prices and costs, investing in control increases the economic returns to farmers.

The time-averaged present value of the establishment cost of this biological control programme per country is US$218 000 which is very similar to the US$209 000 reported by De Groote *et al.* (2003) for the large-scale biological control of water hyacinth in Benin. The variable cost of US$11 780 per country per year is for the mass rearing and release of the histerid, and includes all labour and equipment costs. The returns to such a large investment were estimated in Appendix 5 using the benefit: cost ratio criterion and were shown to be significantly larger than the costs.

Table 15: The economic costs (2006 US$) of the options available to control larger grain borer, taken from a range of reports in the literature. Detailed explanations and the references for these data are presented in Appendix 5.

CONTROL OPTION	DESCRIPTION	COST OF CONTROL	COUNTRY
Chemical[1]	Insecticides: permethrin and pirimiphos methyl; fumigants like phostoxin	Annual: \$15 yr^{-1} per farmer[4]	East & West Africa
Improved storage[2]	Mud silo; improved Ikenne maize variety; insecticides	Establishment: \$151 per farmer Annual: \$26 yr^{-1} per farmer	Benin
Biological[3] *Teretrius nigrescens* (histerid predator)	Requires Research & Development (R&D) Recurrent rearing, releasing, & monitoring	- Establishment: \$218 000 yr^{-1} per country over 6 years Recurrent = \$11 780	SE Kenya SW Benin Togo
Prevention	R&D; education; training; improve quarantine & monitoring; enforce legislation; Int'l cooperation	-	-

[1] *Stored maize must be chemically treated within the first three to four months after harvest (GTZ, undated a & b).*

[2] *The maize is handled pre- and post-harvest (see Appendix 4 for details), treated with recommended insecticides and stored in a closed storage system (mud silos).*

[3] *The German government contributed US$ 7.5 million through GTZ for the bio-control programme which was implemented in three countries: Togo, Benin, Guinea Conakry*

[4] *The average farm size is 0.8 ha, which will make the costs in the table larger on a per-hectare basis*

6.4 Parthenium weed

The most effective control of parthenium depends upon the extent of the infestation and whether it is in an agricultural or natural environment. If the weed is already established and it is in an agricultural system, particularly a commercial crop, the weed can be effectively controlled through the application of herbicides at a cost of between \$0.64 ha^{-1} and \$70 ha^{-1}, depending on the size of the area, type and quantity of herbicide and whether applied aerially or by hand. For small-scale, subsistence farmers, where herbicides are often not affordable or available, hand-weeding and deep ploughing combined with planting other grasses to compete are the only options, and the cost ranges between \$14 and \$45 ha^{-1} depending on the opportunity cost of labour. This, however, excludes medical costs and days off work that 15 to 45% of individuals allergic to the weed experience. The use of herbicides in natural environments tends to be more expensive as it needs to be focussed and done by hand.

Reports from Australia overwhelmingly state that preventing the spread of parthenium is the most appropriate and cost-effective way of controlling the weed. This however, involves an initial outlay of approximately US\$3.4 million and an annual cost of US\$2.9 million. The key to the success of this approach has been the holistic and comprehensiveness of the approach which involved education and training, implementation of appropriate legislation, and monitoring and enforcement.

Table 16: The economic costs (2006 US\$, unless otherwise stated) of the options available to control parthenium weed, from experts and a range of reports in the literature. Detailed explanations and the references for these data are presented in Appendix 6.

