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BY

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ABSTRACT

Local and global changes continue to influence interactions between groundwater and terrestrial ecosystems. Changes in precipitation, surface water, and land cover can affect the water balance of a given watershed, and thus affect both the quantity and quality of freshwater entering the ground. Groundwater management frameworks often abstract from such interactions. However, in some cases, management instruments can be designed to target simultaneously both groundwater and an interdependent resource such as the invasive kiawe tree (*Prosopis pallida*), which has been shown to reduce groundwater levels. Results from a groundwater-kiawe management model suggest that at the optimum, the resource manager should be indifferent between conserving a unit of groundwater via tree removal or via reduced consumption. The model's application to the Kona Coast (Hawaiʻi) showed that kiawe management can generate a large net present value for groundwater users. Additional data will be needed to implement full optimization in the resource system.

Keywords: groundwater, kiawe, *Prosopis pallida*, renewable resources, resource management, dynamic optimization

1. INTRODUCTION

It is common in resource economics to solve for optimal harvest rates of an implicitly independent resource (e.g., a forest stand, fishery, groundwater aquifer, or oil reserve). Yet, the premise of ecological economics is that resources are interdependent. The objective of this chapter is to help extend the principles of resource economics to deal with the joint management of interdependent resources. It particularly considers the case where the groundwater uptake of an invasive species detracts from the aquifer stock.

The standard economics approach of maximizing the present value (PV) of net benefits generated by a natural resource specifies the optimal steady state stock level and characterizes the path of optimal resource extraction leading up to that steady state. Decision rules for the dynamically efficient (PV-maximizing) allocation of groundwater were first developed almost half a century ago (Burt, 1967; Brown and Deacon, 1972). More recent efforts have refined the hydrogeological aspects of the management framework, developed instruments for implementing optimal extraction, and considered the welfare implications of various management strategies (Gisser and Sánchez, 1980; Feinerman and Knapp, 1983; Moncur and Pollock, 1988; Tsur and Zemel, 1995; Krulce et al., 1997; Brozović et al., 2010). Few, however, have considered the simultaneous management of natural resources that are interconnected with the aquifer of interest. Those that have modeled resource interdependency (both within and outside the groundwater literature) typically focused on management of a single resource, taking harvest from the adjacent resource as exogenous, e.g., shrimp farms and offshore fisheries (Barbier et al., 2002), and groundwater and nearshore species such as seaweed (Duarte et al., 2010). In the model presented herein, management decisions consider tradeoffs both between resources (groundwater and kiawe) and over time.

Throughout Hawai‘i, kiawe (*Prosopis pallida*), a non-native tree introduced to the islands in the early 19th century, can be found in both coastal wetlands and upland ecosystems, covering 58,766 ha or 3.55 percent of the state's total land area A nitrogen-fixing legume. kiawe can potentially reduce groundwater quality by providing nitrogen-rich organic material for leaching, as well as reduce regional groundwater levels via deep taproots (Richmond and Mueller-Dombois, 1972). In an application to the Kona Coast on the island of Hawai‘i, a basic groundwater management model was modified to include water uptake by kiawe. When kiawe is removed, groundwater extraction is higher in every period, corresponding to a lower water scarcity value. In addition, the need for an alternative backstop resource such as desalinated brackish water to meet growing demand is delayed. Both factors contribute to higher welfare in present value terms. Present value gains from kiawe management were compared with present value costs of removing and maintaining kiawe using several different methods. The net present value is positive for each method, ranging from USD 17.0 million to 31.8 million.

2. GROUNDWATER-KIAWE MANAGEMENT FRAMEWORK

Although kiawe can affect nearshore ecosystems via increased nutrient loads, the study focused only on its ability to reduce regional groundwater levels. A single-cell coastal aquifer model was modified to include groundwater uptake by kiawe and was integrated into a management framework, the objective of which is to maximize the present value of net benefits from water consumption.

