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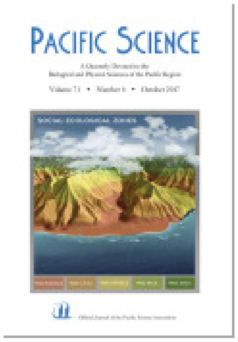

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Toward Cost-Effective Restoration: Scaling up Restoration in Ecosystems Degraded by Nonnative Invasive Grass and Ungulates[1]

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Abstract: Nonnative, invasive grasses displace native plant communities and challenge ecological restoration globally. Ecological monitoring of restoration is typically short term and rarely reassessed to determine if initial findings are indicative of multiyear outcomes, and economic costs of restoration are seldom quantified. To address these knowledge gaps, we resampled a restoration experiment in an invasive *Megathyrsus maximus*–dominated ecosystem in Hawai‘i to compare success of restoration treatments at 8 and 36 months. We calculated cost to establish and maintain (for 3 yr) experimental field trials (0.13 ha) and management-scale (1 ha and 10 ha) units, estimated 30-yr costs for management-scale units, and determined key drivers of costs. Survival of native outplant species did not differ between 8- (56%) and 36-month (51%) monitoring periods, and *M. maximus* cover was lower in restoration treatments than in control plots at both time periods. Cost to establish and maintain the experimental trial was \$14,299 (Present Value at 2% annual discount rate, 2015 US\$; \$109,993 ha^{-1}). Scaling up restoration to 1 and 10 ha units produced economies of scale, with 3 yr costs declining with increasing area (\$149,918 ha^{-1} for 1 ha; \$124,139 ha^{-1} for 10 ha). Total Present Value to restore and maintain a 1 ha site for 30 yr ranged from \$153,195 to \$302,917 ha^{-1}, varying primarily based on labor and seedling costs. This study demonstrates that early restoration results can be indicative of longer-term results, establishment expenses drive long-term costs, and restoration efforts are most cost-effective when maintained over large spatial scales and long time periods. Importantly, this study allows other projects in the region to estimate restoration costs based on site-specific criteria.

NONNATIVE INVASIVE SPECIES are a major challenge to ecological restoration. Invasive species can alter disturbance regimes (Veldman et al. 2009), modify biotic interactions (Vitousek 1990, Mitchel et al. 2006), and cause substantial loss of native biodiversity (Vitousek et al. 1997; Mack et al. 2000; Cabin et al. 2002, “Effects of microsite”; Ammondt et al. 2013). Although preserving or returning native biological diversity is often a primary objective of ecological restoration, most restoration projects likely require active and

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long-term management of invasive species to meet native biodiversity goals (Cabin et al. 2002, "Effects of light"; Falk et al. 2006; Ammondt et al. 2013; Ellsworth et al. 2015). This is particularly true where nonnative invasive grasses displace native communities due to superior competition for limiting resources (D'Antonio and Vitousek 1992, Ammondt et al. 2013), high tolerance of disturbances (Nepstad et al.1990, Bryson and Carter 2004, Litton et al. 2006), and contribution to feedback cycles that result in a perpetually degraded state (Thaxton et al. 2012).

Throughout the main Hawaiian Islands and much of the tropics, the African pasture grass *Megathyrsus maximus* (Jacq.) (guinea grass) dominates many lowland areas, where its competitive superiority and capacity for rapid recovery following fire and grazing make it a major threat to dry and mesic forest conservation and restoration (Breugmann 1996, Ammondt and Litton 2012, Ammondt et al. 2013, Ellsworth et al. 2014). To promote native species in ecological restoration projects in these areas, there is an urgent need to find cost-effective methods to control *M. maximus* and promote native vegetation (Naidoo et al. 2006, Ammondt et al. 2013, Duke et al. 2013).

Examples of restoration projects can be found throughout the literature where success is defined and based on results from very early stages of management, with very few studies examining whether the initial results of restoration activities are indicative of longer-term success (Cabin et al. 2000, Daehler and Goergen 2005, Ellsworth et al. 2015), despite the fact that invasive nonnative grasses such as *M. maximus* often require aggressive and ongoing monitoring and maintenance (Ammondt et al. 2013, Ellsworth et al. 2015). Ongoing management can require large monetary commitments that may affect project feasibility (D'Antonio and Meyerson 2002, D'Antonio and Chambers 2006, Naidoo et al. 2006), yet the costs of ecological restoration are often not quantified for larger-scale projects or over the lifetime of the project. Understanding the costs of a restoration project (both preparation and establishment costs occurring in the first year of restoration, as well as ongoing maintenance costs) is required for successful and sustainable restoration planning over large spatial and long temporal scales (Holl and Howarth 2000, Naidoo et al. 2006, Watzold et al. 2006, Dorrough et al. 2008). Cost information can help to ensure that adequate funding is secured, limited resources are allocated most efficiently, and decision makers are better informed of cost-effective, sustainable long-term restoration strategies (Dorrough et al. 2008, Goldstein et al. 2006, 2008), especially when scaling up experimental restoration efforts to management scales.

The objectives of this research were to: (1) determine if restoration results for native species outplant treatments (i.e., suites of species planted in the field) in a dry lowland ecosystem in Hawai'i at 8 months (Ammondt et al. 2013) accurately predict outcomes at 36 months by comparing survival of native species outplant treatments and relative differences in percentage cover of native species and invasive *M. maximus* at those two time periods; (2) assess the costs associated with ecological restoration in this system over different spatial scales; and (3) evaluate how restoration costs in this system differ under a variety of restoration scenarios and over longer temporal scales.

