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Research article

Scenarios for the management of invasive *Acacia* species in a protected area: Implications of clearing efficacy

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ABSTRACT

In many protected areas in South Africa, invasive Australian *Acacia* species pose on-going management challenges, perpetuating high long-term management costs. Due to limited availability of resources, conservation actions need to be prioritised within and across Protected Areas (PA). We draw on comprehensive datasets spanning over 20 years from the Table Mountain National Park to model long-term outcomes of clearing *Acacia* species at different levels of management clearing efficacy. We test a 50 year outlook based on current and 38 incremental levels of management efficacy, ranging from 5 to 100%, to assess under which scenarios a management goal of reducing *Acacia* density to below 1 plant per hectare for the 22,671 ha protected area is achieved. With the current clearing resources and maximum clearing efficacy (100% control), it would take between 32 and 42 years to attain the management goal. The modelling revealed two main drivers of *Acacia* persistence. Firstly, germination of seeds added to the seedbank from standing plants made a significantly larger contribution to future clearing requirements than fire stimulated seed germination or the existing (pre-management) seedbank. Secondly the relationship between the number of hectares and management units that could be treated and the efficacy of the treatment was non-linear. When clearing efficacy was decreased from 100% to the current project minimum target of 80% efficacy, the goal was not achieved in all areas, but the area that reached a density of < 1 plant per hectare was significantly reduced to 53% of the PA for the simulated 50 years. Results emphasize the need to differentiate between increasing financial resources and increasing efficacy. While increasing financial resources allows for increased effort, this is of little value for *Acacia* management in the absence of an increase in clearing efficacy, as low quality implementation perpetuates the need for large budgets over time. Conversely, improving efficacy allows for decreased budget requirements over time, allowing fund redirection to additional areas of alien species management such as the early detection and rapid control of newly introduced species.

1. Introduction

Protected area (PA) managers are required to respond to a range of biodiversity threats and pressures, including legal and illegal harvesting of resources, pollution and invasion by alien species (Wilson et al. 2007; Schulze et al. 2018). Conservation targets for managing these threats and pressures are often set through a range of objectives with measureable thresholds (Biggs and Rogers, 2003; Foxcroft, 2009). The degree to which the specific targets and desired outcomes are achieved influences the overall management effectiveness of the PA (Watson et al. 2014). A frequent argument for not meeting conservation objectives is the limited availability of resources or funding (Frazee et al. 2003; Bruner et al. 2004; van Wilgen et al. 2016a). This results in the need to prioritise conservation actions within and across PAs, or to confine actions to particular or vulnerable sections alone. For example, 'conservation triage' (accepting biodiversity loss in lower priority areas over gains or sustained benefits in higher priority areas) has been proposed as an appropriate strategy for apportioning conservation budgets where funds are limited (Downey et al. 2010; van Wilgen et al. 2016a).

Within South Africa's Cape Floristic Region (CFR), invasive alien plants (IAP) pose one of the largest direct threats to biodiversity and ecosystem services (Richardson et al. 1996; Gaertner et al. 2009; Le Maitre et al. 2011). For example, a conservation status assessment of

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the region's flora in 2009 found more than 1000 native plant species were threatened by IAPs (Raimondo et al. 2009). To address the negative impact of IAPs, the South African government has for more than 20 years, funded a national invasive alien plant control programme, 'Working for Water' (WfW). A main aim of the programme is to restore and maintain habitat structure and function to mitigate the loss of ecosystem services, especially water, through the control of invasive alien plants (van Wilgen et al. 2012). Depending on the implemented management approach, high level budget estimates for IAP control in the CFR are projected to be in excess of ZAR 900 million (1 US$ ~ 16 ZAR in 2017) over the next 20 years (van Wilgen et al. 2016a).

Specific IAP genera pose on-going management challenges, perpetuating these high long-term management costs (McConnachie et al. 2012), including Australian *Acacia* species which are particularly difficult to control. *Acacia* is a highly diverse genus (~1012 species, Richardson et al. 2011), over 20 of which are highly invasive globally (Richardson and Rejmánek, 2011). These plants tend to dominate interspecific interactions, having profound impacts on ecosystem processes (e.g. altered community dynamics though changed fire regimes and altered nutrient cycling though changed soil properties) (Le Maitre et al. 2011). The genus is a model group for studying many facets of alien plant invasions (Richardson et al. 2011; van Wilgen et al. 2011). The successful establishment and long-term persistent invasion of *Acacia* species has been attributed to several factors, including early maturity (< 2 years), prolific production of long-lived seed (up to 12000 seeds/m^2/annum) and prolific post-fire germination (Marchante et al. 2010; Souza-Alonso et al. 2017; Strydom et al. 2017).

The Table Mountain National Park (hereafter TMNP or the park) is a well-known protected area in the CFR biodiversity 'hot spot' (Cowling et al. 1996), with 158 endemic plant species (Helme and Trinder-Smith, 2006). However, the park is facing severe pressure from the invasion of many alien species from the surrounding landscape (Spear et al. 2013). Despite a well-established IAP control plan, with over 20 years of continuous implementation, supported by extensive resources, the programme goal of achieving a 'maintenance level' of control, where plants occur at a density of less than one plant per hectare (10,000 m^2) (Le Maitre and Versfeld, 1994) has yet to be reached (Cheney et al. 2018). This goal, which essentially seeks to reduce Acacias to being 'rare' in the landscape (Le Maitre and Versfeld, 1994), is considered feasible within current management time frames and will ensure significant reduction in ecological impact. A common management reaction is to seek additional funding to achieve this maintenance control level, but with studies suggesting that clearing implementation is sub-optimal (McConnachie et al. 2012; van Wilgen et al. 2016a; Kraaij et al. 2017), it is uncertain to what extent larger budgets will address the problem.

