Restoring to the future: Environmental, cultural, and management trade-offs in historical versus hybrid restoration of a highly modified ecosystem

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Abstract
With growing calls to scale up reforestation efforts worldwide, conservation managers increasingly must decide whether and how to restore highly altered ecosystems. However, empirical research on potential trade-offs remains scarce. We use a Hawai‘i watershed to demonstrate a collaborative, interdisciplinary approach to identifying synergies and trade-offs associated with maintaining an unrestored forest, versus restoration to a historical or hybrid (native and non-native plant species) state. We focused on restoration scenarios designed by conservation managers and measured ecological, hydrologic, and cultural outcomes they identified as important metrics of success. The hybrid restoration scenario maximized potential outcomes at moderate cost, and increased two rarely measured but often critical metrics to managers and communities: cultural value and resilience to disturbance. Hybrid restoration approaches developed collaboratively can provide a viable option for scaling up restoration in island ecosystems and other contexts where invasive species pose significant challenges and/or where community support is important.

KEYWORDS
conservation, cultural value, ecosystem services, functional traits, Hawai‘i, hydrology, hybrid ecosystems, restoration costs, trade-offs

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INTRODUCTION

There are growing calls to dramatically scale up reforestation efforts around the world for multiple ecological and socio-economic goals (Suding et al., 2015). The Bonn Challenge is a global initiative to promote restoration of 350 million hectares of degraded land by 2030, with the explicit goal of restoring ecosystem function and a suite of related goods and services, focusing on active and passive native species restoration and mixed-use agroforestry systems. A key component of achieving this in an effective, durable, and equitable manner is engaging landowners and stakeholders in the design and implementation of restoration strategies.

Yet, operationalizing decision-making around forest restoration strategies for multiple benefits involving diverse stakeholders remains challenging. Conservation managers are increasingly faced with making restoration decisions constrained by multiple objectives and limited budgets. Multiple sometimes competing goals include biodiversity enhancement, carbon sequestration, water quality, quantity and regulation, timber and nontimber forest products (Lamb, Erskine, & Parrotta, 2005; Sasaki et al., 2011), while aligning conservation initiatives with community priorities and cultural values (Kurashima, Jeremiah, & Ticktin, 2017; Winter & Lucas, 2017).

Multiple goals for restoration outcomes are coupled with competing views on whether active or passive restoration strategies are needed and the state to which systems should be restored (Hobbs, Higgs, & Hall, 2017). While a recent meta-analysis showed that for tropical forests, success is higher for passive than for active restoration, in areas highly threatened by invasive species and/or depleted soil seed banks, active restoration is necessary (Crouzeilles et al., 2017). A common approach in these contexts remains “historical restoration,” i.e., attempting to actively restore systems to states within their historical range of variation. Additional complementary or portfolio approaches to scale up restoration efforts and meet multiple stakeholder interests have now gained recognition (Suding et al., 2015). For example, the forest and landscape restoration paradigm centers on restoring ecosystem function and services while meeting human well-being needs. It includes multifunctional landscapes and is increasingly being adopted across the globe (Chazdon et al., 2017; Mansourian, Dudley, & Vallauri, 2017). Other authors emphasize the view of ecosystems as mosaics of patches in varying states of modification, where evaluation of the relative value and possible management of each, is needed (Hobbs, Higgs, & Harris, 2009; Hobbs et al., 2014, 2017).

In this framework, some highly altered patches have been irreversibly transformed from the historic condition, referred to as novel ecosystems. Others, however, can potentially be restored to a diversity of hybrid ecosystems consisting of mixtures of native and non-native species (Ostertag, Warman, Cordell, & Vitousek, 2015). Despite recognition of the need for multiple approaches, and the importance of meeting the needs of multiple stakeholders, little empirical research investigates the social, economic, and ecological outcomes of different restoration choices. What is lost and what is gained through different restoration strategies, and can this be quantified to aid restoration decisions?