2.1. Groundwater Dynamics

Given that the study is interested in the long-run aquifer-level implications of management decisions (i.e. it abstracts from spatial externalities associated with short-term pumping decisions such as cones of depression), a single-cell aquifer model is used to determine changes in groundwater stock over time. Under certain conditions (detailed in section 3), the stored volume of water in a coastal aquifer is approximately related to the head level (h) – the distance between mean sea level and the water table – by a constant factor of proportionality (γ). Recharge from precipitation or adjacent water bodies (R) is assumed constant and exogenous. Stock-dependent natural leakage along the freshwater-saltwater interface (L) is an increasing and convex function of the head level; a high head level implies a larger groundwater lens, which exerts greater pressure along a larger surface area. The quantity of groundwater extracted (q) is determined by the resource manager in every period, and uptake (U) is an increasing function of the kiawe stock (K). In what follows, a dot over a variable indicates its derivative with respect to time. The head level evolves over time according the following relationship:

(1) $$\gamma \dot{h}_t = R - L(h_t) - q_t - U(K_t).$$

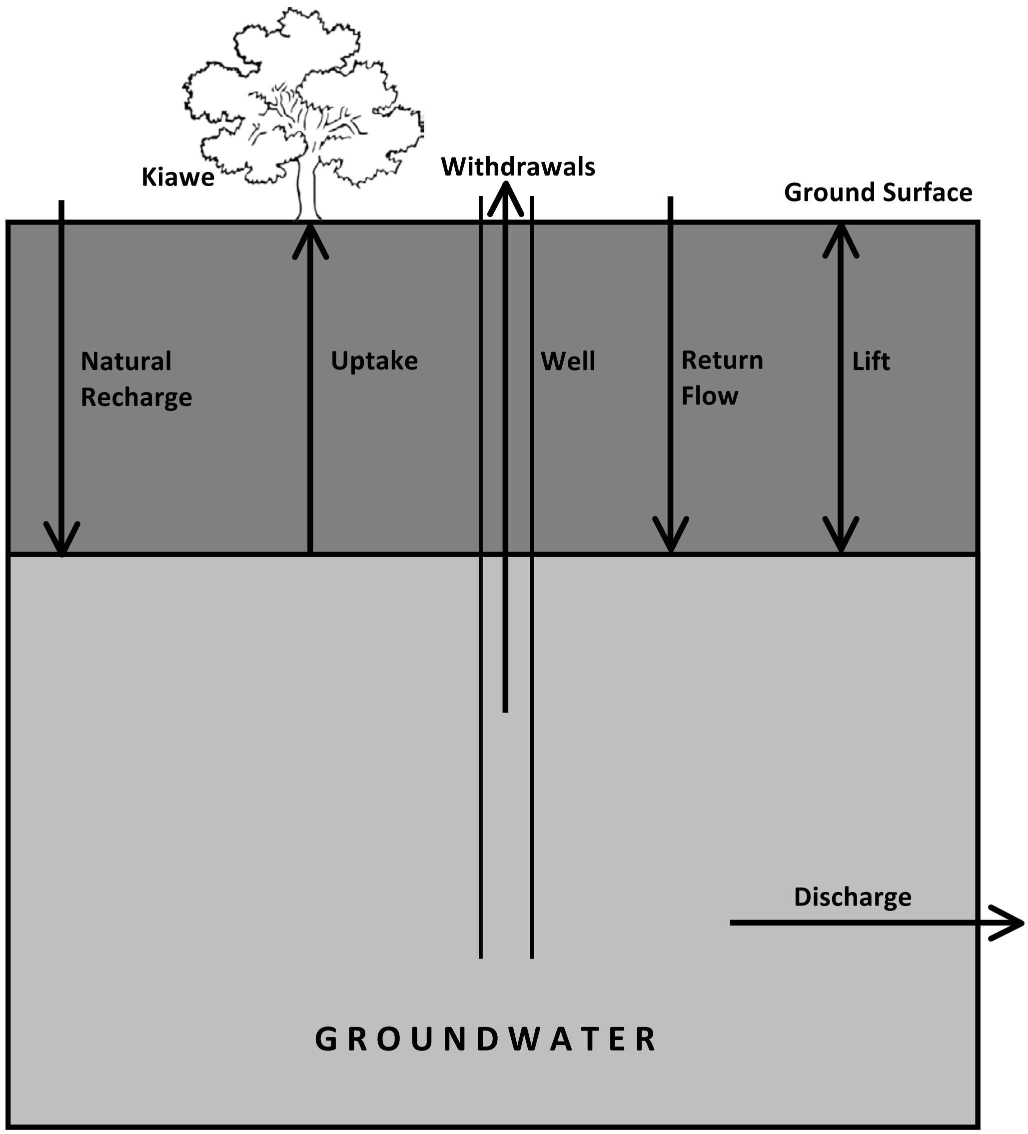
2.2. Kiawe Dynamics

Kiawe provides some stock (e.g., pollen for the honey production industry) and extraction (e.g., charcoal) benefits to users in the region. However, the study views such benefits as small enough relative to the potential value of water salvage from which they can be abstracted. In the more general case where the benefits provided by both resources are substantial, the model can be easily adjusted to include those benefits in the objective functional. The stock of kiawe increases according to its natural net growth function (F) and decreases with anthropogenic removal (r):

(2) $$\dot{K}_t = F(K_t) - r_t.$$

The general framework is amenable to other invasive plant species, provided that one can parameterize the net growth and damage (in this case groundwater uptake) functions. The integrated terrestrial-hydrological system is depicted in **Error! Reference source not found.**.