Specific hypotheses included the following: (1) native outplant survival rates at 8 months would be indicative of results at 36 months in outplant treatments due to expected low mortality following establishment (Ammondt et al. 2013); (2) native species cover at 36 months would be higher than at 8 months in the outplant treatments because growth of natives would suppress nonnative plants (Ammondt et al. 2013, Ellsworth et al. 2015), but that relative differences across treatments would remain unchanged; (3) economies of scale (i.e., cost per unit area declines with increasing size) would exist in restoration costs with increased size of restoration, and the effect would increase over time; and (4) restoration costs would increase with the degree of difficulty to restore the site.

To test these hypotheses we quantified native species survival and cover at 8 and 36 months after outplanting; calculated the restoration costs associated with the 3 yr experimental field trial (all costs are Present Value calculated at 2% annual discount rate and expressed in 2015 US$); estimated the cost of scaling up the 3 yr experimental restoration site to 1 ha and 10 ha management units; and estimated long-term management costs over a representative 30 yr period for hypothetical 1 ha and 10 ha management units with varying degrees of difficulty using various restoration scenarios. The 30 yr time period for the long-term restoration cost analysis was selected to account for stand development and canopy closure. Overall this study provides an example of early ecological benefits that can be gained from restoration activities, as well as the monetary commitments required for establishing and maintaining restoration projects at management scales.

MATERIALS AND METHODS

Study Site

This study was conducted from 2010 to 2013 in a Hawaiian dry lowland ecosystem within the Wai‘anae Kai Forest Reserve on leeward O‘ahu, Hawai‘i (300 m a.s.l., 158° 9′ 181″ W, 21° 28′ 53″ N). The study area is highly degraded and dominated by the invasive nonnative grass *M. maximus*. Soils are of the Ewa series and are characterized as well-drained reddish silty clay loams (fine, kaolinitic, isohyperthermic Aridic Haplustolls) formed from alluvium weathered from upland basalt (Soil Survey Staff 2006). Mean annual precipitation and mean annual temperature are estimated at 1,258 mm (Giambelluca et al. 2013) and 22°C (Giambelluca et al. 2014). From 2010 to 2013, annual precipitation averaged 716 mm/yr, well below the long-term average annual precipitation for this site, and ranged from a minimum of 437 mm in 2012 to a maximum of 905 mm in 2013.

Restoration Treatments

This study builds upon work describing initial survival and response of native species 8 months after outplanting (Ammondt et al. 2013) by remeasuring native species survival and native and invasive grass cover 36 months after outplanting at an experimental field trial located in the Wai‘anae Kai Forest Reserve. In July 2009, the study area was mowed, in September 2009 herbicide was applied to the entire study area except control plots, and in October 2009 a 0.13 ha fence (62 m long and 21 m wide) was erected to exclude feral and domesticated ungulates common in the area. Four blocks, each consisting of five 9 m^2 square treatment plots (20 plots total), were established along a ~10 m elevation gradient. On 7 January 2010, three different suites of native species were planted in three of the 9 m^2 square treatment plots of each block (12 treatment plots total, totaling 108 m^2). All three outplant treatments included *Dodonaea viscosa* Jacq. (‘a‘ali‘i), a shrub species; *Plumbago zeylanica* L. (‘ilie‘e), a ground cover; and one of three canopy trees, either *Thespesia populnea* (L.) Sol. (milo), *Cordia subcordata* Lam. (kou), or *Myoporum sandwicense* A. Gray (naio). In addition, herbicide control (herbicide without native outplants) and untreated control (no herbicide or native outplants) plots were assigned to plots within each block. Twenty-five plants were hand planted in each treatment plot (12 ground cover (*P. zeylanica*), nine shrub (*D. viscosa*), and four canopy trees). Each plant was given 1 liter of supplemental water immediately after planting and once per week for the 3 weeks following outplanting. Plants that died within 1 month of outplanting (*P. zeylanica*, 15% mortality; *D. viscosa*, 29% mortality; *T. populnea*, 13% mortality; *M. sandwicense*, 6% mortality; *C. subcordata*, 38% mortality) were replaced.

Clearing and herbicide maintenance was performed during the 3 yr experimental field trial. On 12 April 2010, 30 November 2010, 21 May 2011, and 3 May 2012, the post-emergent, grass-specific herbicide fluazifop p-butyl (Fusilade DX, EPA reg. no. 100-1070) was applied to all plots, with the exception of the four untreated control plots, for continued suppression of *M. maximus* regrowth. On 30 November 2010, cut stumps of scattered *Leucaena leucocephala* (Lam.) de Wit individuals were treated with an application of triclopyr (Pathfinder II, Dow AgroSciences, Indianapolis, Indiana, EPA reg. no. 62719-176). On 3 May 2012 secondary weeds, corridors, and fence lines were treated with glyphosate (KleenUp, Loveland Products, Inc., Greeley, Colorado, EPA reg. no. 34704-890). Surveys to ensure the integrity of the perimeter fence (i.e., fence maintenance) were completed in the second and third years.

Vegetation Sampling

Survival and cover of outplants were estimated on 24 August 2010, 8 months after outplanting (Ammondt et al. 2013), and again on 12–13 January 2013, 36 months after outplanting. Identical procedures were used at both time periods, with one exception: survival of *P. zeylanica* was not reassessed at 36 months because individual plants could no longer be distinguished. Percentage cover of native species and *M. maximus* was measured using a point-intercept method (81 point frame overlaid on each 9 m^2 treatment plot).

Cost Analysis

Data for the cost analysis were derived from actual unit costs (i.e., labor and material costs), material needs, and required labor for the establishment, preparation, and maintenance of the 3 yr experimental field trial at the 0.13 ha Wai‘anae Kai Forest Reserve site. To determine costs, we documented the time, labor, and material requirements to establish, prepare, and maintain the 3 yr experimental field trial and conducted interviews with land managers and contractors involved in the field experiment. Specifically, we compiled data (i.e., baseline parameters) on labor time rates (dependent upon planting rate, water delivery rate, invasive species clearing rate, fence construction rate, and fence maintenance rate), labor costs, and material costs (fencing materials, plants, water, and equipment) to conduct the 0.13 ha experimental field trial for 3 yr. The baseline parameters used to estimate the 3 yr cost of conducting the 0.13 ha experimental field trial are outlined in the Results section.