We use a watershed in Hawai‘i to demonstrate a collaborative, interdisciplinary approach to identifying synergies and trade-offs associated with different approaches to restoration in contexts where active restoration is necessary. Most island ecosystems, having high levels of endemism and a disproportionate share of global biodiversity, include these contexts (Kueffer & Kinney, 2017). They also tend to be highly modified, with invasive plants and animals posing critical threats to conservation and restoration of key species, functions, and ecosystem services (Ewel et al., 2013; Glen et al., 2013). In Hawai‘i, about 90% of the native vascular flora is endemic (Wagner, Herbst, & Sohmer, 1999) and over 40% of endemic species are listed as endangered or threatened (USFWS, 2012). Much of Hawai‘i’s remaining forests are highly modified systems, dominated by invasive species. Active restoration projects occur across the islands, yet face practical and financial challenges in managing invasive species, the need for continual intervention, scaling up (Wada et al., 2017), and garnering support from local communities. Many previous attempts to intervene in unrestored ecosystems on islands have shown that considering a range of ecosystem values, including social values, and attention to local constraints and opportunities, is key to success (Ewel et al., 2013).

We collaborated with conservation managers to codesign our research questions to directly inform management questions. First, we asked managers to identify priority metrics of success for management and restoration. They highlighted a series of ecological, hydrologic, and cultural outcomes, and management costs. Cultural outcomes can be as or more important than other restoration outcomes (Bremer et al., 2018; Higgs, 2003; Kimmerer, 2013; Pascua, McMillen, Ticktin, Vaughan, & Winter, 2017). There exists a substantial body of complementary efforts, including recent work highlighting international efforts to quantify nature’s contributions to people with a focus on reciprocal or relational values (Diaz et al., 2018; Pascual et al., 2017), efforts to better understand how the multifaceted connections that contribute to well-being feed into management (Breslow et al., 2017), and, most relevant to our work, a growing recognition of the multiple linked benefits between ecological restoration and cultural forms of reciprocity (Kimmerer, 2011). However, cultural benefits are rarely explicitly quantified alongside other restoration outcomes (Benayas, Newton, Diaz, & Bullock, 2009). Similarly, although conservation managers cannot make realistic decisions without considering budgets,
cost analyses are rare in restoration research, as cost data are often incomplete (Aronson et al., 2010; Hobbs et al., 2017; Wada et al., 2017).

Second, we asked managers to describe the existing or potential restoration strategies most relevant for them. They provided two historical and one hybrid restoration scenario: (1) pre-European restoration, the most common restoration practice statewide and currently carried out at the study site; (2) a hypothetical pre-rat restoration, similar to pre-European restoration but also excluding rats (Pacific rats, Rattus exulans, brought by Polynesians, and black and brown rats, R. rattus and R. norvegicus, brought later by Europeans), which disperse some native plants but heavily consume the seeds of many endemic species (Shiels & Drake, 2011), preventing seedling recruitment with ecosystem-wide effects; and (3) a hypothetical hybrid restoration scenario utilizing native plant species able to persist on their own, along with culturally important introduced species (Figure 1, Table 1). The hybrid system was motivated by the fact that many native plant species cannot persist independently, even within restored systems without ungulates or invasive plants (due to factors including loss of pollinators and dispersers, seed predation by invasive species, and non-native insect and fungal pathogens). Cultural connections to forests and the value of continued community participation (Kurashima et al., 2017) also motivated this restoration scenario.

Based on this, we asked:

(1) How do ecological, hydrologic, and cultural metrics of success, as prioritized by restoration managers, and long-term management costs, vary across unrestored forest, and forest restored to pre-rat, pre-European, and hybrid states?

(2) What benefits and trade-offs are involved in maintaining the unrestored forest versus restoring to these three different states?

2 | METHODS

We conducted this research in the ahu’pu’a (traditional landdivision) of Hā‘ena, Kaua‘i Island. The study site is within Limahuli Valley, a 400-ha nature preserve, privately owned and managed by National Tropical Botanical Garden. We focused on the Lower Limahuli Preserve, much of which comprises non-native species (Table 2, Appendix SI). We refer to this as the unrestored ecosystem.