Figure 5-1. Coastal aquifer cross section



2.3. Present Value Maximization

The resource manager's problem is to choose the rates of groundwater extraction (q), desalination (b), and kiawe removal (r) in every period to maximize the net present value (NPV), that is:

$$(3) \qquad \max_{q_t, b_t, r_t} \int_{t=0}^{\infty} e^{-\rho t} \left[B(q_t + b_t, t) - c_q(h_t) q_t - c_b b_t - c_r(K_t) r_t \right] dt$$

subject to Eq. 1 and 2, given a positive discount rate ρ. Benefits (B) are a function of water consumption (e.g., the area under the inverse demand curve). The unit extraction cost of groundwater, $c_q(h)$, is a function of the head level because it is determined primarily by the energy required to lift groundwater to the surface; as the water table declines, the distance groundwater must be lifted increases. The cost of kiawe removal $c_r(K)$ is also stock-dependent because management would entail targeting the lowest cost (e.g., the most accessible) areas first. Desalinated water serves as a costly backstop resource, which can be used to supplement groundwater at a constant unit cost c_b.

If the price for which the marginal benefit and marginal cost of water extraction are equal is defined as $p_t \equiv B'(q_t + b_t, t)$, then it is straightforward to construct the following efficiency price equation for water (see Appendix I for a detailed derivation):

$$(4) \qquad p_t = c_q(h_t) + \frac{\dot{p}_t - \gamma^{-1} c_q'(h_t) \left[R - L(h_t) - U(K_t) \right]}{\rho + \gamma^{-1} L'(h_t)}.$$

The second term on the right hand side of Eq. 4 is the marginal user cost (MUC), or the loss in present value resulting from an incremental reduction of the groundwater stock in period t. It is identical to the usual MUC associated with groundwater extraction, except that the net recharge term is adjusted by natural leakage and natural groundwater uptake from kiawe. All else equal, the larger the uptake term, the larger is the MUC. Intuitively, this is because uptake adds to anthropogenic extraction in drawing down the head level, thus creating higher future extraction costs and hence larger PV losses than would be realized in the absence of kiawe.