We develop a spatio-temporal population model to investigate clearing scenarios for *Acacia* species in TMNP. We assess the potential impact of the currently-available resources under current and incremental levels of management clearing efficacy and determine the long-term resource requirements for optimal management and return on investment. Specifically, we aimed to:

- Assess whether the available resources are adequate to successfully control *Acacia* species in the long-term;
- Determine the extent to which present resources impact current standing plants versus reducing the potential for future invasions (i.e. plants and seedbank increases that result from uncleared plants or remnant seedbanks)
- Determine the optimal clearing efficacy thresholds that achieve the conservation target of reducing invasions to a maintenance level of less than one plant per hectare.

2. Materials and methods

2.1. Study area

Table Mountain National Park is located on the Cape Peninsula, South Africa, and covers approximately 25,000 ha. For model simulation and analysis we considered 809 management units (polygons) that cover 91% (22,671 ha) of the PA with only the very steep, largely inaccessible areas not included. Each management unit currently has, or historically had, different levels of invasion by a range of alien plant species. The dominant alien taxa in TMNP comprise woody alien species from the genera *Acacia*, *Pinus* and *Hakea*. For our purposes only *Acacia* species are considered as they are the most common alien plants in the PA (Cheney et al. 2018) and arguably pose the greatest threat to TMNP's biodiversity (Richardson et al. 1996; Higgins et al. 1999).

2.2. Model description

A spatio-temporal, polygon-based, population model was developed for the park using Visual Basic in MS Excel (2013 v15.0). The model simulates *Acacia* population size, age structure and area invaded within each management unit. The model's purpose is to estimate the potential future outcomes of the alien plant control programme by varying clearing efficacy (effective permanent removal of alien plants) in relation to two drivers of *Acacia* persistence, namely, ecosystem processes (fire) and plant population dynamics (age, density dependence and seedbank dynamics) (Le Maitre et al. 1996; Krug et al. 2010). Twelve model scenarios were simulated based on the current levels of *Acacia* abundance as determined by fine scale population data (Cheney et al. 2018), historic fire records spanning 35 years (Forsyth and van Wilgen, 2008), and 20 years of alien plant control history for TMNP (van Wilgen et al. 2016a).

As a model starting point, population data on *Acacia* species were collected for each management unit as part of a fine scale systematic monitoring programme (Cheney et al. 2018). This entailed sampling 10,057 plots and counting the number of individuals present per alien plant species. The *Acacia* species included in the model were clustered into two groups based on their response to management, i) species that readily coppice if not treated correctly (e.g. through the incorrect clearing method or application of herbicides), such as *Acacia saligna*, *A. mearnsii*, *A. melanoxylon* and ii) species that do not readily coppice, namely *Acacia cyclops* and *A. longifolia*.

The simulation model comprised six time-based modules relating to the management, population dynamics and ecology of *Acacia* species (Fig. 1). The population parameters (growth rates, seed production and seed germination) for the coppicing or non-coppicing species were modelled primarily on *A. saligna* for coppicing species and on *A. cyclops* for non-coppicing species. Each module simulated the population dynamics, clearing efficacy and ecological processes influencing the clearing of *Acacia* and each could be included (turned-on) or excluded (turned-off) in a simulation run. For example, the fire module or the seed production module could be turned on or off to test the incremental effect that these processes have on the overall model outputs.

The model was run for the equivalent of 50 simulation years. Within a simulation year, the model incremented quarterly, in alignment with current IAP clearing operations, *Acacia* population dynamics and ecological processes (Fig. 1). Quarter 1 spanned from April to June, with the relevant modules of alien clearing, plant population dynamics and seed germination called within this timeframe. Similarly the modules called in quarter 2 aligned with the alien clearing and plant population dynamics that would occur between July and September.

2.3. Module descriptions

2.3.1. Alien plant clearing module

The clearing module (Sup. Mat. Fig. 1) simulated the control of

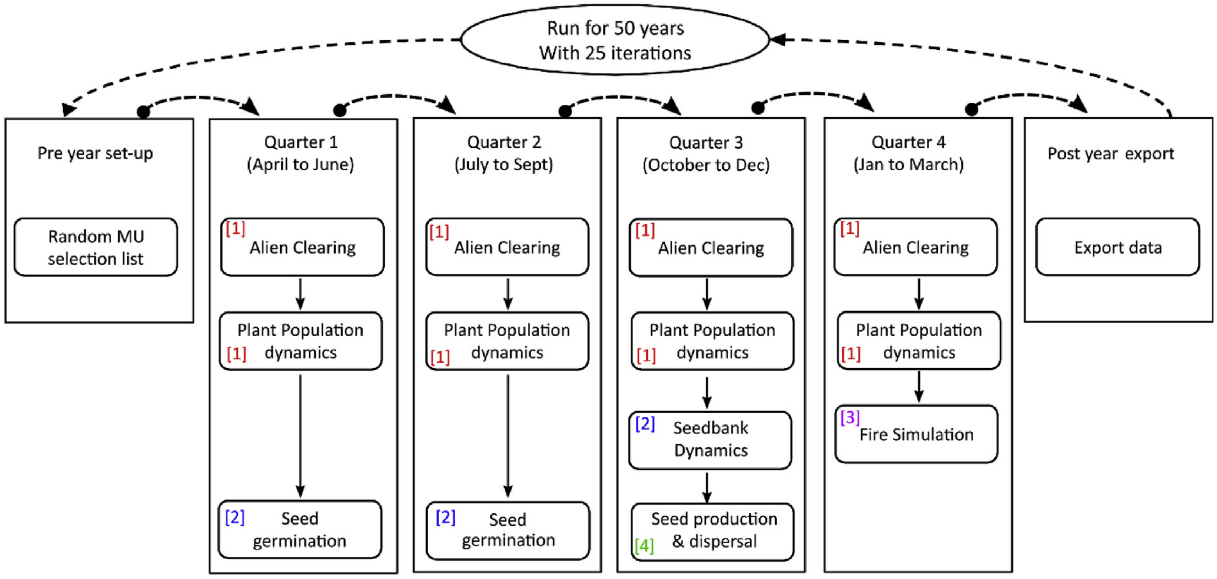

Fig. 1. Overview of the modules in the simulation model and the equivalent calendar quarter in which they are called. The growing season is approximated as April to September, during the peak rainfall period. *Acacia* plants flower at the end of the growing season and release seed during October to December. Most natural fires occur in the summer to early Autumn (January to March) which stimulate seeds to germinate from the soil seedbanks following the first rains in April. Numbering [1–4] denote model scenarios described in section 2.4 and Fig. 2.