We then used the outplant composition, density, and mortality data, and baseline parameters derived from the 3 yr experimental field trial, as well as information from the literature and expert interviews with scientists, land managers, government employees, and other professionals knowledgeable about restoration of Hawaiian dry lowland ecosystems, to extrapolate 3 yr costs across various spatial scales (0.13 ha, 1 ha, and 10 ha management units [1 ha and 10 ha management units are assumed to be square sites]) to investigate economies of scale. For the larger 1 ha and 10 ha management units we assumed that a water truck would be rented (at a rate of $3,550/month) to supply the sites with the needed water (i.e., 1 liter of water per plant once per week for 4 weeks following outplanting) during the establishment phase.

To provide managers with an idea of the long-term costs of restoration we compared the 3 yr costs of restoring 1 ha and 10 ha management units over a longer time horizon. We chose a 30 yr time period for the long-term restoration cost analysis to reflect a reasonable restoration project time horizon. Of course, cost savings can be achieved in restoration projects (e.g., employing volunteer labor, utilizing on-site propagation and seed banks, etc.); therefore, we modeled cost-reduction strategies to estimate reduced unit costs. We individually varied labor costs, planting costs, planting speeds, and watering method for the 1 ha and 10 ha management units over the 3 yr and 30 yr periods to evaluate the benefits of utilizing volunteer labor, developing nurseries, and upgrading equipment in the initial phase of restoration. An additional cost-reduction strategy was applied to the 30 yr restoration cost estimate for the 1 ha and 10 ha management units to account for the discontinuing of invasive plant removal (i.e., herbicide application and tree-clearing maintenance) at 5 and 10 yr after restoration, assuming success of the restoration project and no need for ongoing invasive grass and/or tree suppression.

Finally, the experimental site within the Wai‘anae Kai Forest Reserve is very accessible, is gently sloping, has a fairly rough and rocky terrain, and is occupied primarily by invasive grass with a moderate number of invasive trees. Compared with remote sites with more arduous restoration conditions (i.e., less accessible, steeper, moderate rough and rocky terrain, dominated by invasive grass and dense invasive trees), the experimental site is considered to be on the easy end of the spectrum; thus the estimates of labor and material needs may be too optimistic for all restoration scenarios. To better understand the costs for more-arduous restoration scenarios, we compared a hypothetical "Easy" 1 ha site (modeled after our baseline conditions at the Wai'anae Kai Forest Reserve study site) to two 1 ha hypothetical sites of greater difficulty that would have more labor and material needs [i.e., Moderate and Difficult sites (see details in Supplemental Methods)]. We ran these more arduous conditions for the longer 30 yr time horizon.

Authors' Note: Supplemental materials available online at BioOne (http://www.bioone.org/toc/pasc/current) and Project MUSE (http://muse.jhu.edu/journal/166).

In all cases, we give the Present Value of the costs. Present Value represents the current value of all costs over time and is calculated by discounting future costs by a specified rate to reflect the time value of money. We applied an annual discount rate of 2% and report costs in 2015 US$. For more details of the parameters used to extrapolate costs for various restoration site conditions and strategies, see the Supplemental materials (details are provided in Supplemental Tables S1 to S8). Although other regional restoration projects will have different costs for some or all aspects as those assumed here, we provide estimated costs from an individual study to exemplify the need to include economic analyses in restoration projects generally and to highlight a methodology for doing so. The Supplemental materials provided with this study facilitate the fine-tuning of values for other restoration projects in the region.

Statistical Analyses

Mixed-effects models were used to test for differences in percentage survival for each woody plant outplant species and *D. viscosa* by treatment and time, and percentage cover of *M. maximus*, *D. viscosa*, and *P. zeylanica* by treatment and time. Where data did not meet the assumptions of analysis of variance (ANOVA) (outplanted native tree cover), a square root–transformation was used before analysis. Tukey's multiple comparison post hoc analyses were used to determine which treatments had significantly different means following significant F tests. Block was treated as a random factor, and treatment and time were fixed factors. IBM SPSS v.20 (IBM SPSS, Inc., Chicago, Illinois) was used for all statistical analyses, and results were considered significant at $\alpha = .05$.

RESULTS

Ecological Results

Across all native canopy and shrub species, survival did not differ significantly at 8 months (56%) and 36 months (51%) after outplanting ($P \geq .13$). A small increase in survival of the canopy species *T. populnea* after 36 months resulted from the recovery of two individuals that were determined to be dead at 8 months (Table 1). Cover of *M. maximus* was significantly reduced in all native outplant treatments when compared to herbicide control and untreated control ($P \leq .01$), and invasive grass cover did not differ with time since restoration ($P = .20$). Cover of all native species, with the exception of *C. subcordata*, increased significantly between 8- and 36-month time periods ($P \leq .01$) but remained significantly higher over time in all native outplant treatment plots when compared to herbicide control and untreated control ($P \leq .01$) (Table 2).

TABLE 1

Native Woody Outplant Species Survival at 36 Months in a Restoration Field Experiment at Wai'anae Kai Forest Reserve, O'ahu, Hawai'i

Species	% Survival (SE)
Dodonaea viscosa	56.5% (6.8)
Thespesia populnea	68.8% (12.0)
Myoporum sandwicense	31.3% (6.3)
Cordia subcordata	12.5% (12.5)

Note: Plants that died within 1 month of outplanting were replaced (*D. viscosa*, 29% mortality; *T. populnea*, 13% mortality; *M. sandwicense*, 6% mortality; *C. subcordata*, 38% mortality; *P. zeylanica*, 15% mortality). Survival of *P. zeylanica* was not reassessed at 36 months because individual plants could no longer be distinguished.