2.1 | Measurement of success metrics across restoration scenarios

Conservation managers identified the following priority metrics of restoration success (Table 2): ability to conserve native (especially endemic and single-island endemic) plant species; ability to conserve native insect and bird species; ability of native plants to persist independently within the restored context; potential to recuperate from disturbance (motivated by Hā‘ena’s history of hurricanes); ability to conserve water; ability to maintain cultural interactions with the forest; and long-term management costs. We compared these metrics across the unrestored forest, the pre-European restored forest, and two hypothetical restoration scenarios, pre-rat and hybrid restoration (Table 1).

To determine species composition, we established permanent plots in the pre-European restored forest (18) and unrestored forest areas (20), identifying all species within them (SI Methods, Table S1). Species-accumulation curves reached an asymptote, indicating adequate sampling effort (Figure S1). Species lists for the hypothetical pre-rat and hybrid restoration scenarios are adapted directly from pre-European plots (Table 1, Table S1).

2.1.1 | Ecological outcomes

We assessed ability to conserve native species by comparing numbers of indigenous, endemic, and single-island endemic plant species in each scenario (SI Methods, Table S1). To determine ability to conserve native wildlife, we counted the number of native birds and insects supported by the species in each scenario, in terms of food, nesting, and host plants (SI Methods, Table S2). To assess ability of native species to persist, we elicited expert opinion of the two most senior conservation managers with a combined 25 years of restoration effort in Hā‘ena to rank species according to their ability to: (1) survive and grow to adulthood and (2) recruit seedlings. To assess the potential for recuperation from disturbance, we calculated the functional dispersion (Laliberte et al., 2010) of seven response traits (SI Methods, Table S4). Restoration scenarios with lower functional dispersion values have species with more similar disturbance responses, indicating lower potential resilience (Laliberte et al., 2010).

2.1.2 | Cultural outcomes

Presence or absence of particular species can strongly influence the ability of communities to maintain or restore cultural practices, heritage, and identity (Kurashima et al., 2017). These are critical cultural ecosystem services in the Hā‘ena community (Pascua et al., 2017). We assessed ability to maintain and support cultural interactions with the forest by enumerating the highly culturally important plant species in each scenario. These plants were identified by ranking species based on historic and continued interactions due to their presence (Winter & McClatchey, 2008). Each species was scored for its past and present use in each of 17 categories (Table S5), then classified as low, medium, or highly culturally important, based on total scores.
| Description                                                                 | Restoration strategies                                                                 |
|-----------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|
| **Outplanting**                                                             | **Weeding**                                                                                 | **Animal control**                                                                 |
| **Unrestored forest**                                                       | None                                                                                       | None                                                                                  |
| Forest dominated by non-native, mostly invasive species (95.8% ± 0.02 SE of stems >1 cm dbh are non-native invasive species). | None                                                                                       | None                                                                                  |
| **Pre-European**                                                            | Local native species only. Focus on endemics and threatened and endangered species. Plantings of roughly equal densities across species. | Removal of all non-native plant species except some Polynesian-introduced trees, which maintain shade needed to prevent spread of understory non-native invasive species (mostly grasses); and because of their cultural value. Some non-native understory plants remain as they are impossible to fully eradicate. | Ungulate hunting program and ungulate exclosure. |
| Current restoration practice at Hāʻena; most common restoration approach in Hawaiʻi. | Same as for pre-European, but in addition includes large-seeded native tree species heavily predated by rats (nine species). | Removal of all non-native plants. Some non-native understory plants remain as they are impossible to fully eradicate. | |
| **Pre-rat (hypothetical)**                                                 | Same as for pre-European, but in addition includes large-seeded native tree species heavily predated by rats (nine species). | Removal of all non-native plants. Some non-native understory plants remain as they are impossible to fully eradicate. | Ungulate hunting program, rat-traps and rat-exclosure (excludes ungulates too). |
| Restoration of forest to state before the arrival of humans (ca. 1,000 years ago), and therefore before rats. | Native species able to persist without intervention; Polynesian introductions that remain culturally important today; modern introduced food crops. Plantings of roughly equal densities across species | Removal of all non-native species except culturally important Polynesian-introduced trees. Some non-native, not useful understory plants remain as they are impossible to fully eradicate. | Hunting program and ungulate exclosure. |
| **Hybrid (hypothetical)**                                                  | Native species able to persist without intervention; Polynesian introductions that remain culturally important today; modern introduced food crops. Plantings of roughly equal densities across species | Removal of all non-native species except culturally important Polynesian-introduced trees. Some non-native, not useful understory plants remain as they are impossible to fully eradicate. | Hunting program and ungulate exclosure. |
Unrestored forest (mostly introduced species, highly altered from the historical state) can be restored to historical states: pre-rat (native plants only), or pre-European (native plants and a few Polynesian-introduced plants); or to a hybrid (native, Polynesian-introduced and modern useful introductions) system. Note: Each has different ecological, hydrologic, economic, and cultural outcomes. Icons represent examples of species in each scenario. Polynesian introductions refer to species brought approximately 1000 years ago modern introductions refer to species brought post-European contact—1779.