Acacia based on WfW clearing norms and standards (Neethling and Shuttleworth, 2013). The standard resource unit for alien plant control is based on the number of person days required to treat an invaded area. The TMNP's 2017 annual allocation of 40,128 person days (ZAR35.4 million, 1 person day = ZAR350) was used as the available resource with which to undertake clearing (Working for Water, 2017). The allocation of person days to each management unit was calculated based on the recorded *Acacia* abundance and age class of individuals in each management unit (Neethling and Shuttleworth, 2013). The management units for clearing were randomly selected at the beginning of the simulated year and person days were divided per quarter until the total available person days of 40,128 was reached. Any unused person days in a simulation year were not carried over to the next simulation year. The random selection of management units held 'no memory' of clearing history and each management unit was available for selection at the start of each simulation year. Clearing efficacy was varied for 38 incremental levels of efficacy, from 5 to 100% which was taken as the probability that each plant present in a management unit

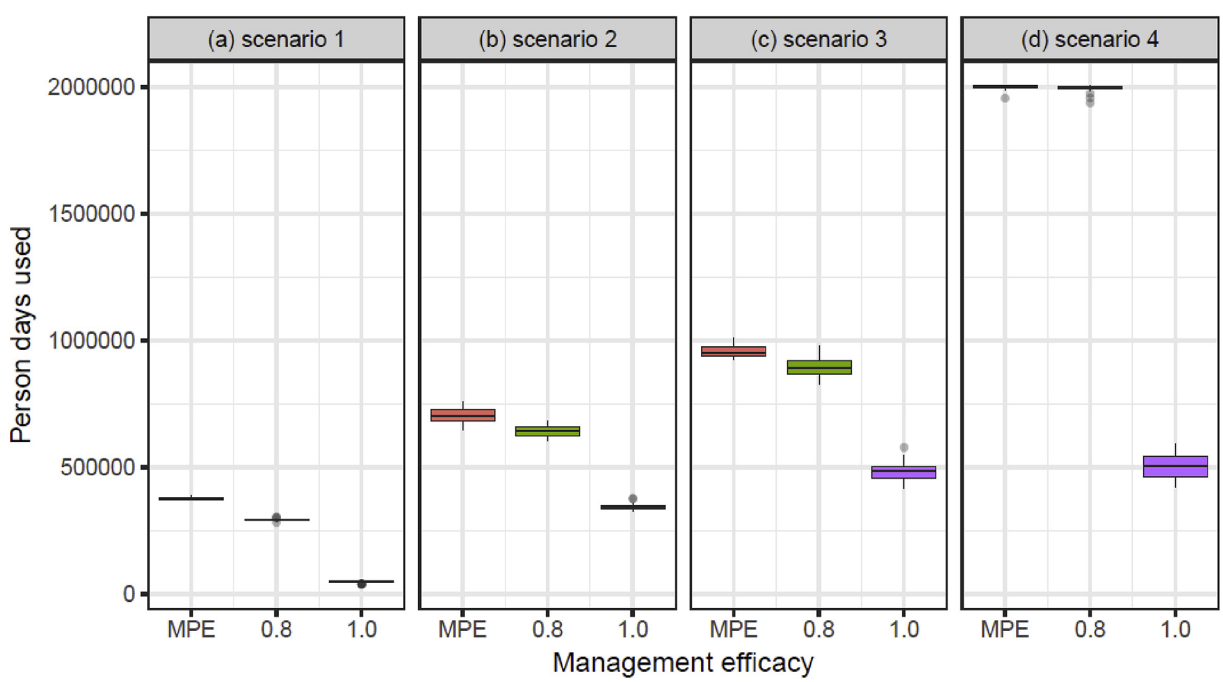

Fig. 2. The person days utilised after 50 simulation years to clear: (a) Scenario 1: current standing plants; (b) Scenario 2: current standing plants (a) plus seedlings germinating from non-dormant and post clearing operations; (c) Scenario 3: current standing plants and seedlings germinating from non-dormant post clearing operations (a & b) plus seedlings geminating post-fire; (d) Scenario 4: all propagules considered in a-c, plus plants resulting from additional seed being added to the seedbank from the current population; under 100%, 80% and the mean project efficacy (MPE, approximated across coppicing and non-coppicing species as 66%). For all scenarios, MPE levels required significantly more person days than higher efficacy scenarios, $p < 0001$.

would be treated correctly (i.e. killed via the correct treatment method).

2.3.2. Fire simulation module

The fire module (Sup. Mat. Fig. 2 and Sup. Mat. Table 2) determined i) the number of fire ignition points, ii) the size of individual fires and iii) the total area to be burnt per fire season (quarter 4, January to March). At the beginning of the fire season, the number of fire ignition points and the total area expected to be burnt was determined as a function of the Normal distribution of the fire history dataset of TMNP between 1980 and 2016 (Table Mountain National Park Fire history records 2008–2016, unpublished data). Because certain areas are more prone to frequent burning, management units were assigned to one of five fire frequency classes based on the number of ignitions recorded in the management unit's fire history (Sup. Mat. Table 1). For each fire ignition, a fire frequency class was selected at random, adjusted for the probability of each class burning. The management unit within the selected fire frequency class was then randomly selected. To determine if fire ignition would result in the management unit burning, a probability function based on vegetation age was calculated (Sup. Mat. Table 2), where vegetation 25 years and older had a probability of 1 (would always burn) and vegetation less than 5 years old would have a probability of 0 (Forsyth and van Wilgen, 2008; Van Wilgen et al. 2010). Once burning was initiated, additional management units directly adjacent to the source management unit with a vegetation age of 5 years and older burned until the expected size of the individual fire had been reached.