CONTROL OPTION	DESCRIPTION	COST	COUNTRY
Mechanised Hand-weeding & deep ploughing	Hand-weeding 100 plants per square meter	\$14 to \$42 ha^{-1}	India
	40 – 140 days labour	-	Ethiopia
	10 days per ha	\$45 ha^{-1}	South Africa
Chemical 1 to 2 additional sprays (aerial or hand-spray) per cropping season	Atrazine-based mixtures @ 3 l per hectare	\$70 ha^{-1}	South Africa & India
	Total cost of \$1 121 000 to aerially spray 17 542 km^2	\$0.64 ha^{-1}	Australia
Biological *Z. bicolorata* (leaf feeding beetle) & *E. strenuana* (stem galling moth)	Requires Research & Development (R&D) Recurrent rearing, releasing, & monitoring	(1991 US\$) \$181 500 yr^{-1} (1975 – 90)	Australia
		\$69 500 yr^{-1} (2000 – 06) \$138 900 yr^{-1} (2007)	South Africa
Preventing long-distance dispersal	wash-down facilities; mandatory inspections; eradication; adoption of codes of practice	\$4 667 000 yr^{-1} to \$6 426 000 yr^{-1}	Queensland & NSW Australia

6.5 Triffid weed

Triffid weed can be controlled by mechanical, herbicidal and biological methods and each of these has its advantages and disadvantages. The most cost-effective and sustainable approach is an integrated management approach (US\$35 to US\$125 ha^{-1}, depending on weed density) where all of the control options, particularly biological control, are used in the most appropriate manner. Fire can also play an important role in the control of this weed, but also presents certain environmental problems (Appendix 7). Although mechanical and chemical control are more costly than using biological control (Table 17) they have been widely and intensively adopted in South Africa's Working for Water programme. This is largely because the programme was also designed to provide employment and because, until recently, biological control in South Africa has not been effective. Recent introductions of the defoliating moth, *Parachaetes insulata,* from Jamaica (the source of the South African biotype of the weed), however, have established and if this proves to be as successful as the biological control programme in Ghana (using the moth *Pareucheates pseudoinsulata*) which reduced triffid weed populations from 85% infestation to 32% infestation then the US\$231 000 invested annually over the last 7 years is expected to reap positive returns. However, because the biological control programme against triffid weed is still in its early stages, quantitative post-release evaluations and pre-release evaluations are ongoing.

Table 17: The economic costs (2006 US\$, unless otherwise stated) of the options available to control triffid weed in South Africa, from experts and reports in the literature. Detailed explanations and the references for these data are presented in Appendix 7.

CONTROL OPTION	INPUTS	COST
Mechanical Physical removal of weeds (excl. herbicides)	85 man days ha^{-1} in dense stands	\$770 ha^{-1}
	Labour + equipment	\$140 ha^{-1} plus frequent, long-term follow-up costs
	Initial clearing	\$224 ha^{-1} (1670ha)
	Follow-up clearing	\$185 ha^{-1} (1670ha)
Chemical	Herbicides	\$70 ha^{-1} \$40 ha^{-1} (1670ha)
Integrated	Initial clearing	\$125 / dense ha \$83 / medium ha \$35 / light ha
	Follow-up clearing	\$35 ha^{-1}
Biological *C. flavinotum* (leaf-mining fly) *P. insulata* (defoliating moth)	Research & development incl. salaries & overheads	\$231 000 yr^{-1} (2000 – 2007)
	Annual costs	No data available

7. SIMILAR SPECIES, AND COSTS AND STRATEGIES FOR PREVENTION

The five invasive species investigated in this report have very different modes of spread, life cycles, invasion pathways and options for control, and therefore the similar species and the costs of preventing their introduction need to be discussed separately. The strategies for prevention, however, are quite similar for most invasive species and a generic list of these prevention strategies is listed first. Very few estimates of the costs of these prevention strategies exist; therefore little can be presented on the costs of prevention. Where examples do exist, however, as in the case of the parthenium-prevention programme in Australia, the costs of prevention are listed and discussed.