An optimal management rule can also be constructed for the stock of kiawe (see Appendix I for a detailed derivation):

$$(5) \qquad \gamma^{-1}\lambda_t = \frac{c_r(K_t)[\rho - F'(K_t)] - F(K_t)c_r'(K_t)}{U'(K_t)}.$$

Kiawe should be removed until its marginal benefit in terms of avoided uptake, i.e., the shadow value of water ($\gamma^{-1}\lambda$), is equal to its marginal cost. The numerator of the cost term accounts for the forgone interest that would have accrued had the income not been spent on tree removal, as well as the effect on future kiawe growth and removal costs. Removing a tree today means that future removal of the remaining trees is more expensive on a per-unit basis. It also means that the rate of future kiawe growth is higher or lower, depending on where the stock resides on the growth curve (F). The denominator converts the units of the numerator from dollars per tree to dollars per unit of water. At the optimum, the manager should be indifferent between conserving water via tree removal and via consumption reduction.

2.4. The Optimal Steady State

The optimality conditions (Eq. 4 and 5) must hold in every period, even when the system is in a long-run equilibrium or steady state. By definition, the costate and state variables remain constant in a steady state, i.e., $\dot{h}_t = \dot{K}_t = \dot{\lambda}_t = \dot{\mu}_t = 0$, which implies that $\dot{p}_t = 0$. If demand for water grows over time as a result of rising per capita income and population expansion, desalination will be eventually required at a finite time T to supplement groundwater withdrawals. For $p_T = c_b$, Eq. 4 and 5 can be solved for unique values of head and kiawe stock, h^{ss} and K^{ss}, respectively. If the solution yields a negative value for K^{ss} and/or $h^{ss} < h_{min}$, however, one must instead conclude that $K^{ss} = 0$ (i.e., eradication) and $h^{ss} = h_{min}$, where h_{min} is a minimum allowable head level beyond which further pumping yields water of unacceptable quality.

The terminal conditions for head and kiawe stock can then be used in conjunction with initial field measurements for h_0 and K_0 to numerically solve the system of equations (Eq. 1-2, 4-5). Intuitively, any set of paths that satisfies Eq. 1 and 2 is feasible, but optimality requires that the state variables also satisfy Eq. 4 and 5 in every period. Solving the problem thus involves selecting the endogenous terminal time T such that the resulting paths are feasible, optimal, and consistent with the initial conditions.

3. AN APPLICATION TO THE KONA COAST OF HAWAI‘I

A simplified version of the model presented in section 2 was applied to data from the Kiholo aquifer and its surrounding watershed on the Kona Coast of Hawai‘i Island. The main departure from the general framework is the absence of kiawe stock dynamics (Eq. 2). Although the simplification rules out the possibility of dynamic tree management, the results still illustrate the tradeoff between the recharge benefits and costs of kiawe removal.

3.1. Hydrology

The Kiholo aquifer is a thin basal or Ghyben-Herzberg lens of freshwater floating on underlying denser seawater. Given the high porosity of the aquifer and hence its relatively thin brackish transition zone (Duarte, 2002), the freshwater-saltwater mixing region was modeled as a sharp interface. Although not amenable to characterizing spatial disequilibrium relationships in the short-run, a one-dimensional aquifer model is still useful for identifying the long-run optimal extraction path. The equation of motion for the head level of a one-dimensional, sharp-interface, coastal aquifer can be expressed as $\dot{h}_t = (2000/41\theta WE)[R - L(h_t) - q_t]$, where θ is porosity, W is the aquifer width, and E is the aquifer length (Mink, 1980). For the values θ=0.3, W=6000 meters, and E=6850 meters, the volume (thousand gallons) to head (feet) conversion factor (γ^{-1}) for the Kiholo aquifer is 0.0000000492.