Fire intensity for the individual fires was varied by equating the burn intensity to Fire Danger Index (FDI; South African Government Gazette 37014 No. 1099 of 2013; Sup. Mat. Table 3). The FDI, was calculated based on available summer climate data between 1990 and 2008 (2296 days) from the South African Weather Services' Cape Point weather station. The fire intensity for an individual fire was assigned by selecting one of the days at random. The intensity of the fire effects the proportion of plant mortality between 0.1 (Low fire intensity) to 1.0 (Extreme fire intensity), (Sup. Mat. Table 3) as well as seed bank dynamics (see 2.3.4). Mortality is assumed to be constant across tree age classes.

2.3.3. Seed production and dispersal module

This module simulated the annual rate of seed accumulation within and dispersal to adjacent management units. For plants between the age of 8 and 30 years old, the annual accumulation rate was set to 360 seeds/m^2 (range: 340–380 seeds/m^2) for non-coppicing *Acacia* and 4250 seed/m^2 (range: 4040–4460 seeds/m^2) for coppicing trees (Holmes et al. 1987; Correia et al. 2014; Strydom et al. 2017). For trees younger than 8 and older than 35 years, seed accumulation was reduced using logistic equations (Sup. Mat. Table 4). *Acacia* seed dispersal is largely localised, with up to 5% of the annual seed production available to disperse to adjacent areas (Rebelo et al. 2013; van Wilgen et al. 2016a). Five percent of seeds were made available to disperse to adjacent management units and allocated based on the percentage of common boundary between the seed source and other units.

2.3.4. Seed bank dynamics

This module accounted for the seeds in the soil profile, i.e. litter, top soil layers (generally up to 10 cm deep) and deep soil layers (greater than 10 cm deep). Initial seedbank size was estimated for each management unit by reviewing both clearing and fire history of the management unit. The post-fire residual seed bank of each management unit was taken as between 5 and 15% of the density of plants that had germinated as a result of the last fire in the management unit (Holmes et al. 1987). This seedbank was then adjusted based on the clearing history of the management unit, where additional seed was added to the seedbank in areas where no clearing had taken place within a two year period, because adult plants produce seed and replenish seedbanks. These initial starting seedbank sizes were randomly varied by 5% at the start of each model simulation.

Seeds are deposited through seed production and seed dispersal into the litter layer, where they are held for a year (Milton and Hall, 1981; Richardson and Kluge, 2008; Strydom et al. 2012). Seeds move into deeper soil layers at rate of 10% per year until they reach deep storage after 10 years and are unavailable for germination, except in extreme fire conditions (Holmes, 1990; Richardson and Kluge, 2008; see Sup. Mat. Table 3). An upper limit of seedbank density (seed saturation) of 12,000 seeds/m^2 was set for each management unit (Milton and Hall, 1981; Strydom et al. 2012; Strydom et al. 2017; Sup. Mat. Table 5). Within the model, seeds undergo natural decay from the seedbank at a rate of between 10 and 17%. (Higgins et al. 1997; Richardson and Kluge, 2008). The model varied fire intensity which removed seeds from the seedbank at differing rates (due to incineration, Richardson and Kluge, 2008), for example low intensity fires (FDI < 20) only affected the upper soil layers, while extreme fires (FDI > 75) affected both the upper and deeper seedbank layers (Sup. Mat. Table 6).

2.3.5. Seed germination

This module simulated seed germination. A small percentage (up to 3%) of non-coppicing *Acacia* seeds germinate after two years in the seedbank (Holmes et al. 1987). Clearing of dense stands of aliens can trigger larger recruitment of seedlings (75–95% of the seedbank) for non-coppicing *Acacia* species and a small proportion of seedling recruitment (1–5% of seedbank) for coppicing *Acacia* species (Holmes et al. 1987). The majority of seeds germinate in the winter rainy season (quarter 1 and 2 in the simulation model), following a fire event where up to 95% of the seedbank in the top soil layers and up to 10% of the seedbank in the deep soil layers can germinate depending on the intensity of the fire (see Sup. Mat. Table 6 for the effect of fire intensity, as measured by the FDI, on post-fire seedbank mortality and germination rates).

2.3.6. Plant population dynamics

The population dynamics module accounted for the mixed age plant population within each management unit and set population parameters that bound the population within observed limits from published sources (Sup. Mat. Table 5). These dynamics included maximum seed bank and seedling density (Milton and Hall, 1981; Holmes et al. 1987; Strydom et al. 2017), density dependent competition (Le Maitre and Versfeld, 1994), age specific mortality, age dependent seed production (Holmes, 1990; Strydom et al. 2017), rates of increasing or decreasing invasion and regrowth from ineffective alien clearing (van Wilgen et al. 2016a), as determined by the efficacy level set for the particular model.

2.4. Simulation scenarios

To determine the effect of different ecological parameters (as determined by the key model components) on *Acacia* population outcomes, four simulation scenarios were run on each of three clearing efficacy levels (varied within the Alien plant clearing module), resulting in twelve simulation outputs. Each scenario included sequential addition of key ecological processes (scenario 1: impact of clearing only; scenario 2: scenario 1 + seed germination; scenario 3: scenario 1 & 2 + fire; and scenario 4: scenario 1 to 3 + seedbank replenishment by mature plants; Fig. 1). While biologically unrealistic, separating these biological processes can pinpoint the most influential drivers that determine management success or failure. The three levels of clearing efficacy for each scenario were (i) 1.0 for all Acacias (i.e. all plants present in a managed unit were treated 100% correctly); (ii) a mean of 0.8 (Range: 0.6–1.0) across species, which is considered the minimum quality standard for the PA (Working for Water, 2015), and (iii) a mean of 0.77 (SD: 0.08) for non-coppicing taxa and 0.54 (SD: 0.15) for coppicing taxa, which is the mean project efficacy (MPE) currently observed for the clearing programme (Working for Water, 2018).