Preventing the introduction and/or further spread of an invasive species requires that the prevention programme/strategy be comprehensive, regional, and financially sustainable. Some of the essential components that are required for any prevention programme to have a high chance of succeeding include:

- Knowledge and understanding of the present distribution and likely pathways of spread of the invasive species;
- The availability of infrastructure and trained personnel at all levels of society from landowners to government officials;
- The appropriate legislation that: limits dispersal through traffic and trade; prohibits the import of certain high risk commodities; and gives authorities a mandate to enforce these activities;
- A well-developed monitoring and surveillance programme (including quarantine) including the appropriate technology, equipment and staff training
- Research into identifying possible entry routes which need to be surveyed and inspected on a regular basis;
- Adequate and sustained financial backing; and
- The establishment of codes of good practice by government, landowners, traders and agribusinesses.

7.1 Nile tilapia

The costs of prevention of the spread of Nile tilapia are impossible to calculate as this is not a species that can be removed or eradicated once it is in a system. The costs of preventing further spread of the species are primarily for the development and dissemination of extension and education messages, for monitoring, and for management and conservation. For invasive alien fishes in general, the prohibition of movement of such fishes and effective enforcement is essential. A further unquantifiable “cost” of prevention of spread of the species is the loss of aquaculture and fisheries potential created by the greater growth and reproductive success of Nile tilapia in comparison with known indigenous tilapiine species.

7.2 Water hyacinth

Water hyacinth has a very wide distribution within Africa but as yet has not been recorded from Botswana. An early warning and rapid response system must be set up as a matter of priority to ensure that it does not get into that country. Some systems are in place, which include the spraying of boats coming into the country to remove any water hyacinth plants and seeds from boats and boat trailers. Furthermore, there are several species of aquatic plants that are known to be invasive in other parts of the world that have not yet been recorded in Africa. These include *Eichhornia azurea*, *Alternanthera philioxroides* and *Cabomba caroliniana*. The most likely mode of introduction would be through the aquarium trade into some of the more developed countries on the continent. Black listing these species and awareness in the aquarium trade would be the best methods for preventing introduction.

Hydrilla verticiliata has recently been recorded on the Pongolapoort Dam in KwaZulu-Natal Province of South Africa. Its distribution within Africa is, at present unknown. This example has highlighted the lack of knowledge on submerged aquatic plants. This knowledge gap needs to be addressed.

7.3 Larger grain borer

A storage pest that is very similar to larger grain borer is the khapra beetle, *Trogoderma granarium* (Everts) (Coleoptera: Dermestidae), which originates from India and thrives in hot (mean temperatures greater than 20°C) and dry (relative humidity below 50 %) conditions. The pest is found in food stores, fodder production plants, dried milk factories, stores of packing materials (used or unused sacks, bags, crates) and kitchen pantries. It is capable of maintaining its presence in stores in very low numbers and is able to survive long periods of inactivity. It can live up to seven years in the egg stage and at any stage during these years it is able to hatch, multiply and cause substantial damage to stored food, seeds and fodder. The presence of the beetle in stored grain can cause significant losses and in the case of seeds it may lead to significant reductions in seed viability. Grain weight loss often ranges between 5 and 30% but in cases of extreme infestations can be as high as 70 %. The pest has been recorded in 25 African countries and has successfully established in Algeria, Morocco and Zimbabwe. Accurate distribution records for the khapra beetle are difficult to obtain because admission of its presence in a country may result in trade restrictions being imposed (Banks 1977). In most cases the invasive pest is introduced through commercial activities, primarily trade (sea and air) and tourism (ignorant possession combined with increased human movement).

The costs of preventing the spread of khapra might be similar to those incurred in the attempted eradication of larger grain borer from Tanzania. In this eradication attempt all infested areas were isolated by allowing only treated maize and/or fumigated cassava between regions, especially from infested to non-infested areas. All empty bags were also fumigated. The total operational cost of this programme was $59 000 (in 2000 US$) between 1986-1990[7], with an average expense of approximately $0.55 (63 TSh) per household (Mallya, 1992). This attempt at eradicating the larger grain borer failed because sufficient time was allowed to elapse for larger

[7] The programme cost 7,116,490 Tanzanian Shillings, which at an inflation rate of 15% and a 2000 exchange rate of 612 TSh to the US dollar, this equates to US$59 000.

grain borer to establish itself in its natural forest environment from where it could reinvade the dis-infested stores. Eradication of the khapra beetle is also likely to be difficult because detecting it at low densities is unreliable and it has the ability to hide in cracks and crevices, which reduces its susceptibility to some control methods. It is therefore essential that control methods are designed to thoroughly penetrate infested materials and facilities. In case of low infestation detection by inspection is not reliable.

