Removing invasive conifers - considerations, complexity and costs

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Abstract
Invasive conifers are a significant problem in countries such as New Zealand, requiting a substantial investment to bring them under control. One of the critical elements of controlling invasive conifers is operational planning—determining where to control them, which trees to control, what methods to use, and the estimated cost. However, it is challenging to determine accurate costs due to the complexity of multiple site- and tree-related factors. In New Zealand, control costs are highly variable because understanding of costs per method are outdated and the complexities involved are not well elucidated. This paper explores why and how control costs vary to better predict costs in the future. To explore the factors that influence cost, we ran an online workshop that generally followed a nominal group process with several experienced project managers and contractors involved in invasive conifer control. To effectively estimate the cost of control, contractors and project managers must first understand how various site and tree-related factors influence the choice of control method. Contractors and project managers then determine how the factors influence cost. These results come at an important time in the management of invasive conifers in New Zealand and elsewhere. Control operations are increasing and expanding, requiring accurate estimates of costs to plan future operations. The findings will also be useful for training new staff and updating guidelines on invasive conifer control.

Introduction
Exotic conifers are important commercial forestry species and have been used for erosion control and shelterbelts in several countries including New Zealand, Australia, South Africa, Argentina, and Chile (Simberloff et al 2010). With excellent growing conditions, natural seeding, and regeneration, they have spread as invasive or ‘wildings’ outside of their intended areas (Froude 2011) such that their population has increased exponentially in New Zealand (Howell 2016). Where they have become invasive, problems such as overwhelming native species, reducing water flows and adversely affecting landscape values have occurred (Froude 2011), although perceived problems depend on values, landscape context and stakeholder perceptions (Dickie et al 2014, Edwards et al 2020, Mason et al 2021). Mason et al (2017) and Nuñez et al (2021) describe the positive and negative economic or ecosystem value of invasive conifers.

Exotic conifers can positively contribute to environmental goals such as contributing to climate mitigation through carbon sequestration. Dependent on the planting/distribution of the invasive conifers, additional biophysical benefits may include providing habitat for obligate forest species, erosion control and hydrological stabilization (Pawson et al 2008, Mason et al 2017, Hughes et al 2020). However, Mason et al (2017) Nuñez et al (2021) also identify important negative impacts, including higher frequency of fire, reduced soil carbon and negative effects on biodiversity, reduced water yield and lower economic opportunities.

Invasive conifers also impact landscape values, although the nature of this effect varies across stakeholders (Kirk 2019). For example, Edwards et al (2020) report that landscape perceptions depend critically on geography.
and environmental engagement. Gawith et al (2020) find that perceptions of invasive conifers is highly influenced by cultural values. Similarly, Mason et al (2021) note that perceptions of invasive conifers in New Zealand vary by ethnicity.

Despite these potential benefits, in New Zealand and other countries in the Southern Hemisphere, invasive conifers are some of the most pernicious, multi-species pests (Simberloff et al 2010). Invasive conifers reduce the water yield of water-sensitive catchments, thereby decreasing the water availability for agricultural irrigation schemes and hydroelectric generation (Farley et al 2005, Hughes et al 2020). Furthermore, invasive conifers alter soil nutrient cycling and the belowground microbiome and can have detrimental impacts on biodiversity (Dickie et al 2014, Castro-Díez et al 2019, Davis et al 2019). Particularly when these trees invade grassland ecosystems, invasive conifers change the fire regime, increasing the fuel load availability and the headfire intensity (Taylor et al 2017). Because of these negative impacts, some counties with conifer infestations have launched significant and expensive control programmes. For example, South Africa’s Working for Water spends over R400 million ($88.65 million in 2019 using purchasing power parity3) per year controlling invasive alien species (Martin 2018), while in New Zealand, the National Wilding Conifer Control Programme now spends an average of $25 million per year (New Zealand Government 2020). These figures reflect national spending and don’t account for what individual landowners and volunteers contribute. Neither does this figure reflect the marginal cost to control an additional hectare.

A crucial component of invasive conifer control is operational planning—determining where and how to control these trees and estimating costs (Froude 2011, Ministry for Primary Industries 2014). However, it is very difficult to accurately estimate the costs of control because where figures are published about control costs, they are outdated, and programmes often underestimate the cost of control (Tessa Roberts Pers. Comm. 05/05/2020). Other published material suggests that control during different life stages of invasive conifers is relatively more or less expensive, but no figures are presented (Nuñez et al 2017). Unless there is clearer understanding of control costs and what influences them, future control operations will not be accurately planned.