Due to the stochastic nature of some of the model variables, the four different scenarios were run for 25 iterations at each of the three efficacy levels. The mean number of person days required by each scenario was considered as the requirement to manage the sub-set of model conditions. The expected change in person days required between two successive simulation scenarios would be the result of the additional conditions added by each scenario.

2.5. Clearing efficacy thresholds

The management goal was set to have all management units in TMNP in a maintenance state, where *Acacia* density is < 1 plant per hectare, thus classing *Acacia* species as 'rare' in the landscape according to the WfW standards (Le Maitre and Versfeld, 1994). Fine-scale population data for the park (Cheney et al. 2018) found 161 (20%) of the management units and 5646 ha (25%) in a maintenance state. Clearing efficacy is expected to impact on the likelihood of achieving this goal, but the relative impact of a given reduction in efficacy on management ability to clear areas is unknown. To test the relationship between clearing efficacy and the extent of *Acacia* invasion, 15 iterations of the fourth simulation model (including all modules) were run at 38 incremental levels of efficacy, from 5 to 100%. The mean number of years and the cumulative number of person days taken to reach the management goal was calculated at each level of efficacy. Where the management goal was not obtained for a model-run within the 50-year period, the number of management units that had reached the target and the cumulative number of person days used by the end of year 50 was calculated. Model outputs were regressed against each clearing efficacy level. Regression models were fitted to the resultant curve to assess the nature of the relationship between efficacy and clearing outcomes, with the best fit relationship chosen using the Akaike information criterion (AIC).

3. Results

3.1. Current and future resource allocation

At 100% clearing efficacy, clearing only the current distribution of standing *Acacias* (Scenario 1) to below < 1 plant per hectare across all management units would take only 1.8 years (SD = 0.4), using 48,590 (SD = 5296) person days (Fig. 2a; Sup. Mat. Table 7). When clearing efficacy was lowered to 80%, both the time taken (19.1 years, SD = 0.4) and the person days required (292,370, SD = 4512) to reach the management goal increased significantly. At current project efficacy rates (approximated across the groups at 66%), clearing only the standing plants would take 25.2 years (SD = 0.4), requiring 377,205 person days (SD = 5388).

Clearing the seedlings that germinate post-clearing (Scenario 2, Fig. 1) required an additional 23 years (in total 24.7 years, SD = 2.5, requiring 344,462 person days, SD = 13,231) when clearing was 100% effective (Fig. 2b, Sup. Mat. Table 7). A reduction in efficacy to current implementation levels would require 42.2 years (SD = 2.4) and 706,235 person days (SD = 31,152). The addition of clearing requirements from seed germination following fire events (Scenario 3) would require an additional 12 years (36.6 years, SD = 4.2, and 482,496 person days, SD = 36,642.0, in total) at 100% efficacy (Fig. 2c, Sup. Mat. Table 7). With the addition of fire-induced seedling germination, the management goal was not achievable in all areas with efficacy below 100%. At 80% efficacy, the time taken to achieve the desired target approached 50 years, with an average of only 804.6 (SD = 3.5) of a possible 809 management units (mean area of 22,645 ha, SD = 18.8) reaching the goal of < 1 plant per hectare. Similarly, at the current level of efficacy, the management target was only met within a mean of 798.5 management units (SD = 8.4), by the end of the 50 years simulation, utilising approximately 957,883 person days (SD = 22,345.5).

When implementing the full model (Scenario 4), the first year in which invasions across all management units reached the desired level of < 1 plant per hectare was 37.2 years (SD = 5.3) at a clearing efficacy of 100%. This clearing required a mean of 507,475 person days (SD = 50,163) (Fig. 2d; Sup. Mat. Table 7). Neither the 80% nor current project efficacy levels resulted in a long-term reduction of *Acacia* abundance. At 80% efficacy, after 50 simulation years, 344.1 (43%) management units (SD = 54.7) and 58% of hectares achieved < 1 plant per hectare, but required a mean of 1,992,947 person days (SD = 16,203). The number of management units reaching the maintenance goal was reduced to 285.4 (SD = 53.9, 35%) covering 55% of hectares at current mean management efficacy requiring a mean of 2,000,082 person days (SD = 10,366) over 50 years.

For the full model (Scenario 4) at 100% effective control, the current standing alien plants required 9.6% of the utilised resource allocation, while post-clearing seed germination from current seedbanks required the majority with 58.3% (295,872 person days). Post-fire seed germination from current seed banks required 27.2% and clearing plants from future seed banks, the smallest portion of the available effort (4.9% or 24,979 person days). The allocation of resources was significantly different when the clearing efficacy decreased to 80% and lower ($p < 0.0001$). At 80% efficacy, 55.1% (1,099,026 person days) of the utilised person days went to clearing plants from future seedbanks, while current seedbanks collectively accounted for 30.2% (602,046 person days). This outcome was similar to the current project clearing efficacy where 52.1% of the 2,000,082 utilised person days were required for treatment of plants from future seedbanks and 29.0% (580,679 person days) was used for plants from current seedbanks, resulting in the continued need for clearing over time.

3.2. Clearing efficacy thresholds

While linear models provided a good fit to the data (Adjusted R-squared > 0.8 in all instances), the best fit models (Adjusted R-squared > 0.95 and ΔAIC in excess of 40) indicated a non-linear, polynomial relationship between the number of hectares and management units treated and the efficacy of the treatment (Fig. 3). Below 25% clearing efficacy, there was little difference in the number of hectares or management units achieving a maintenance state in year 50. The achievement of this goal increases steadily to around 80% clearing efficacy, followed by a sharp increase in the impact of increasing clearing efficiency between 80 and 100% (Fig. 3 a and c). A similar pattern was observed for the cumulative number of hectares and management units cleared over time (Fig. 3 b and d).