7.4 Parthenium weed

Several alien plant invaders can be compared with parthenium's rapid and aggressive ability to spread, its allelopathic effects (competitiveness), and its effect on animal and human health. Most of these falls under the genus *Parthenium* and only one falls outside of this genus. It is not yet known if any of the *Parthenium* species have established in countries outside of their natural distribution, but if found, it is expected they will behave and respond to control in a similar manner. Outside the genus *Parthenium* burr ragweed (*Ambrosia confertiflora)* stands out as being very similar to parthenium in that it is extremely competitive and readily suppressing pasture species and it produces copious amounts of pollen that cause severe hay fever in susceptible individuals. Burr ragweed also has additional negative characteristics including: burred seeds which contaminate wool and are not easy to remove and a perennial root, which makes manual clearing extremely difficult. The most likely modes of introduction would be through contaminated food aid, grain imports, and movement of fodder, pasture seeds, vehicles, farm implements, and stock and soil. It is expected that many of the same control and preventative actions will be needed to contain and control burr ragweed as are used with parthenium.

An estimate of the costs of preventing the further spread of an invasive species such as parthenium weed can be got from the parthenium prevention programme implemented in NSW and Queensland, Australia. In the case of NSW, the establishment cost of the programme was AU$240 000 (four wash-down facilities were set up) and it had an average annual cost of AU$2 690 000 which involved running and maintaining the wash-down facilities, road-side inspections and control, inspections of import products and properties (the biggest contributor to cost), and the eradication and control of incipient infestations. The Queensland prevention programme cost AU$4 200 000 to implement (70 wash-down facilities were required) and AU$1 132 000 in annual costs, which includes the costs of running and maintaining the wash-down facilities, undertaking road-side inspections and control, and undertaking inspections of export products and properties.

7.5 Triffid weed

There are many species within the Asterceae that might be considered potential weeds in South Africa. However, it is only *Austroeupatorium inulaefolium* that is closely related to triffid weed and is recorded as a pest in the Philippines, Indonesia, southeast Asia and Sri Lanka and has been recorded from a few localities in Australia. The only likely mode of introduction is through the horticultural industry. However, there are two biotypes of chromolaena (West Africa and South Africa). It is uncertain how far north the South Africa biotype of the weed extends, but almost certainly into Moçambique and Zimbabwe. The West African biotype has been reported from the savanna regions of Uganda and is moving southwards naturally. It is important that the spread of these two biotypes is halted. The only possible mechanism for doing this would be to implement a no go barrier at the leading edge of the invasion. However, this is impractical and not guaranteed to be successful.

8. CONCLUSIONS

Since the case studies for this report were selected to cover an appropriate distribution of invasive species across Africa and to include both animals and plants, only a few conclusions can be made that apply to each and every invasive species, therefore the main conclusions and recommendations from each case study are presented separately. However, certain issues, particularly the limitations experienced in undertaking the case studies, were found to be relatively consistent across all the case studies and these are discussed in a single section, along with the lessons learned.

The most obvious and severe constraint experienced in all case studies, except maybe water hyacinth, was the lack of accurate, consistent and reliable data. This reality is the result of many factors including: 1) few invasive species research projects include an economic component and therefore do not collect the appropriate data that are necessary to undertake economic analyses; 2) the recording and storing of data that are collected do not follow appropriate and consistent protocols and are often unusable as a result; 3) accessing the data that do exist is difficult because research organisations are often not prepared to share these or the data are not in electronic form or have never been collated and reported; and 4) little or no information is available on the productivities of the resources used and the values of the outputs produced from rural, subsistence and small-scale farms.