TABLE 2

Megathyrsus maximus and Native Outplant Cover (%) at Wai‘anae Kai Forest Reserve, O‘ahu, Hawai‘i

Parameter	Sample Month	*Thespesia populnea* Treatment	*Myoporum sandwicense* Treatment	*Cordia subcordata* Treatment	Herbicide Control	Untreated Control	Block *P* (df_{Hs}, df_{error}, *F*-statistic)	Time *P* (df_{Hs}, df_{error}, *F*-statistic)	Treatment *P* (df_{Hs}, df_{error}, *F*-statistic)	Time * Treatment *P* (df_{Hs}, df_{error}, *F*-statistic)
M. maximus	8	26.9 (14.0)	6.8 (3.2)	11.7 (5.7)	69.8 (12.5)	84.0 (12.0)	.49 (3, 12, 0.86)	.20 (1, 15, 1.80)	<.01 (4, 12, 43.50)	.01 (4, 15, 4.61)
	36	35.2 (9.4)	21.0 (7.4)	9.6 (5.9)	92.9 (3.9)	99.1 (0.6)				
P. zeylanica	8	36.1 (6.1)	44.1 (5.6)	59.9 (3.6)	0 (0)	0 (0)	.13 (3, 12, 2.33)	<.01 (1, 15, 10.85)	<.01 (4, 12, 78.10)	.15 (4, 15, 1.96)
	36	53.7 (9.8)	59.9 (10.2)	83.3 (6.0)	0 (0)	0 (0)				
D. viscosa	8	6.2 (2.8)	13.6 (4.5)	8.0 (3.0)	0 (0)	0 (0)	.31 (3, 12, 1.35)	<.01 (1, 15, 52.36)	<.01 (4, 12, 7.97)	<.01 (4, 15, 8.80)
	36	50.9 (12.4)	57.7 (14.0)	58.3 (15.3)	0 (0)	0 (0)				
Native trees	8	0.6 (0.4)	1.9 (1.9)	0 (0)	0 (0)	0 (0)	.51 (3, 12, 0.82)	.01 (1, 15, 8.70)	.10 (4, 12, 2.52)	<.01 (4, 15, 6.33)
	36	1.2 (0.9)	9.6 (7.5)	0 (0)	0 (0)	0 (0)				

Economic Results

Baseline parameters were identified for labor time rates, labor costs, and material costs for the establishment, preparation, and maintenance of the 0.13 ha experimental field trial within the Wai‘anae Kai Forest Reserve, with the following site conditions: fully accessible by road, ~10 m elevation gradient, fairly rough and rocky terrain, dominated by an invasive grass with few scattered invasive trees, and requiring exclusion of ungulates via fence construction (Table 3). The total estimated cost of the 3 yr restoration experiment was $14,299. Establishment and site preparation costs during the first year accounted for 97.6% ($13,962) of the total 3 yr costs, and maintenance costs in years 2 and 3 accounted for just 2.4% ($337). Cost of fence construction ($11,197, accounting for 78.3% of the overall costs) dominated the 3 yr overall costs, followed by outplanting and replanting due to mortality (i.e., labor, water, plants, equipment) ($1,403, 9.9%), clearing ($752, 5.3%), and herbicide application ($611, 4.3%).

We found evidence of economies of scale (Table 4). Scaling up from the experimental plots to the full 0.13 (i.e., entire area within fence treated rather than just small experimental plots within the fence), 1, and 10 ha sites increased the total costs to $27,154 (+90% from experiment), $149,918 (+452% from the 0.13 ha management unit), and $1.2 million (+728% from the 1 ha management unit), although the cost per unit area declined from $208,883 ha^{-1} (0.13 ha) to $149,918 ha^{-1} (1 ha) to $124,139 ha^{-1} (10 ha). The general trend of establishment costs dominating maintenance costs held for all spatial scenarios. For the scaled-up management units, the establishment costs were ~98.7% of the total cost, with costs of outplanting and replanting due to mortality driving costs, particularly for the larger areas (52.4% for 0.13 ha, 76.7% for 1 ha, 87.2% for 10 ha). Notably, the importance of the cost of fencing declined with increasing area (41.2% for 0.13 ha to 17.9% for 1 ha to 6.9% for 10 ha), reflecting the benefit of larger area to perimeter ratios. To provide insight on how a longer time period affects the scaling-up re-

TABLE 3

Baseline Parameters for Labor Time Rates, Labor Costs, and Material Costs Used to Estimate the 3 Yr Cost of Conducting the 0.13 ha Experimental Field Trial within the Waiʻanae Kai Forest Reserve, Oʻahu, Hawaiʻi, with the Following Site Conditions: Fully Accessible by Road, ~10 m Elevation Gradient, Fairly Rough and Rocky Terrain, Dominated by an Invasive Grass with Few Scattered Invasive Trees, and Requiring Exclusion of Ungulates via Fence Construction

Restoration Activity	Labor Time Rate	Labor Costs	Material Costs
Fence construction	2.7 m/hr/4-person crew	Project manager $25/hr, crew leader $15/hr, and two crew $13/hr	$43/m for fencing materials
Fence maintenance[a]	100 m/hr/person	$35/hr/person	Assumed to be included in labor costs
Initial site clearing and clearing maintenance of invasive trees	120 hr/ha/person for initial site clearing; 10 hr/ha/person for maintenance clearing	$20/hr/person for clearing and clearing maintenance[b]	Clearing: $200/chain saw and $120/weedwacker
Herbicide application	52.5 hr/ha/person (year 1); 11.5 hr/ha/person (year 2); and 7 hr/ha/person (year 3)	$16.50/hr/person for herbicide application and herbicide maintenance	Herbicide: $65/backpack sprayer and approximate herbicide rates[c] of $2,349/ha (year 1), $962/ha (year 2), and $137/ha (year 3)
Outplanting/Replanting during first month[d]	20 plants/hr/person	$16.50/hr/person	$2/plant and $45/planting bar/bag
Water delivery[e]	132 liters/hr/person	$16.50/hr/person	$0.0005/liter water (municipal) and, $65/backpack sprayer

[a] Fence maintenance is assumed to take place twice per year during the second and third years to ensure the integrity of the fence; this is a key consideration in areas with ungulates where ingress can rapidly degrade ecosystems.