Very little has been written or published about the costs of controlling invasive conifers outside of South Africa (cf Working for Water 2002, Marais & Wannenburgh 2008, Preston et al 2018, The Nature Conservancy 2018). In South Africa, Marais and Wannenburgh (2008) determined that the initial cost of removing one hectare of invasive Pinus spp. at 75%–100% density was R1127 ($401), while subsequent follow-up treatments cost R363 ($129) per hectare. The cost of initial treatment for Pinus spp. at 1%–5% density was R38 ($14) per hectare, while follow up costs were R21 ($7.50) per hectare. Other species, such as Acacia and Eucalyptus had different costs, R3301 and R3201 per hectare at 75%–100% density ($1175 and $1140 respectively). More recently, The Nature Conservancy (2018) calculated costs of removing invasive species from several catchments around Cape Town. These catchments had variable terrain, different levels of access and distance from Cape Town and different species and densities. Calculated costs per hectare ranged from R2146 to R13137 ($467 to $2860), demonstrating that there can be a large variation in costs by genera and density of invasive conifers.

There have been two guides written about the costs of different control methods in New Zealand; however, these have not been updated for over 10 years and do not address the complexity involved (Ledgard & Langer 1999, Ledgard 2009). Further, the National Wilding Conifer Control Programme in New Zealand has been investing in, coordinating, and operating invasive conifer control since 2016. The Programme received $37 million from central government for funding conifer control between 2016 to 2020, and recently received another $100 million over four years to control conifers and create job opportunities (New Zealand Government 2020). The government agencies involved in the invasive conifer control report their costs spatially and also estimate their costs annually when writing their operational plans. However, there is a disparity between these estimates and the actual costs, and there is a lack of understanding why.

This article brings together the experiences of pest control contractors, operational managers and researchers involved in invasive conifer control to provide a more complete picture of control costs and understanding why and how these costs are incurred. There is a need to better understand the costs of controlling invasive conifers, as it will help with planning and estimating costs of control operations in the future, improve operational efficiency and train new operations managers and contractors.

**Methods**

Previous attempts to provide a full estimate of costs for invasive conifer control by interviewing experts have failed to capture the range of factors and complexity involved. To overcome the failure with individual interviews, we determined that a workshop with a variety of contractors, operational managers and researchers

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3 All dollar figures in this paper are in New Zealand dollars. In 2019, $1 NZ = $0.66 US.
that are knowledgeable about different control methods and the factors that influence the choice of method was appropriate. Thus, we organized a workshop with a convenience sample of knowledgeable people (rather than a random sample of experts) (Dietz 1987) to assess control methods and associated costs on different sites. The participants included experienced private-sector contractors and project managers from local and central government, all of whom have extensive experience in invasive conifer control in New Zealand. We used a real site (Flock Hill, Canterbury, New Zealand; figure 1) as an example to make our discussions more tangible. All participants were familiar with this site.

The workshop was designed to emphasise ‘variable costs’, i.e., costs that depend on site-specific factors described in table 1. These factors were sourced from the literature (e.g. Ledgard 2009, Froude 2011, Woolons & Manley 2012, Mason et al 2017, Satchell 2018, South African Department of Environment, Forestry and Fisheries 2019, Paul unpublished data). Thus, we developed a baseline ‘scenario’ and the variables or factors in table 1 were changed iteratively (table 2). To maintain a consistent approach, a specific definition of ‘control’ was used during this workshop as follows: all costs associated with local eradication, including any repeat visits to eradicate seedlings sprouting from the seed bank or trees not killed in the first round.

Similar to what Fink et al (1984) call a ‘nominal group process’, all participants were in the same videoconference and were able to discuss and debate different aspects of controlling invasive conifers on a known plot. Like a Delphi process, this workshop brought together expert opinions to formulate a knowledgeable prediction generally arriving at a consensus on costs (cf Kennedy 2004). In some cases, consensus on the method to control them was unattainable, thus multiple methods could be used in a given scenario. That said, participants generally arrived at consensus on an average cost to control one hectare of invasive conifers under each scenario. However, where uncertainty arose, a cost range was agreed upon. While this marginal approach provided insight into how each factor influenced cost, it did not evaluate multiple factors

Table 1. Variables influencing invasive conifer control and their definitions that were used in this research.

| Variable           | Definition                                                                 |
|--------------------|-----------------------------------------------------------------------------|
| Coning             | Maturity/age of trees                                                       |
| Hindrance          | Physical object in field that may be obstacles to clearing operations, e.g. boulders, vegetation density, rivers/streams, etc |
| Vegetation         | Trees or other vegetation that you do not want to kill                      |
| Size               | Height and diameter at breast height                                         |
| Density            | Number of stems per hectare                                                 |
| Slope              | Steepness of the terrain                                                    |
| Control methods    | Which method best suited for the context, along with other suitable methods |
| Fixed costs        | Transport/access, planning and other logistics costs                        |
simultaneously. Thus, the estimates included costs associated with initial control methods and follow-up methods with additional or different costs. We separately assessed fixed costs such as transportation, access, and planning costs.