Following Pongkijvorasin et al. (2010), the aquifer's natural recharge is assumed constant and equal to 3,992,700 thousand gallons per year (tg/yr). However, leakage or discharge from the aquifer, as discussed previously, is not constant. Mink (1980) derived a structural expression for discharge as a function of head: $l(h)=kh^2$, where k is an aquifer-specific coefficient. Since the leakage function needs to satisfy current conditions, a discharge rate of 3,883,330 tg/yr and head level (h_0) of 5.74 feet imply that k is equal to 117,864.

3.2. Groundwater Extraction and Desalination Costs

The cost of extracting groundwater is primarily determined by the energy required to lift water from the subsurface aquifer to the ground level (e). Duarte (2002) estimated the energy cost of lifting groundwater from the Kiholo aquifer to be USD (2001) 0.00083/m^3 per meter. In 2012 dollars, the cost is USD 0.00108/m^3 per m or equivalently USD 0.00125/tg/ft. Given that the average ground elevation relative to mean sea level is 1,322.5 feet, the unit cost of groundwater extraction as a function of the head level can be expressed as $c_q(h)$=0.00125(1322.5-h).

Pitafi and Roumasset (2009) used a straightforward amortization procedure for capital costs (e.g., treatment facility construction) in combination with cost projections for annual operation and maintenance (e.g., wages, materials, energy) of a reverse osmosis desalination plant to estimate the unit cost of desalination: USD (2001) 7/tg. After adjusting for inflation, c_b was estimated to be USD (2012) 9.07/tg.

3.3. Demand for Water

The County of Hawai‘i Department of Water Supply charges a fixed “standby charge,” a volumetric “power cost charge,” and a volumetric “general use” rate that varies discretely by water quantity blocks. Assuming that the average family falls into the second price block—which is consistent with the average household use of roughly 13,000 gallons per month on O‘ahu—the retail price for water in the region was USD (2008) 4.80/tg.

At the price of USD 4.80/tg, 1074.4 m^3 of groundwater were extracted for consumption in 2008. Based on Griffin (2006) and Dalhuisen et al. (2003), the price elasticity of demand for water (η) is assumed at -0.7, which corresponds to a constant elasticity demand function of the form q_t=850983$p_t^{-0.7}$, measured in tg/yr. With the development of projects in the area, extraction is expected to increase to 3809 m^3/yr (Pongkijvorasin, 2007). A 5 percent growth rate of demand is consistent with a 25-year period to project completion and similar growth thereafter. However, a more reasonable assumption may be that in the years following completion of the projects, population and per capita income growth would converge to a lower level. Therefore, it is assumed that demand grows at an average rate of 3 percent per annum, such that period t demand is determined by q_t=850983$p_t^{-0.7}e^{0.03t}$.

3.4. Groundwater Uptake by Kiawe

Ideally, a relationship between kiawe and water uptake could be constructed using a time series of relevant data. In the absence of the requisite data, however, potential water salvage of kiawe removal can be roughly estimated using such a relationship for a similar type of tree. Saltcedar

(*Tamarix spp.*), for example, is also known to lower water tables via deep taproots, particularly in the southwestern United States. Barz et al. (2009) estimated that removal of 8,954 acres of saltcedar from the Texas Pecos River Basin would release 7.41 million m^3 of water per year. This translates to an annual recharge gain of 218.62 tg of water per acre of trees removed.

Assuming that kiawe is roughly distributed in proportion to land area for each of the islands across the state and that one-fourth of the kiawe habitat on Hawai‘i Island lies on the Kona Coast in close proximity to the Kiholo aquifer, the total potential water salvage associated with removing all of the kiawe in Kiholo is 2,936,570 tg/yr. These along with the other functions and parameters discussed in sections 3.1-3.3 are summarized in **Error! Reference source not found.**.