[b] Clearing maintenance includes clearing of invasive trees and application of herbicide to cut stumps and is assumed to occur in year 2.

[c] See Supplemental Table S2 for the calculated herbicide amounts per ha and unit costs for each herbicide used.

[d] Plants that died within 1 month of outplanting were replaced (*D. viscosa*, 29% mortality; *T. populnea*, 13% mortality; *M. sandwicense*, 6% mortality; *C. subcordata*, 38% mortality; *P. zeylanica*, 15% mortality).

[e] Water delivery occurs four times, with 1 liter per plant each time; assumes first watering included at initial planting time, followed by watering once per week for 3 subsequent weeks, then discontinuing thereafter; water is transported to site in work vehicles via plastic tanks.

sults, we also analyzed how 1 ha and 10 ha costs compared over 30 yr. It is not surprising that the proportion of costs due to maintenance were higher in both cases compared to the 3-yr analysis [20.7% (1 ha) and 16.3% (10 ha) of 30 yr costs, compared to 1.2% (1 ha) and 1.3% (10 ha) of 3 yr costs, respectively], but the economies of scale persist and get stronger over the longer term (cost per hectare for a 10 ha site is 17.2% less than that of a 1 ha site over 3 yr, and 21.6% less over 30 yr.

We evaluated cost-reduction strategies over the 3 yr and 30 yr periods for the 1 ha and 10 ha management units to estimate the benefits of using volunteer labor, developing nurseries, and upgrading equipment in the initial phase of restoration, and to account for the discontinuing of invasive plant removal for the longer time period (Table 5). Reducing planting costs by 50% reduced overall costs the most (–22.4% for 1 ha and –27.0% for 10 ha over 3 yr; and –18.0% for 1 ha and –22.9% for 10 ha over 30 yr). It is interesting that for the 10 ha site, installation of an irrigation system (at a flat rate of $25,000 to provide water infrastructure to the site) and drip system (at a rate of $2,000 ha^{-1}) became cost-effective. Although installation of an irrigation and a drip system have a large up-front cost to supply water to the site, it eliminates considerable labor (i.e., hand watering) and equipment (i.e., backpack sprayer and water truck rental) for watering ($130,043 for the 10 ha site), which was assumed to continue

TABLE 4

Summary of Present Value and Cost per Hectare of Restoration Costs for Scaled-Up Restoration, Modeled after a 0.13 ha Experimental Site within the Wai‘anae Kai Forest Reserve, O‘ahu, Hawai‘i, for 3 Yr and 30 Yr Periods[a]

	Restoration Costs US$ 2015 (% Total)					
	3 yr				30 yr[b]	
Parameter	Experiment (Table S3)	0.13 ha (Table S4)	1 ha (Table S6)	10 ha (Table S7)	1 ha	10 ha
Establishment	97.6%	98.7%	98.8%	98.7%	79.3%	83.7%
Clearing	$752 (5.3%)	$752 (2.8%)	$2,840 (1.9%)	$24,880 (2.0%)	$2,840 (1.5%)	$24,880 (1.7%)
Fence	$11,197 (78.3%)	$11,197 (41.2%)	$26,803 (17.9%)	$85,316 (6.9%)	$26,803 (14.4%)	$85,316 (5.8%)
Herbicide	$611 (4.3%)	$620 (2.3%)	$3,346 (2.2%)	$32,568 (2.6%)	$3,346 (1.8%)	$32,568 (2.2%)
Outplanting	$1,180 (8.3%)	$11,744 (43.2%)	$93,141 (62.1%)	$894,868 (72.1%)	$93,141 (49.9%)	$894,868 (61.1%)
Replanting	$222 (1.6%)	$2,501 (9.2%)	$21,950 (14.6%)	$187,488 (15.1%)	$21,950 (11.8%)	$187,488 (12.8%)
Maintenance	$337 (2.4%)	$342 (1.3%)	$1,839 (1.2%)	$16,274 (1.3%)	$38,636 (20.7%)	$238,295 (16.3%)
Present Value	$14,299	$27,154	$149,918	$1,241,395	$186,716	$1,463,415
Cost per hectare	$109,993 ha^{-1}	$208,883 ha^{-1}	$149,918 ha^{-1}	$124,139 ha^{-1}	$186,716 ha^{-1}	$146,341 ha^{-1}

Note: All costs are in Present Value, calculated at a 2% annual discount rate; the proportion of total costs is in parentheses.

[a] Costs were calculated using the baseline parameters in Table 3. Additional cost of $3,550/month for water truck rental during planting/replanting applied at 1 ha and 10 ha sites (not used to estimate cost of experimental or 0.13 ha site).

[b] Based on interviews with experts, a number of variables were adapted to account for the longer time horizon (30 yr): clearing maintenance frequency (once every other year); replacement period for fencing (20 yr); and time period and frequency for herbicide application (Supplemental Table S2), clearing and fence maintenance (30 yr).