2.1.3 Hydrologic outcomes

We assessed the difference in water yield between unrestored forest and pre-European restoration scenarios. Since the other two scenarios are hypothetical and include many of the same tree species as the pre-European restoration, differences in water yield are potentially relatively small. We calculated water yield using a water balance approach where

$$\text{Water yield} = \text{Precipitation} - \text{AET}$$

The pre-European scenario assumed all non-native areas (240 ha) of Lower Limahuli Preserve are restored. The unrestored scenario assumed current land cover remained unchanged through time. Precipitation estimates for Hāʻena are from the Rainfall Atlas of Hawaiʻi (Giambelluca et al., 2013). We estimated AET following Wada et al. (2017; SI Methods).

2.2 Calculation of restoration costs

We estimated upfront and ongoing maintenance costs for restoration of Lower Limahuli Preserve over a 50-year time horizon. Restoration involves fully or partially clearing existing non-native canopy trees, planting desirable species, establishing adequate shade, then repeating for the understory (SI Methods). We included the expected cost of maintaining the unrestored forest in its current state (preventing further spread of invasive species). We estimated weeding and planting labor costs from a recent pilot project in Limahuli Garden, gathered plant costs from a commercial nursery, and estimated animal control costs from past projects and contractor estimates (Figures S2 and S3). Since our study site is designated conservation land, cost estimates excluded potential forgone benefits of alternative land uses.

3 RESULTS

3.1 Ecological outcomes

Restoration to the pre-rat scenario conserves the highest number of native species, including the most Hawaiian and single-island endemics (nine more than the pre-European restoration; Figure 2). The hybrid scenario includes 17 fewer
**TABLE 2** Restoration outcomes identified as priority by Hāʻena restoration managers and methods to quantify them

| Category          | Outcome                                                                 | Definition                                                                                           | Measurement                                                                                   |
|-------------------|--------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|
| Ecological        | **Ability to conserve native plant species**                            | Numbers of indigenous, endemic, single-island endemic species.                                        | Species counts from 20.5 x 5 m survey plots in unrestored forest and 18 in pre-European restoration. Hypothetical scenarios derived from these species lists (Table S1). |
|                   | **Ability to support native wildlife**                                   | Number of native bird and insect species each scenario would be able to provide resources for.      | Based on plant food sources, nesting sites for birds and recorded host species for insects (Table S2). |
|                   | **Ability of native plants to persist without continued intervention**   | Ability to: (1) survive, grow to adulthood; (2) reproduce (produce seedlings).                       | Species ranked by two senior managers on scale of 0-3 for both ability to survive and ability to reproduce (Table S3). |
|                   | **Potential to recuperate from disturbance**                            | Functional trait response diversity.                                                                  | Functional dispersion of traits associated with response to disturbance: growth form, life form, maximum plant height, clonality, dispersal mode, and seed mass (Table S4). |
| Cultural          | **Ability to support continued cultural interactions with forest**       | Number of highly culturally important species.                                                       | Highly culturally important species, identified by scoring system for each plant species based on past (from historical sources) and present uses (from focus group discussions with community members) for 17 use categories (Table S5). |
| Water yield       | **Ability to conserve water**                                           | Amount of surface water and groundwater recharge (mm/year).                                         | Modeled using a water balance approach (rainfall-evapotranspiration, see Wada et al., 2017). |
| Restoration costs | **Total costs over 50 years**                                           | Animal control, plants, and labor.                                                                   | Compiled from records with Limahuli managers.                                                   |