The above scenarios are stylised and were helpful for the purposes of estimating costs, although participants recognised that invaded sites typically reflect multiple scenarios. As such, our estimates of control costs reflect the lower bound of control costs. For example, one approach may be the least expensive option for one scenario and the second-least expensive option for a second scenario. If the actual invaded area included both scenarios, it may be more pragmatic to adopt that control even though costs were not strictly minimised.

### Results

#### Workshop discussion—factors that influence cost

The workshop was useful to discuss how to estimate the costs of control for an area and the factors which influence control cost. It emerged that operators and contractors rely primarily on their experience to estimate costs. The cost of control is tightly linked to the control method, but which method is selected depends on cost.

Based on the discussions at this workshop, we have compared/contrasted the factors from table 1 and additional factors that became apparent during the workshop, which influence the choice of control method and those that influence cost in table 3. The workshop participants were asked after the workshop to rank these factors from most to least influential in determining cost.

The first consideration of a site is tree or stand density since density narrows down the list of control methods that may be undertaken. For example, if the site has a dense infestation of trees, control options available include aerial boom spraying, logging and mechanical control. If the site has a low density of trees, then the control options available include ground control (chainsaw cut and paste; drill and fill; ground basal-bark application using X-Tree herbicide; and foliar spray) and aerial control (aerial basal-bark application or aerial foliar spray). Tree size, slope/terrain and access further narrow control options.

Based on our definition of control, species influences control methods because different species of invasive conifers have different coning ages. Species influences the timing of initial and follow-up control used as this

#### Table 2. Range of scenarios explored during the workshop. Italicised factors were the factors changed from the baseline in each scenario.

| Scenario | Description |
|----------|-------------|
| 1 (Baseline) | High density, flat, large, mature trees, no hinderance or native vegetation |
| 2 | High density, flat, small/medium trees, no hinderance or native vegetation |
| 3 | High density, flat, small trees, no hinderance or native vegetation |
| 4 | High density, slight (10%) slope, large trees, no hinderance or native vegetation |
| 5 | High density, steep (20%) slope, large trees, no hinderance or native vegetation |
| 6 | Medium density, flat, large trees, no hinderance or native vegetation |
| 7 | Low density, flat, large trees, no hinderance or native vegetation |
| 8 | Mixed density and size, flat land |
| 9 | High density, flat, large trees, no hinderance, sensitive vegetation |

#### Table 3. Relative importance of factors influencing the choice of control method and costs from more important to less important.

| Factors influencing choice of method | Factors influencing cost |
|-------------------------------------|-------------------------|
| Tree/stand density                  | Control method used—influences initial cost and cost of ongoing maintenance control |
| Tree size                           | Species                 |
| Slope/terrain at site               | Tree/stand density      |
| Road/wheeled access                 | Tree size               |
| Tree species                        | Slope/terrain           |
| Area                                | Hindrance and risks to nearby native vegetation |
| Outcomes—what will happen to the land following the removal of invasive conifers. | |
| Social licence to operate           | |
| Hindrance                           | |
| Risks to nearby native vegetation—applicable around boundaries of where control is happening | |
| Control method efficacy - want to use a method that works well and minimises follow-up treatment required | |

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| Hindrance                           | |
| Risks to nearby native vegetation—applicable around boundaries of where control is happening | |
| Control method efficacy - want to use a method that works well and minimises follow-up treatment required | |
helps determine how soon afterwards follow-up control would be required. Species and their unique coning ages also influences the timing of control. For example, Pinus contorta (lodgepole pine) needs to be controlled when it is small before it starts to cone at 4–5 years of age (Ledgard & Langer 1999, Ledgard 2009), but Pinus nigra (Corsican pine) doesn’t start to cone until 10+ years of age (Sullivan 1993, Ledgard & Langer 1999) so the trees can be older and larger before they must be controlled. Species also influences the preferred control method(s) to be used—some species can be harvested (i.e. Pinus radiata - Radiata pine or Pseudotsuga menziesii - Douglas fir) whereas others it is not economically viable to harvest (i.e. Pinus contorta - Lodgepole pine).