Due to this non-linear relationship, even a small reduction or increase in clearing efficacy between 80 and 100% had large effects on the number of hectares and management units that could be treated (Fig. 3a–d; Supplementary Material, Table 8). At 90% clearing efficacy, a mean of 527.1 (65%) (SD = 53.5) of the 809 management units and a mean of 16,840.7 ha (74%) (SD = 1296.3) would be in a maintenance state after 50 years, compared to 99% of management units and 99% of hectares when efficacy is 100% (Sup. Mat., Table 8). The model showed that even at 100% efficacy, fire events would stimulate seedbanks in certain management areas that would require continued follow-up work.

The relationship between the number of person days required and clearing efficacy showed that for the long-term, clearing efficacy below 83% would require all the available annual person days (40,128 person days) for the foreseeable future (Supplementary Material, Table 8). Above 83% clearing efficacy, the required person days dropped sharply until 100% clearing efficacy where 9491.5 person days (SD = 7.2; 24% of current annual allocation) would be required from around year 20 to maintain the maintenance state (Figs. 3e and f; 4g). Over the long-term, a decline in clearing efficacy is costly, with a decreasing number of outputs (management units and hectares treated annually), for

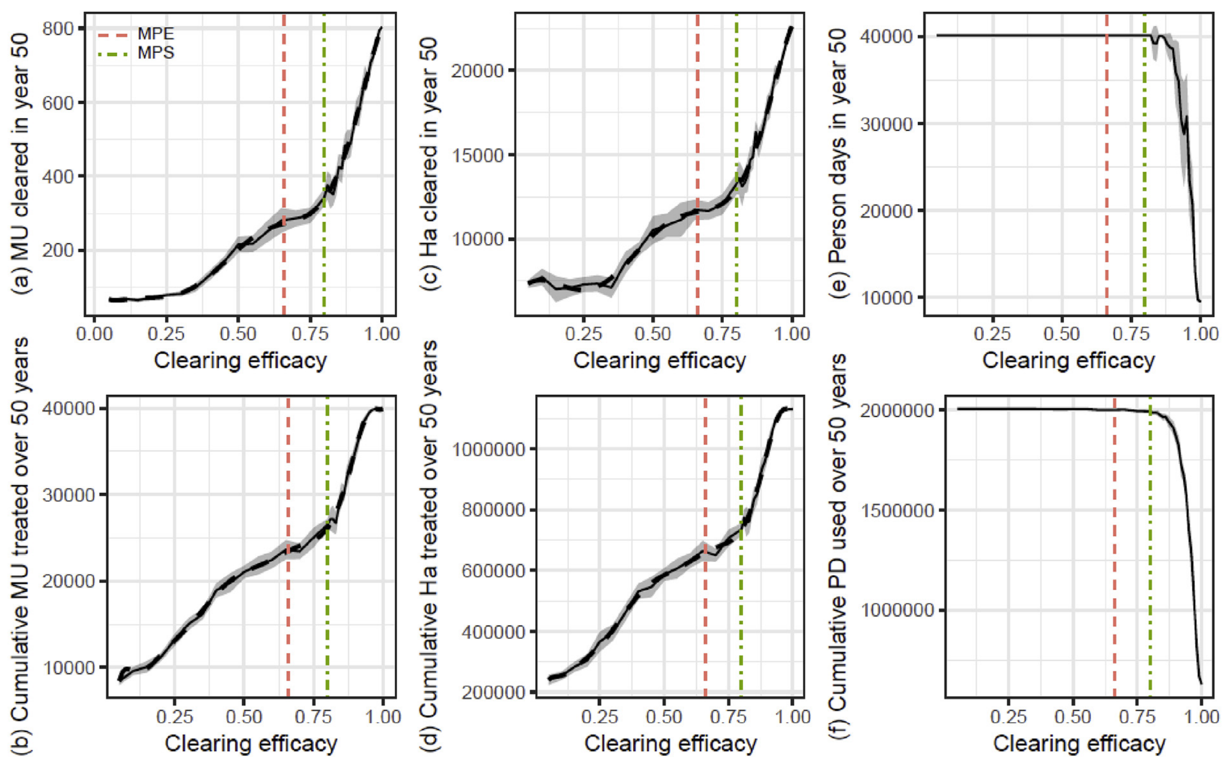

Fig. 3. The relationship between clearing efficacy and (a) management units (MU) and (c) hectares, cleared at year 50 and (e) the associated person days required and the respective total cumulative MU (b) and hectares (d) treated over the 50 years with the total cumulative person days (f). Vertical gridlines have been added at 66% and 80% to indicate the current mean project efficacy (MPE) and required minimum project standard (MPS) for clearing. Dotted lines indicate a 4th order polynomial, used to describe the nature of the relationship between management efficacy and measured response: (a) Adjusted R^2: 0.9772, F-statistic: 501.7, $p < 0.001$, (b) Adjusted R^2: 0.9892, F-statistic: 804.8, $p < 0.001$, (c) Adjusted R^2: 0.9793, F-statistic: 415.7, $p < 0.001$, (d) Adjusted R^2: 0.9796, F-statistic: 421.1, $p < 0.001$. The number of model iterations for each of the clearing efficacy levels was 15.

continued maximum input (Fig. 4). Even a clearing efficacy of 90% required sustained high person day use (mean 38,582; SD = 2299.9, Fig. 4g), at levels close to the maximum annual person day allocation of 40,128 for the duration of the model simulation.

4. Discussion

Several studies have highlighted that IAP control programmes targeting *Acacia* species can be ineffective (van Wilgen et al. 2012; McConnachie and Cowling, 2013; Kraaij et al. 2017). Studies point to poor treatment of management units where in some instances less than 25% of the treated areas met minimum clearing standards. The long-term implications of clearing inefficiency (e.g. resource allocation, timeliness of clearing, correct treatment and effectiveness of minimum standards) had not yet been quantified, which we set out to do here. We found that the resource allocation of 40,000 person days was adequate to bring the park to a maintenance level (i.e. < 1 plant per ha), within 37 years, if clearing was completely effective. There was a positive non-linear relationship between treatment efficacy and the area that could be treated for *Acacia* species in the long-term, with the chance of reaching a maintenance level within 50 years declining significantly at efficacies below 100%. The current minimum clearing standard of 80% efficacy as determined in the WFW norms (Neethling and Shuttleworth, 2013), therefore realises slow progress towards the goal of achieving maintenance levels for Acacias, despite using the maximum allowable resources.