endemic species than the pre-European—lacking 7 of the 10 single-island endemics and 10 of the 22 endemics. However, the hybrid system still supports a high number of native species because it includes common species (mostly native and some Hawaiian endemics) not currently outplanted or present in the pre-European or pre-rat restoration systems. The unrestored system includes 20 native plant species compared to 43 in pre-European, including 8 Hawaiian endemics (vs. 20 in pre-European) and zero single-island endemics (vs. 11; Figure 2). Single individuals of two additional single-island endemics not currently outplanted in the pre-European restoration were found, but since we observed no regeneration, these species are unlikely to persist.

All scenarios can support two native bird species: ‘apapane (*Himatione sanguinea*) and Kaua’i ‘elepaio (*Chasiempis sclateri*). This is because both rely primarily on ‘ōhi’a lehua (*Metrosideros polymorpha* and *Metrosideros waiialealae*) trees for nesting, foraging insects, and for ‘apapane, nectar. ‘Ōhi’a lehua occurs in all scenarios (including unrestored forest) at similar densities. For native insects, all three restoration scenarios support similar numbers of species (Figure 2), while the unrestored system supports just under 60% of these species.

The hybrid restoration scenario is designed so native species can persist unaided. Ninety percent of the native plant species (n = 12) in the unrestored system can persist, compared to 60% of native plants in pre-European and 70% in pre-rat (Figure 2). In terms of disturbance recuperation potential, functional traits associated with response to disturbance are more dispersed in unrestored and hybrid scenarios than in the historical scenarios (Figure 2).

Hybrid restoration ranks highest in sustaining cultural interactions, followed by unrestored forest, as almost all Polynesian-introduced plants present rank as highly culturally important, as do some common native species in both scenarios.

Pre-European restoration significantly increases water yield by 25% within the restoration area and 4.9% over the entire ahupua‘a (Figure 3, Table S6), driven by a 30% decrease in AET in the management area (SI Results).

### 3.2 | Restoration costs

For all restoration scenarios, per-area labor, outplanting, and weeding costs start high and decline over time, as native plant populations establish and weed management efforts shift from
FIGURE 2  Variation in environmental and cultural outcomes across unrestored forest and three different restoration strategies

Note: Axes are scaled minimum to maximum for each dimension.

In summary, total cost for the pre-European and hybrid scenarios are roughly equal, whereas pre-rat scenario costs are more than double in either alternative (Table 3). The hybrid scenario costs slightly less than the pre-European, due to lower replacement rates assuming all plants survive and reproduce unassisted. The cost of maintaining unrestored forest is an order of magnitude lower than that of the active restoration scenarios. This difference is driven largely by the fact that status-quo management is limited to ungulate control and some weed removal, whereas active restoration requires more aggressive weed management and outplanting.

4 | DISCUSSION

As highly altered ecosystems extend across the globe (Perring & Ellis, 2013), conservation managers are increasingly faced with decisions on whether to restore and how best to do so. Our research provides an approach to help managers identify restoration strategies addressing multiple goals in regions...
TABLE 3 Costs for each scenario, by category (USD)

| Scenario                              | Cumulative over 50 years | Average annual Per hectare |
|---------------------------------------|--------------------------|-----------------------------|
|                                       | Animal control | Plant | Labor | Volunteer labor | Total |                                           |
| Hybrid                                | 2,178,060     | 14,559,203 | 6,489,944 | 3,512,862 | 26,740,069 | 2,203                                      |
| Pre-European                          | 2,178,060     | 14,559,203 | 7,055,590 | 3,726,413 | 27,519,265 | 2,267                                      |
| Pre-rat                               | 13,831,943   | 19,346,417 | 13,594,811 | 9,250,507 | 56,023,678 | 4,616                                      |
| Status-quo (prevention of further degradation of unrestored forest) | 2,178,060     | 75,312 | 270,049 | 133,286 | 2,656,707 | 14,589                                      |

Note: We assume management costs for the unrestored scenario are zero.