Operations managers will also choose a control method based on the desired site outcome. For example, land ownership (public or private) can influence costs due to possible restrictions on control methods (e.g. herbicides). There is ongoing research to determine the effects of control methods on sites (i.e., how boom spraying affects soil and germination of invasives and other species) (Paul et al 2020). The desired site outcome indirectly affects control costs through the choice of control method appropriate for the site end-use.

Further, when there is variation within individual factors involved (e.g. a mix of densities or terrain), the complexity involved impacts decision-making processes. For example, a range of tree sizes could mean a mix of different control methods; however control methods will also depend on density. Individual contractors, managers and experts apply their experience to determining control methods, thus no consensus could be reached in workshop discussions of these situations.

Figure 2 shows how and where the factors in table 3 influence the choice of method, cost and follow-up treatments.

**Workshop discussion - costs**

Tree and site characteristics influence control methods and thus costs. Tree density determines which methods are applicable to a site, and density and tree size will also influence control costs through the time it takes to control an area. Species influences control cost through the herbicides and dosages used. For example, Douglas fir can be controlled using metasulfuron, which is significantly cheaper than the herbicide brew TDPA used to control Pinus spp.

In terms of site characteristics, slope influences costs by decreasing accessibility for machinery and using higher amounts of herbicide and other costs based on chosen control method(s). Participants noted that for each 10% increase in land gradient, there is a corresponding ~10% increase in cost due to an increase in the amount of herbicide needed to be applied to foliage on slopes, as well as overflying the area more slowly to ensure the appropriate amount of herbicide is applied (table 4). Depending on the control method used, hinderance directly impacts cost if machinery or manual labour are involved. The greater the area to be controlled, the greater the cost.

Participants identified multiple possible control options and thus multiple possible costs for some scenarios. However, for other scenarios, only one control option was identified. Depending on individual approaches to using a particular method, a range of costs were presented by participants (See table 4).

Where commercial species exist in appropriate condition, trees may be harvested and sold for timber, pulp or other uses. Expert appraisal considering tree quality and quantity, species, market conditions, road access and distance to ports is required before this method is considered. In most cases, the costs associated with harvesting are recouped through timber sales. Factors which will influence the costs for mechanical harvesting are fixed costs, e.g. road access and distance to ports or processing facilities. For example, one workshop participant described spending $4055 to harvest an area of pines while $4160 was recovered from the sale of the timber.

In scenario 9, if the sensitive vegetation is mixed in with the invasive conifers, the only option is to use the more expensive drill and fill to control the invasives. If there was sensitive vegetation on the edge of a dense conifer infestation, contractors would likely boom spray the main area and leave a large buffer around the edges. The buffer would be drilled and filled. The total cost of this scenario would be highly dependent on the specific site characteristics.

Depending on the initial control method, tree conning, seed bank and seed rain can influence the number and timing of follow-up treatments. Significant differences in costs for spot spraying are based on the participants’ experience of the success of initial control. For example, in scenario two, almost all boom sprayed small/medium trees would be killed in the initial control, and follow up could be minimal. While we can estimate total control costs relatively well, it depends heavily on the efficacy of the control methods used and environmental factors (e.g. tree physiology or environmental conditions during control).

**Discussion and conclusions**

In New Zealand, information about control costs is both patchy and outdated (cf Ledgard 2009), leading to inaccuracies in estimates of future control costs. Thus, uncertainty and underbudgeting have led to inadequate
Figure 2. Progression of invasive conifer control from choice of methods through to costs at different stages with the site and invasive factors that influence each of them.
resources being allocated in many control operations. This may be due to area not being at the forefront of contractors cost estimations; however, being able to estimate costs by area is highly useful for planning control operations. Operational managers and contractors know the size of the areas they are controlling and through the National Wilding Conifer Control Programme are encouraged to map control operations.

While this paper focuses on New Zealand, much of the complexity—the factors involved and decision-making processes—are similar in other areas facing problems with large woody invasive species. Australia, South Africa, Chile and Argentina face similar issues with invasive conifers (Simberloff et al. 2010). We propose a two-step process for determining control costs in which the first step is to analyse a set of ranked factors that determine what control methods can be used on a site (see figure 2). The second step then becomes analysing a subset of the above ranked factors that have a more direct influence on the cost at a particular site. While it is not directly reported that positive ecosystem services are explicitly considered in conifer removal, Mason et al. (2017) highlight the trade-offs between value that invasive conifers bring through ecosystem services and the damage they cause. From anecdotal experience, we believe that these considerations factor implicitly into the complex considerations that need to be made. The workshop participants determined that there is a different ranking of factors that influence the control method than those factors that more directly influence the cost.