Getting estimates of the economic values for resources (goods and services) that are not traded in markets is extremely difficult (if not impossible), costly and time consuming. Examples of such resources include: cattle farmed for cultural reasons (i.e., indicators of wealth); productive farm labour; beautiful scenery; and biodiversity. However, the determination of the economic values of these non-marketable goods and services is not possible in short-term projects such as this one. A consequence of this is that best estimates of the Total Economic Revenues or income to activities or products were estimated that did not include the input costs of production and the indirect-use and non-use benefits derived from these. Wherever possible appropriate proxies for the values of these goods and services were used and these were based on the opportunity costs of the resources to the society.

8.1 Nile tilapia

When considered purely in economic terms, the invasions of African river systems by Nile tilapia have been beneficial to livelihoods. The costs of introducing the species are in the form of decreased biodiversity, for instance the extinction of *O. esculentus* and *O. variabilis* in Lake Victoria. But, what value can be placed on this biodiversity and the cost if it is lost? The value of biological diversity cannot simply be represented in monetary terms as is done with resources for which markets exist. And, since improvements in livelihoods often lead to changes in the use of rivers for food production to recreation and finally to aesthetic and nature conservation, the existing value placed on biodiversity by many societies in Africa is likely to under value its possible future value. In light of the findings in this report, particularly the fact that once introduced Nile tilapia cannot be eradicated, it is recommended that Nile tilapia be listed as an invasive species and that calls for its introduction into new areas be dealt with using a precautionary approach, and if deemed appropriate to do so, it is introduced under the strictest of regulations (i.e., restricted to re-circulating systems with zero possibility of escape of fish to the environment).

8.2 Water hyacinth

Water hyacinth (*Eichhornia crassipes*) remains a problematic aquatic weed throughout the tropical and subtropical regions of the world where it degrades aquatic ecosystems and impacts all aspects of their utilization. This study quantified the economic impact of water hyacinth on two small river systems, one in the Central African Republic and one in the KwaZulu-Natal Province of South Africa. The Central African Republic case study showed that water hyacinth reduced the income of people utilizing the aquatic ecosystem for fishing and palm wine collection. In this situation biological control offered a cost-effective and sustainable solution to the problem. Water hyacinth on the Nseleni River in KwaZulu-Natal Province posed a threat to industry, water abstraction and biodiversity. In this case study, an integrated approach using herbicide application, mechanical and biological control reduced the water hyacinth cover 100% to less that 10% of the surface area in the period of five years. Ongoing management of the system has ensured that the weed does not exceed 15% cover of the river.

Water hyacinth infestations have been controlled biologically in a number of sites around the world, notably Papua New Guinea and East Africa (Lake Victoria). In other areas, however, the biocontrol success has been variable. This is usually in areas where the water quality is poor (i.e. high levels of nitrates and phosphates). In these areas it is recommended that water quality be addressed and that an integrated approach rather than a pure biological control approach be adopted. Finally, due to the persistent and pervasive nature of water hyacinth, and the substantial costs it causes in the form of damage to infrastructure, increased time and effort on control, lost productivity, and being a threat to biodiversity, preventing its introduction to areas where it currently does not exist is promoted as the optimal control strategy.