TABLE 5

Overall Effect of Cost-Reduction Strategies on Total Management Costs and Cost per Hectare for 1 ha and 10 ha Management Units over 3 Yr and 30 Yr Periods in an Invasive Grass–Dominated Lowland Ecosystem on Oʻahu, Hawaiʻi

	Total Restoration Costs and Cost per Hectare US$ 2015 (% Change from 1 ha and 10 ha Baselines[a] over 3 yr and 30 yr)			
	3 yr		30 yr[b]	
	1 ha ($149,918)	10 ha ($1,241,395)	1 ha ($186,716)	10 ha ($1,463,415)
Cost-reduction strategies				
(1) Volunteer labor[c]	$118,306 $118,306 ha^{-1} (−21.1%)	$920,205 $92,021 ha^{-1} (−25.9%)	$155,103 $155,103 ha^{-1} (−16.9%)	$1,142,226 $114,223 ha^{-1} (−21.9%)
(2) Plant costs reduced by 50%[d]	$116,398 $116,398 ha^{-1} (−22.4%)	$906,172 $90,617 ha^{-1} (−27.0%)	$153,195 $153,195 ha^{-1} (−18.0%)	$1,128,193 $112,819 ha^{-1} (−22.9%)
(3) Planting speed doubled[e]	$136,613 $136,613 ha^{-1} (−8.9%)	$1,101,182 $110,182 ha^{-1} (−11.2%)	$173,428 $173,428 ha^{-1} (−7.1%)	$1,327,387 $132,739 ha^{-1} (−9.3%)
(4) Irrigation[f]	$156,855 $156,855 ha^{-1} (+4.6%)	$1,152,801 $115,280 ha^{-1} (−7.1%)	$193,652 $193,652 ha^{-1} (+3.7%)	$1,374,822 $137,482 ha^{-1} (−6.1%)
(5) Discontinue invasive removal after year 5/10[h]	NA[g]/NA	NA/NA	$170,959/$174,415 $170,959 ha^{-1} (−8.4%)/ $174,415 ha^{-1} (−6.6%)	$1,325,707/$1,355,471 $137,571 ha^{-1} (−9.4%)/ $135,547 ha^{-1} (−7.4%)

Note: Present Value is calculated at a 2% annual discount rate.

[a] Baseline values calculated in Table 4 are shown in parentheses next to hectare sizes for both the 3 yr and 30 yr time periods.

[b] Based on interviews with experts, a number of variables were adapted to account for the longer time horizon (30 yr): clearing maintenance frequency (once every other year); and time period and frequency for herbicide application (Supplemental Table S2), clearing and fence maintenance (30 yr) [with the exception of cost-reduction strategy (5)]; replacement period for fencing (20 yr).

[c] Assumes a labor rate of $25/hr for one person to supervise 10 volunteers during planting, replanting, and watering; assumes planting activities would take 1.5 times longer (i.e., 13 plants/hr/person) when employing volunteer labor versus trained land managers, and watering would be completed at the same speed (132 liters/hr). Although survival can be reduced when employing volunteers, increased mortality beyond the baseline is not accounted for in replanting costs.

[d] Assumes plant costs are $1/plant, or half the cost assumed under the baseline ($2/plant). See Supplemental Table S8 for propagation labor/equipment cost breakdown per plant.

[e] Assumes planting speed is 40 plants/hr/person, or twice as fast as the baseline (20 plants/hr/person) through use of improved and more-costly equipment (e.g., $135/Hatfield Transplanter, or equivalent).

[f] Installation (i.e., labor and materials) of an irrigation system (i.e., getting water infrastructure to the site) at a flat rate of $25,000 and $2,000 ha^{-1} for installation of a drip system at the site, eliminating labor and equipment for hand watering. Cost of water (municipal) still applies.

[g] NA, not applicable, goes beyond the 3 yr time frame.

[h] Assumes maintenance herbicide application and clearing are discontinued after 5 and 10 yr.

once per week for 4 weeks after outplanting/replanting. Overall, the actual cost of municipal water did not change. When evaluating the cost-reduction strategies applicable to long-term management of 1 ha and 10 ha management units where invasive removal was discontinued after 5 or 10 yr, overall project costs decreased for the 1 ha management unit by 8.4% and 6.6%, and for the 10 ha management unit by 9.4% and 7.4% (Table 5).

We evaluated costs for restoration projects that reflect conditions that may be considerably more difficult than our experimental site (i.e., less accessible, steep gradients, rough terrain, and dense invasive trees and grass at the outset) and over the 30 yr time frame. We identified these sites as Moderate and Difficult and compared assessed costs to those for our experimental "Easy" site (Table 6). Costs to restore and maintain 1 ha for 30 yr rose with the level of difficulty [from $186,716 for

TABLE 6

Summary of Present Value of Restoration Costs for 30 yr Period for Three Classes of 1 ha Sites (Easy, Moderate, Difficult) in an Invasive Grass–Dominated Lowland Ecosystem on O‘ahu, Hawai‘i

	Restoration Costs US$ 2015 (% Total)		
Parameter	1 ha Easy[a]	1 ha Moderate[b]	1 ha Difficult[c]
Establishment	79.3%	79.3%	81.5%
Clearing	$2,840 (1.5%)	$5,240 (2.4%)[M1]	$5,240 (1.7%)[D1]
Fence	$26,803 (14.4%)	$30,400 (13.8%)[M2]	$35,110 (11.6%)[D2]
Herbicide	$3,346 (1.8%)	$3,783 (1.7%)[M3]	$5,078 (1.7%)[D3]
Outplanting	$93,141 (49.9%)	$110,084 (49.9%)[M4]	$164,718 (54.4%)[D4]
Replanting	$21,950 (11.8%)	$25,444 (11.5%)[M4]	$36,742 (12.1%)[D4]
Maintenance	$38,636 (20.7%)	$45,546 (20.7%)[M5]	$56,028 (18.5%)[D5]
Present Value	$186,716	$220,497	$302,917
Cost per hectare	$166,716 ha^{-1}	$220,497 ha^{-1}	$302,917 ha^{-1}

Note: Maintenance is assumed to continue for 30 yr. Present Value is calculated at a 2% annual discount rate.