FIGURE 3 Water yield (millimeter/year) in unrestored forest compared with restored Pre-European forest

where passive restoration is challenging—areas where invasive species or other issues limit natural regeneration of native species, and/or where local populations depend on natural resources. These conditions are especially typical of islands, where highly modified ecosystems composed of invasive species tend to dominate (Glen et al., 2013), and local communities are connected to particular species (Kueffer & Kinney, 2017). In these contexts, our research highlights the value of collaboratively designed hybrid restoration efforts containing both native and non-native species that can persist without interventions. We show that this kind of hybrid approach can provide many of the ecological outcomes provided by traditional “historic” restoration approaches, as well as additional outcomes critical to managers—in our case, greater cultural value and resilience. These outcomes are consistent with the four principles of restoration proposed by Suding et al. (2015) to create a foundation for a sustainable and resilient future: (1) increased ecological integrity, (2) long-term sustainability, (3) informed by the past and the future, and (4) benefits and engages society. Lower costs also offer the possibility of scaling up, a critical consideration since island conservation is underfunded compared to continents (Kueffer & Kinney, 2017). We also show that hybrid systems composed of resilient species cannot protect many critically endangered species, highlighting the importance of a mosaic approach to restoration (Hobbs et al., 2014).

The importance of cultural benefits is increasingly recognized, but rarely operationalized in decision-making (Benayas et al., 2009). In our study, the higher cultural value of hybrid restoration results from our including Polynesian-introduced species important to the community, and common natives not included in most restoration projects. Higher community value not only supports perpetuation of cultural traditions and identity (Kimmerer, 2013; Kurashima et al., 2017; Pascua et al., 2017), but also increases chances of success, as restoration projects are unlikely to succeed without community support (Chazdon, 2008). In Hā’ena, the local community values some invasive species, but none rank among the most culturally important, so none were included in the hybrid scenario.

Our results suggest that including some non-native species in hybrid restoration can increase functional diversity of response traits compared to historical systems, increasing their potential resilience to disturbance (Laliberte et al., 2010). Where invasive species are present, hurricanes, fire, and other large-scale disturbances can facilitate the spread of non-native pioneer species, disrupting successional processes and further displacing native species (Trauernicht, Ticktin, Fraiola, Hastings, & Tsuneyoshi, 2018). In these contexts, hybrid systems enhancing functional trait diversity may be more important than historical restoration in ensuring long-term viability of native species.

Highly altered ecosystems are receiving increased attention in terms of their potential benefits or lack thereof (Hobbs et al., 2014). We found that the unrestored forest provides relatively few ecological benefits compared to restored scenarios except for resilience to disturbance, which also makes it difficult to restore. While the proportion of native species able to persist in the unrestored system is relatively high (because those unable to persist have already disappeared), the number of these species is low: 18, versus 36 in the pre-rat scenario and 46 in the hybrid scenario. Moreover, unrestored forest is dominated by non-native invasive species (>90% of stems), which continue to spread. Therefore, the ecological outcomes present today will likely decrease in the future. In contrast, non-native species in the hybrid scenario all have low risk of
becoming invasive based on Hawai‘i’s weed risk assessment (Daehler, Denslow, Ansari, & Kuo, 2004)—a critical consideration in designing hybrid systems. The unrestored system also yields less water than restored native forest, given higher evapotranspiration rates of invasive species like strawberry guava, Psidium cattleianum (Giambelluca et al., 2008) compared with native species. This is consistent with growing evidence of larger-scale differences in water yield between native- and invasive-dominated systems (Burnett, Wada, & Balderston, 2017; Engott, 2011; Le Maitre, Gush, & Dzikiti, 2015).

Finally, although we show that a hybrid restoration approach can provide an ecologically sound, culturally valuable, and economically viable option to scale up restoration efforts, it can fail to protect more vulnerable species. These species are likely best protected by more intensive and higher-cost efforts applied to small areas. In the case of Hawai‘i and other island ecosystems, this would be a pre-rat scenario. This highlights the need for a mosaic or portfolio approach to restoration, where patches of forest may be restored to different states, both historical and hybrid, including potentially multiple kinds of hybrid systems, which are supported by evaluation of costs and benefits across a landscape (Hobbs et al., 2017), as presented in this study.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of the article.