8.3 Larger grain borer

This study has reinforced the existing understanding that the larger grain borer is one of the most destructive pests in rural maize (and cassava) growing regions in Africa. The invasive species is continually increasing its range in Africa and impacts on millions of African's livelihoods. In response to this, many research programmes have been undertaken to better understand the larger grain borer; particularly how it spreads, when and how it causes damage, and how best to control it. These issues are now better understood, particularly where the pest has most impact – in rural small-scale farming systems. The current understanding of the infestation is that it cannot be eradicated from areas already invaded; therefore control efforts focus on minimising its impacts. The most effective approach to minimising stored-grain losses is to integrate 'improved storage' practices with biological control. Little, however, is known about the economics of these control programmes because of a lack of reliable economic and agricultural data. This study has contributed to improving this understanding by economically evaluating the main control practices currently being used by farmers in West Africa. Based on the best available data, this study found that: 1) the adoption of 'improved storage' practices, both with and without biological control and for most combinations of pest damage and control effectiveness, was economically beneficial to farmers; and 2) biological control was beneficial to both cassava and maize farmers if the costs of implementation, monitoring and maintenance were incurred by the financier, but the benefits to the cassava region were insufficient to cover the financier's costs of developing and implementing the programme.

Some of the main recommendations to come from this analysis are: 1) the biological control agent, *T. nigrescens*, should be introduced in the wake of the pest as it spreads in order to reduce the risk of stores being infested with larger grain borer; 2) where infestations are heavy and *T. nigrescens* is ineffective the application of recommended insecticides or other improved storage practices should be adopted; 3) economic analysis can provide many management and policy insights into the best way of controlling larger grain borer to improve livelihoods; and 4) certain control technologies and practices have not been widely adopted by communities because of cost constraints and the discrepancy between the new methodologies and traditional practices. It is therefore essential that, along with a better understanding of the economics of the problem, a clear understanding of the social and cultural dynamics needs to be developed and a participatory approach to implementation be adopted.

8.4 Parthenium weed

Parthenium weed is capable of growing and spreading rapidly and has allelopathic effects, which explains why it is such a competitive and invasive species. The consequences of this are that it can have devastating impacts on pasture and crop productivity, animal and human health, and biodiversity if not controlled. Parthenium already exists in numerous countries in Africa. In southern Africa the invasions are now entering the exponential phase of spread and growth. Approximately 85% of Mpumalanga is at threat of invasion and the only areas in southern Africa unlikely to be invaded are those with less than 400 mm rain.

It is expected that small-scale and subsistence farming systems are most vulnerable and will be most affected. Large-scale commercial crop farming will be less affected because large-scale application of herbicides is effective at controlling the weed. The capacity of natural grazing lands will be severely reduced but well-managed artificial pastures will be less affected. Where areas are overgrazed, deforested and degraded this will aggravate and accelerate invasion. The first allergy problems can be expected in KwaZulu-Natal, where extensive infestations already occur and where manual clearing of weeds is commonly practiced. It is also expected that conservation areas will be severely affected as conventional control operations cannot be used. Also, the costs of mechanically and chemically controlling parthenium are substantial and are only really feasible in large-scale cropping systems. Biological control therefore is believed to be the best long-term option for controlling the weed in Africa. It is also suggested that along with investing in biological control, prevention campaigns at national/provincial and international levels could delay long-distance dispersal.

8.5 Triffid weed

Triffid weed (*Chromolaena odorata*) is a major invader of terrestrial ecosystems in southern and western Africa. In West Africa it has limited application as a fallow crop, but for the most part its impact is considered to be damaging. Impacts of this weed include the loss of biodiversity, grazing and cropping potential and an increase in the frequency and intensity of fires. The Hluhluwe/Imfolozi Park in northern KwaZulu-Natal, South Africa spent US$24 445 000 million over a three year period to reduce infestations of this weed and, in rural KwaZulu-Natal, triffid weed reduced the grazing potential on a state-owned farm by 64% with severe implications on cattle stocking densities and rural incomes.

The mechanical control programmes undertaken against triffid weed have had limited success and have been very costly. Biological control of triffid weed has been successful in West Africa and the programme is in its infancy in southern Africa; although, there are initial signs of a biological-control agent being effective in South Africa. It is believed biological control offers the most cost-effective and sustainable solution to the problem.