[a] Values for the 1 ha Easy site are from the 30 yr 1 ha cost analysis in Table 4. The Easy site is fully accessible by road, ~10 m elevation gradient, fairly rough and rocky terrain, dominated by an invasive grass with few scattered invasive trees, and requiring exclusion of ungulates via fence construction.

[b] Moderate: ~0.8 km from nearest road, ~20 m elevation gradient, moderate rough and rocky terrain, dominated by dense populations of invasive grass and trees, and requiring exclusion of ungulates. Due to more arduous conditions at the Moderate site, the following baseline parameters identified in Table 3 were affected:

[M1] Clearing: The labor time rate for initial clearing slowed to 240 hr/ha/person.

[M2] Fence: Fence construction labor time rate slowed to 2 m/hr/4-person crew.

[M3] Herbicide: The labor time rate for initial herbicide slowed to 79 hr/ha/person.

[M4] Outplant/Replant: The labor time rate for outplanting/replanting slowed to 15 plants/hr/person, and watering delivery slowed to 88 liters/hr/person.

[M5] Maintenance: The labor time rate for fence maintenance slowed to 75 m/hr/person, clearing maintenance slowed to 20 hr/ha/person, and herbicide maintenance slowed to 17.5 hr/ha/person (even years) and 10 hr/ha/person (odd years).

[c] Difficult: ~3.2 km from nearest road, ~20-m elevation gradient, rough, rocky and uneven terrain, dominated by dense populations of invasive grass and trees, and requiring exclusion of ungulates. Due to more arduous conditions at the Difficult site, the following baseline parameters identified in Table 3 were affected:

[D1] Clearing: The labor time rate for initial clearing slowed to 240 hr/ha/person.

[D2] Fence: The labor time rate for fence construction rate slowed to 1.7 m/hr/4-person crew; and fence material costs increased to $49/m, with higher probability of uneven terrain requiring additional materials to accommodate the contour and secure ground pinning.

[D3] Herbicide: The labor time rate for initial herbicide slowed to 157.5 hr/ha/person.

[D4] Outplant/Replant: The labor time rate for outplanting/replanting slowed to 7 plants/hr/person, and watering delivery slowed to 44 liters/hr/person.

[D5] Maintenance: The labor time rate for fence maintenance slowed to 50 m/hr/person, clearing maintenance slowed to 20 hr/ha/person, and herbicide maintenance slowed to 34.5 hr/ha/person (even years) and 20 hr/ha/person (odd years).

Easy, to $220,497 (+15.3% from Easy) for Moderate, to $302,917 (+38.4% from Easy) for Difficult], and establishment costs (clearing, fence construction, herbicide application, outplanting, watering, and replanting) accounted for a larger proportion overall under the Difficult scenario (79.3% for Easy and Moderate; 81.5% for Difficult).

DISCUSSION

Results from this study showed trends of persistent survival of native species and constant relative differences in cover across treatments at 8 and 36 months after initial outplanting. Overall, restoration treatments successfully suppressed *M. maximus* relative to controls, and native species cover increased through time. As originally hypothesized, native survival rates were similar between the 8-month and 36-month time periods. These results suggest that initial success immediately following restoration can be maintained through the early years of restoration, given adequate maintenance (removal of invasive trees, weeding, herbicide, etc.), and that native species, once established, are able to continue to grow and suppress invasive grass over time.

Consistent with our second hypothesis, invasive *M. maximus* cover in the native outplant treatment plots did not differ between the 8- and 36-month time periods, suggesting that after 36 months suppression rates of *M. maximus* were similar to those observed 8 months after restoration. This indicates that a large increase in cover of native species at the 36-month time period had no additional suppression effect on invasive cover, that invasive cover continues to be present in the restored community, and that continued maintenance will be needed.

Cover of invasive *M. maximus* in native outplant plots was significantly reduced compared to herbicide control and untreated control plots at both 8 and 36 months, possibly because maintenance activities helped native plants become established. However, there was additional grass suppression provided by the native outplant treatments compared to that seen in herbicide control plots, suggesting that natives are successfully competing with this invasive grass. We expect that establishment success is dependent on maintaining conditions that enable native species to successfully compete for limited resources, particularly early in the restoration project. These findings are consistent with those from other studies (Engel and Parrotta 2001, Dorrough et al. 2008, Goldstein et al. 2008) and indicate that maintenance may be critical to help native plants become established and to compete with early successional invasive species. Ongoing nonnative grass control and maintenance activities incur costs that should be considered when planning a restoration project.

The costs of ecological restoration are rarely reported in the literature, despite widespread calls for cost-effective conservation (Naidoo et al. 2006, Duke et al. 2013). Although the cost estimates in this study were primarily based on management unit costs conducted at an individual, experimental restoration site, our analysis altering key assumptions confirms that the general findings hold true: establishment costs drive medium- and long-term costs, and restoration costs per hectare decline with economies of scale.

Our results demonstrate that costs in the first year for site preparation, fence construction, and outplanting dominate the budget at all spatial and temporal scales (97.6%–98.8% of all costs over the 3 yr time horizon and 74.8%–92.4% for the 30 yr budget). Maintenance costs during subsequent years were a small portion of total costs (1.2%–2.4% for the 3 yr period and 7.65%–25.2% for the 30 yr budget) but can be critical to restoration success (Vieira and Scariot 2006, Dorrough et al. 2008). These results suggest that ecological restoration projects should consider ways to reduce establishment costs [e.g., utilizing new plant propagation and broadcast seeding techniques (Friday et al. 2015); domestic livestock grazing to reduce invasive grass cover (Evans et al. 2015); reducing fencing costs] and to prioritize long-term maintenance of expensive initial investments.