In approaching the management of Acacias, the drivers that facilitate successful invaders in many Mediterranean type habitats and climates require consideration (Richardson et al. 2011). Much of the invasion success is due to their rapid growth rates, prolific seed production, and persistent seed banks (Milton and Hall, 1981; Strydom et al. 2012; Souza-Alonso et al. 2017). As evidenced by comparison of scenarios, seedbank dynamics played an important role in perpetuating *Acacia* persistence and were the key driver of management resource requirements. Due to the prolific post-fire seed germination by Acacias, stimulating up to 90% of the available seedbanks to germinate (Holmes et al. 1987), many management control strategies focus on treating burnt areas within 24 months after fire (Roura-Pascual et al. 2010). However, the simulation model showed that for all clearing efficacy levels, more clearing effort would be needed annually in areas that did not burn, due to constant low rates of germination from non-dormant seedbanks, particularly at recently cleared sites (Holmes et al. 1987). Although post-fire germination may be very notable, the actual extent of annual fire events covered < 5% of the park (Forsyth and van Wilgen, 2008).

The simulation model showed that the potential seedbank contribution from a single mature individual into the population is considerable. This is key for the management of Acacias, as the potential propagule pressure from seedlings and dispersal is pronounced (Rouget and Richardson, 2003; Lockwood et al. 2005). While areas of low invasion density are often considered lower priority (Roura-Pascual et al. 2010), the consequence of not clearing effectively and not reducing propagule pressure increased long-term future resource requirements. In the simulation model as much as 55% of future management resources (effort and costs) would be directed to treating plants that result from seedbank replenishment. This long-term future resource requirement has been observed in rehabilitation of river catchments and headwaters where re-invasion by Acacias is prominent in the absence of follow-up treatment (Galatowitsch and Richardson, 2005; Le Maitre et al. 2011).

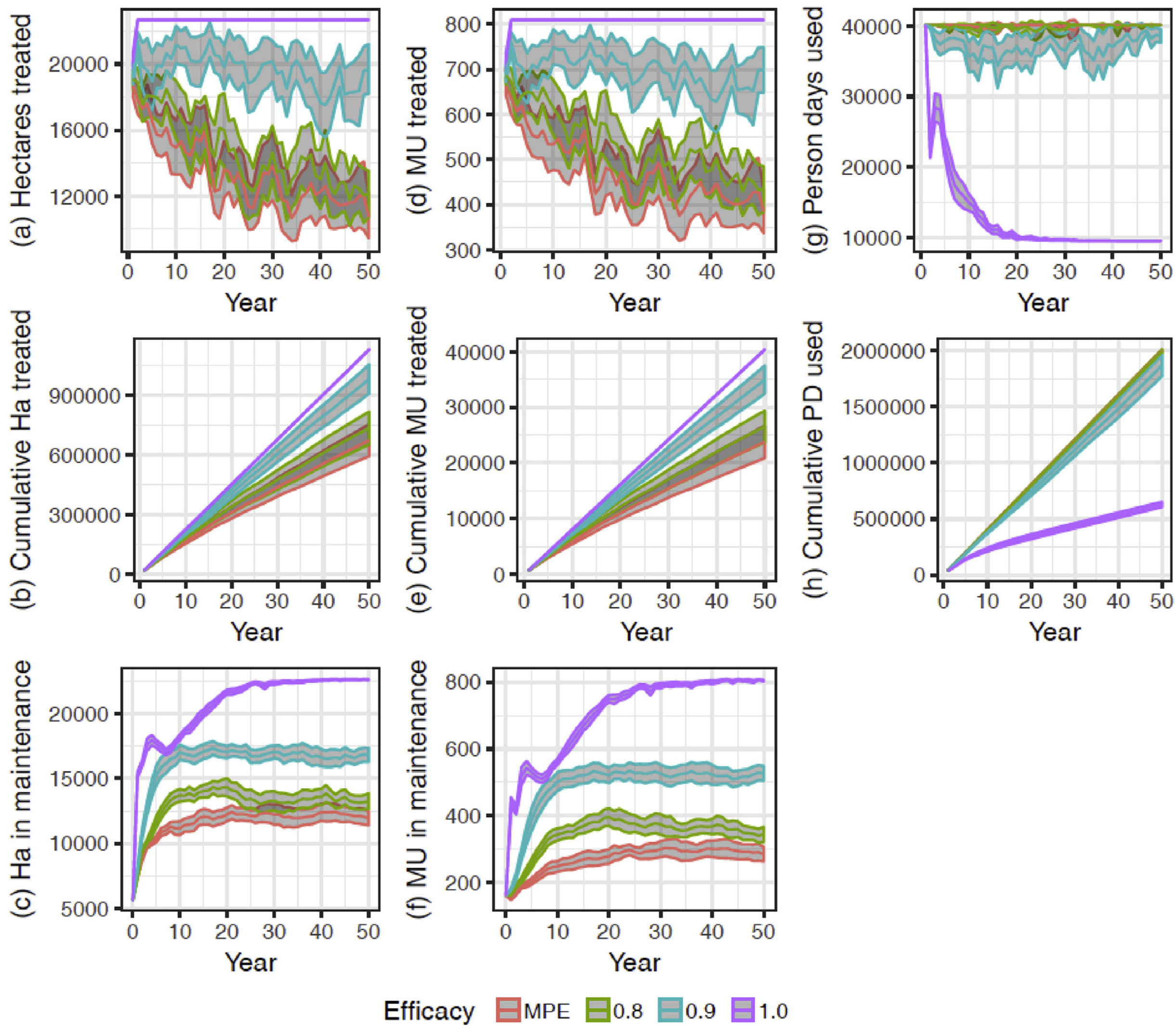

Fig. 4. Annual clearing outcomes over time in terms of hectares (a) and management units (d) treated annually and the cumulatively over time (b, d) as well as the number of person days used per year (g) and cumulatively (h) and the resulting number of hectares (c) and management units (f) that achieved a maintenance level (< 1 plant/ha) over time at four management efficacy levels (mean project efficacy (MPE, approximated across coppicing and non-coppicing species as 66%), 0.8, 0.9 and 1.0). The number of model iterations for each of the four efficacy levels was 25.