Since triffid weed has all of the traits that make it one of the world's worst weeds (i.e., it grows vigorously in many habitats and climates, it produces huge numbers of easily-dispersible seeds, and it impacts on agriculture and biodiversity) it is recommended that its control be approached on a coordinated and regional basis that prevents unnecessary duplication of costs and efforts. Presently in southern and South Africa the control efforts are fragmented and there is little sharing of information and experiences that could ensure better control.

8.6 Concluding remarks

The preceding discussion has highlighted some of the difficulties that face researchers when they attempt to estimate the costs of invasive species and the benefits of control. We have only been able to quantify a few impacts, and then only in limited areas. It is also difficult to estimate the rates of spread and densification of species invasions, especially over larger areas. While it is possible in many cases to estimate the rate of spread of a species over short distances (measured in metres or kilometres), there is consensus among alien species experts that mechanisms and rates of spread at larger scales (10s or 100s of kilometres) are random, and based on natural, long-distance dispersal as well as deliberate and accidental movement by humans. In addition, spread rates are not the only determinant of impact, and the population densities of a species at a site (which increase over time) also need to be considered. It is thus very seldom possible to model the spread and densification of species over longer distances, as would be required in order to carry out accurate economic assessments.

Quantifying the impacts of alien invasions on biodiversity is an especially difficult task. In our Nile tilapia study, for example, the major negative impact of invasions by this species was the extinction of other, similar fish species. This ultimately leads to the replacement of a rich and varied fauna over large areas, with a depauperate, simplified species assemblage (see, for example, Rahel 2000). This is one of the major impacts of invasive species, and it eliminates future options for the use of native species, affects the resilience of ecosystems and threatens the delivery of ecosystem services, and impacts on cultural, recreational and tourism opportunities. Such impacts, however, are notoriously difficult to quantify in economic terms, especially if the assessment attempts to compare the replacement of one species by another in limited areas. The true impacts are felt at the level of ecosystems, not single species. It would also be necessary to consider the cumulative effects of the steady replacement of a large number of indigenous species by a small number of invasive alien species over time, and not simply take each case study on its own – the latter approach seldom provides an adequate reflection of impacts.

Even with limited data, and other constraints, it appears (from our and other studies) that control of invasive species will deliver positive benefits, and that control operations, if carried out effectively, will be worth the effort.

The lack of available data has forced us to focus on the few benefits and costs that could be quantified. There are, however, undoubtedly more impacts than could be quantified, and because the extent and density of invasions will almost certainly increase (but were not explicitly accounted for in our analyses), our estimates are conservative, even if some of the additional effects of invasion might be positive.

This report has also addressed the issue of costs of control, and has listed other invasive alien species that may be introduced and cause impacts. While this may be of some use in the formulation of policies and strategies for dealing with invasive species, and it may provide motivation for their implementation, significant challenges still remain. Firstly, the lack of capacity (in the form of trained personnel, funding, political will, and international co-operation) in and between many African countries is a significant obstacle to the implementation of effective programmes of prevention and control. This is compounded by the fact that many species are the source of a conflict of interests. For example, many aid agencies and organizations actively promote the spread of invasive alien species (such as the Nile tilapia, or forestry and agro-forestry trees) for well-intended purposes, without due consideration of the other consequences that their introduction may cause. If control and prevention programmes are to be effective in Africa, it will be necessary to bring the results of studies such as this one to the attention of such bodies, so that they may better assist with the effective implementation of prevention and control policies and projects.

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PART 2: APPENDICES

Appendix 1:	Economic evaluation and framework
Appendix 2:	Accounting model
Appendix 3:	Nile tilapia (*Oreochromis niloticus*)
Appendix 4:	Water hyacinth (*Eichhornia crassipes*)
Appendix 5:	Larger grain borer (*Prostephanus truncatus)*
Appendix 6:	Parthenium weed (*Parthenium hysterophorus*)
Appendix 7:	Triffid weed (*Chromolaena odorata*)