One way to reduce establishment costs is to minimize labor costs. Estimates of cost savings from volunteer labor presented here are consistent with those of other studies (Goldstein et al. 2008) but do not consider the potential for reduced seedling survival with unskilled labor, nor the requirements for recruiting, transporting, and training replacement volunteers over time. As a restoration project is scaled up, much more labor is required, and reliance entirely on voluntary labor is difficult. Plant costs were another major driver of the overall 3 yr cost, and one whose reduction had the greatest impact on overall cost (Table 5). Reducing plant costs through establishing a nursery and/or having volunteers propagate native plants could be a practicable option because this could take place in a controlled environment that is accessible and easy for managers to oversee.

Another way to decrease establishment costs is to reduce fencing costs. Because fencing drives establishment costs, particularly for smaller areas, the shape of the restoration site can be important because the perimeter to area ratio has a major impact on fencing cost per hectare restored. Moving from a square to a circle shape with the same area protected can save 11.4% of the fencing costs. In smaller-scale projects, the savings can be a considerable portion of overall project costs, and at the larger scale, the absolute cost difference is even larger (replacing a 10 ha square with a circle saves $6,188). Of course, considerable savings could be gained from placing restoration projects within already existing fenced areas. In contrast, additional costs may need to be considered for some projects for items such as control of ingress of both feral and domesticated ungulates, which was a cost we did not consider here.

Watering (during the outplanting and replanting phase as well as the maintenance phase) constitutes a considerable cost. We considered whether irrigation would be a cost-effective intervention. Irrigation was not cost-effective, compared to hand watering, at the smaller 1 ha scale management unit but was cost-effective at the larger 10 ha management unit. Where possible, consideration could also be given to timing outplanting with the rainy season, which would be a cost savings if it eliminated the need for watering.

Given the ecological result that establishment success is dependent on maintaining conditions that enable native species to successfully compete for limited resources, particularly early in the restoration project, and the economic result that establishment costs dominate overall costs, land managers need to allocate funds for initial establishment (Dorrough et al. 2008, Goldstein et al. 2008). That said, maintenance can greatly increase the overall ecological success of the project (Vieira and Scariot 2006, Dorrough et al. 2008). A conservative investment in maintenance (i.e., materials to replace fencing after 20 yr and herbicide, and labor to inspect fencing and perform herbicide and clearing maintenance) could constitute upward of 25% of the overall 30 yr project budget. However, if invasive removal after 5 or 10 yr could be stopped while still ensuring success of the project, a cost savings to the 30 yr budget at the 1 ha and 10 ha sites could be obtained (–8.4% for 1 ha and –9.4% for 10 ha if discontinued after 5 yr, and –6.6% for 1 ha and –7.4% for 10 ha if discontinued after 10 yr).

Our hypothesis that larger restoration sites would show economies of scale was supported, with cost per unit area declining as the area restored increased. The major drivers of cost differences between the three scales were costs of outplanting, replanting, and fencing. As the restoration area increases, outplanting and replanting costs composed a larger proportion of establishment costs (and site preparation and fencing costs much less). Establishment costs for outplanting and replanting due to mortality (plants, labor, water, equipment) made up a larger percentage of overall project costs as scale increased over the 3 yr time horizon (52.4% at 0.13 ha, 76.7% at 1 ha, and 87.2% at 10 ha). Costs in the first year still far surpassed those in later years, suggesting that cost savings, particularly in outplanting and replanting costs, are critical for larger projects, and smaller projects should focus on minimizing fencing costs, if possible. Across all conditions, larger sites were more economical on a per unit area basis than smaller sites. These results suggest that larger restoration projects are more economical, on a per area basis, and increasingly so as the time horizon extends.

Although results from this study suggest that the costs of ecological restoration are substantial, it also highlights how costs can vary depending on actual site conditions, accessibility, and restoration methods. Consistent with our final hypothesis, costs of restoration indeed increased with the degree of site difficulty. The results suggest that a 30 yr cost could be between $186,716 (Easy) and $302,917 (Difficult) to restore, fence, and maintain 1 ha of degraded tropical dry lowland ecosystem. These representative scenarios demonstrate that actual costs will vary depending on location (e.g., restoration sites requiring helicopters will incur much higher costs), fencing needs and configuration, site-specific characteristics (e.g., density and type of outplants and invasive vegetation), and access to in-house resources (e.g., labor and equipment). This study focused on a cost analysis using an individual study and does not, therefore, attempt to precisely estimate costs for every restoration project in the region. Rather, this study highlights the need to include economic analyses in restoration projects generally and highlights a methodology for doing so. The Supplemental spreadsheets provided allow individual projects to vary project-specific costs for more accurate, site-level estimates of economic costs associated with ecological restoration in the region.

CONCLUSIONS

Nonnative grass invasion degrades dry forest ecosystems globally (D'Antonio and Vitousek 1992, Litton et al. 2006). However, ecological restoration of Hawaiian dry lowland ecosystems can be achieved (D'Antonio et al. 1998; Cabin et al. 2000; Cabin et al. 2002, "Effects of light"; Ammondt et al. 2013; Ellsworth et al. 2015), albeit at a high economic cost. This study utilized actual restoration costs from a 0.13 ha experimental site to estimate larger-scale and longer-term budgetary needs, and in doing so it demonstrates that establishment costs, particularly fencing and outplanting, drive medium- and long-term costs, and that restoration costs per hectare decline with economies of scale. This suggests that restoration should be directed at larger-scale sites and long-term objectives and target techniques to reduce site-preparation costs.

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