While estimating general control costs by area alone is highly useful for planning, it does not completely replace operational managers and contractors experience in considering site complexity. For example, many sites have a mix of densities and terrain where multiple control techniques may be required. Further, the medium density sites can be very difficult to estimate costs for because there is not always one particular control technique that is the most suitable.

Coning age is a key consideration, particularly for follow-up control. Coning varies significantly by species and is highly dependent on the environmental conditions where the trees are located. Thus, coning ages that have been determined in other areas or countries (cf Sullivan 1993) are not necessarily applicable. Research into coning age in NZ has not been updated since the 1990s and will likely change significantly with the advent of climate change.

In this paper, we do not explicitly account for the costs of post-control land management. We nevertheless acknowledge that proper land management suitable for the region and land tenure is needed to prevent re-invasion of conifers after they are controlled (Nuñez et al. 2017, Hulme 2020). When there is a nearby seed source of conifers, simply removing the invasive conifers from one site does not solve the problem. Restoration of a site can be as or more expensive than the cost of control, and site managers need to have a post-control plan in place prior to undertaking the control (Nuñez et al. 2017, Hulme 2020).

Our results have been determined using a specific site that is representative of many sites around New Zealand and potentially in other countries. That said, every site is unique, and every site can have different characteristics that influence the actual costs of controlling invasive conifers. Some sites may have limitations on the control methods that can be used, such as whether herbicide application is acceptable to the landowner or public and whether certain control methods may be needed to achieve a particular future land use.

Managing invasive conifers also has a political dimension. In South Africa, the Working for Water programme was primarily an employment scheme that happened to remove invasive species to improve water supply (Marais & Wannenburgh 2008). Previous iterations of the New Zealand National Wilding Conifer Control Programme were focused on removing invasive conifers in the most timely and cost-effective way.

### Table 4. Costs per hectare for initial control of invasive conifers in each of the scenarios described in table 2.

| Scenario                          | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|-----------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Boom spray full strength TDPA+a   | $1800 | $2200 | $2500 | $1800 |
| Boom spray ½ strength TDPA        | Cost neutral | $1100 | $1100 |
| Mechanical harvesting             | Cost neutral | |
| Windrowing                        | $450–1200 | |
| Mulching                          | $360 | $360 | |
| Chainsaw cut & paste              | $450–750 | $450–750 | $100 | |
| Grubbing                          | $750 | |
| Spot spray                        | $1600 | |
| Drill & fill                      | |
| Chainsaw hose & gun               | $3000 | |
|                                  | $1750 | |

*a TDPA is a mixture of herbicides triclopyr, dicamba and picloram mixed with ammonium sulphate, an emulsified spray oil to ensure the spray adheres to its target, and an organo-silicone surfactant to enhance surface penetration (Scion 2015).
possible (Ministry for Primary Industries 2014), but invasive conifer removal has become a job-creation scheme in the wake of the COVID-19 pandemic.

Specifically, the government has created a four-year ‘Jobs for Nature’ programme to provide jobs and economic support to people while ensuring environmental benefits (Ministry for the Environment, n.d.). In addition, the National Wilding Conifer Control Programme has an additional objective of creating ‘green jobs’ (New Zealand Government 2020) in protecting nature, including weed, pest and predator control.

As noted in tables 4 and 5, the more labour-intensive control methods tend to be more expensive. If the Jobs for Nature Programme influences a turn towards these types of control methods, invasive conifer control may become more costly.

In this work, we have assumed that additional, identical hectares are controllable at the same cost as the first hectare. However, the marginal cost of controlling a second identical hectare is likely to be lower than the costs of controlling the first hectare. Further work may explore the relative costs associated with clearing larger and smaller invasions with otherwise similar characteristics.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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Table 5. Costs per hectare for follow up control of invasive conifers in each of the scenarios described in table 2.

| Scenario                        | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    |
|---------------------------------|------|------|------|------|------|------|------|------|------|
| Boom spray full TDPA            | $1800|      |      |      |      |      |      |      |      |
| Spot spray X-Tree               | $100 | $1600| $100 | $100 | $400 | $1600| $100 |      |      |
| Drill & fill                    |      | $1600|      | $3000|      |      |      |      | $1500|
| Loppers                         | $100 | $100 | $100 | $100 | $100 |      |      |      |      |
| Pasture                         |      |      |      |      |      |      |      |      |      |

Tableau 5. Costs per hectare for follow up control of invasive conifers in each of the scenarios described in table 2.
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