4.1. Management implications

Previous models making use of high clearing efficacy parameters have shown a significant reduction in *Acacia* invasion within 20 years (Krug et al. 2010; Le Maitre et al. 1996). Our models produced similar results at maximum efficiency (Fig. 4). However, the modelling scenarios here showed that the long-term resource requirements for the control of Acacias are also directly dependent on the clearing efficacy of current clearing programmes. Although efficacy in this study has largely focused on the treatment of plants, management efficacy can be extended to include several additional management aspects such as area-based, time-based and detection efficacy in the control programme for a protected area.

Area-based efficacy would consider if 100% of the treatment area was actually treated. To adequately manage Acacias, the entire population should be treated, however this is not always the case. In certain control programmes up to 60% of treatment areas did not have full coverage (McConnachie et al. 2012; Kraaij et al. 2017). Time-based efficacy considers i) when the treatment is scheduled for each area and ii) how much time has been allocated to undertake the clearing. Although considerable effort has gone into IAP planning, the implementation is not always satisfactory (Forsyth et al. 2012; McConnachie and Cowling, 2013; Kraaij et al. 2017). Longer-than-optimal return treatment intervals, allow plants to replenish seedbanks before the follow-up treatment is applied. The amount of time allocated to treat an area has compounding effects on clearing efficacy. Over-allocation of time impacts the total available area that can be cleared with the available budget. This results in areas not being cleared because budgets are depleted before all areas can be scheduled. Under-allocation of time results in 'fast-pace' work and treatment quality deteriorates.

The implications of these sources of management inefficacy are important for control programmes. Currently WfW only records work as completed in terms of area covered and person days used (Marais and Wannenburgh, 2008). However, from the simulation models, both the area covered and efficacy should determine if work is considered correctly completed. Red flags should be raised if the follow-up treatment cycle extends beyond two years, since covering the area alone is insufficient for IAP programmes, given seedbank replenishment. A common fall back option for managers is to increase financial resources to allow for more areas to be treated. While increasing financial resources allows for more effort, in the case of poor treatment effectiveness, this works only up to a point. Once an area is ineffectively cleared, it is physically impossible to immediately re-clear the area, as the plants need time to re-grow. Therefore, where funding is available to do the clearing, it is not a budget problem, but a lack of quality that necessitates repeat spending on the same area.

In reality, complete eradication of Acacias is unlikely within in the next 50 years, requiring control programmes to have a very long-term outlook (Rejmánek and Pitcairn, 2002; McConnachie and Cowling, 2013). This long-term view is not unreasonable when viewed against a lengthy, multi-event invasion history spanning more than 200 years (Shaughnessy, 1980). Although managers of control programmes may become disheartened by seemingly slow progress and consider the control efforts a failure (Davis et al. 2011; Vince, 2011), even at the current levels of efficacy, simulations do predict an increase in the percentage of hectares and units in a maintenance state 50 years from now. Management priorities going forward will include minimizing dispersal into uninvaded and low density sites, through early detection and rapid response as well as focussed clearing of isolated or satellite populations (Zenni et al. 2009; Kaplan et al. 2012). Managers should further be encouraged by the non-linear relationship between efficacy and clearing effort whereby even small increases in efficacy above 80% result in significant positive long-term improvements. For example improving the efficacy target to 90% would enable 74% of hectares and 65% of management units to reach maintenance levels in 50 years, compared to the current situation of 25% of hectares and 20% of management units.

Even reducing plants to < 1 plant per hectare (our aim) would leave a few scattered plants capable of seeding on the landscape, which could lead to problematic regeneration relatively quickly. Long-term budgets, for at least for the next 100 years, are required for PAs to control IAPs due to incomplete clearing (van Wilgen et al. 2016a). The notion that the resources from treated areas can be entirely shifted to other conservation areas is not supported by the model output. Even where clearing efficacy is 100%, about 25% (10,000 person days) of the current person day allocation would be required for maintenance control, due to continual recruitment from the existing seedbank. Instead of reducing budget requirements as programme efficacy improves, resources may be redeployed to other control tasks. For example, if efficacy was improved above 80%, the small unused person day allocation could be redirected to an early detection programme that seeks to ensure rapid control of new arriving species, as such working towards preventing future invasions (Leung et al. 2002). This extension of clearing programmes is important to tackle the global challenge of increasing numbers of alien species arriving at a site each year (Seebens et al. 2017), coupled with unpredictable responses to climate change (van Wilgen et al. 2016b; Slingsby et al. 2017) and other global change drivers (van Wilgen and Herbst, 2017). Such expansion in the scope of clearing projects without increased budgets is however only possible if the long-term efficacy of current control programmes is improved.

5. Conclusions

Quality of work is a primary driver of control success for invasive alien Acacias. Our model found that incremental improvements in efficacy above 80%, with a key focus on limiting seedbank replenishment, can result in large gains in the realisation of adequate control of Acacias in TMNP. Managers should not see slow progress as control failure as a long-term view of the problem is required. PA managers should undertake regular reviews that can readily identify where short terms gains can be made and where long-term interventions are needed. Going forward, there are already plans in place in Table Mountain National Park to focus on improving quality of work. A new monitoring and evaluation programme now provides an improved focus on quality of work rather than amount of work completed or person days delivered.

Declaration of interests

The authors declare that they have no financial or personal relationship(s) that may have inappropriately influenced them in the writing of this article.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2019.02.112.

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