Table 5.1. Equations and parameters

Description	Unit	Equation or value
State equation for water	tg/yr	$\dot{h}_t = 0.0000000492[R - L(h_t) - q_t]$
Recharge	tg/yr	$R = 3{,}992{,}700$
Leakage	tg/yr	$L(h_t) = 117{,}864 h_t$
Extraction cost	USD/tg	$c(h_t) = 0.00125(1322.5 - h_t)$
Desalination cost	USD/tg	$c_b = 9.07$
Water demand	tg/yr	$q_t = 850{,}983 p_t^{-0.7} e^{0.03t}$
Kiawe uptake	tg/yr	$U = 2{,}936{,}570$

3.5. Kiawe Removal Costs

Several previous studies had estimated the cost of removing kiawe using a variety of methods, ranging from bulldozing to aerial broadcast of herbicides to controlled burning. The initial per acre costs ranged from a low of USD (2012) 7 for burning to as much as USD (2012) 295 for bulldozing. Follow-up treatment for each method tended to also vary, suggesting that a present value approach to calculating costs is necessary to ensure that streams of costs accruing in different time periods are converted to comparable units. Thus for an initial treatment cost of $X followed by maintenance treatment every Y years at a cost of $Z, the PV cost of removal is calculated as $\$X + \sum_{t=1}^{\infty}[\$Z(1+\rho)^{-Yt}]$ per acre. Per acre costs and PV costs for removing all existing acres of kiawe in the Kiholo region are presented in **Error! Reference source not found.**.

Table 5.2. Kiawe (*Prosopis pallida*) removal costs in 2012 dollars

Author	Year	Location	Method	Cost (USD/acre)	Follow-up	PV (million USD)*
Campbell et al.	1996	Australia	Single pull	30		1.57
			Double pull	64		3.36
			Bulldoze	295		15.5
March et al.	1996	Australia	Aerial spray	133		6.98
			Blade-plough	61		3.20
Teague et al.	1997	Texas	Hand spray	35	Re-treat every 10-12 yr	1.84
			Spray + chain	56	Chain again after 2 yr; Spray every 10-12 yr	2.83
			Roller chopping	92	Re-treat every 6-8 yr	7.60
			Root plowing + reseed	127	Grub every 12 yr	3.34
			Fire	7	Burn every 5-7 yr	0.68
			Grub	106	Re-treat every 10-15 yr	5.56

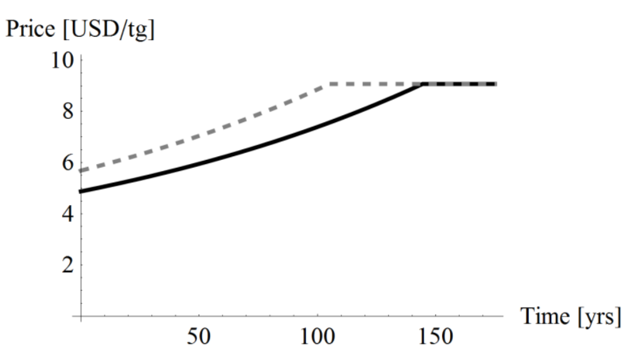
*If the study does not provide recommendations for follow-up treatment, it is assumed that the initial treatment is repeated every 10 years in perpetuity.

4. RESULTS

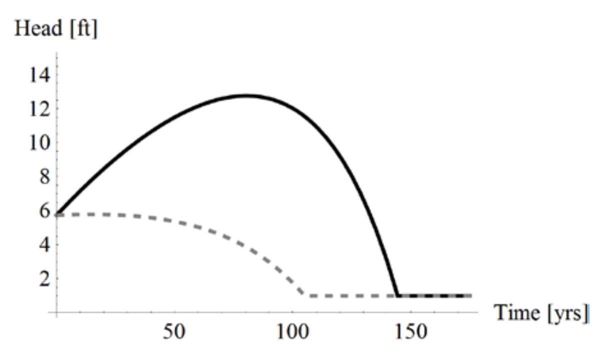
The maximization problem (Eq. 3) is solved for U=0 (all kiawe removed) and U=2,936,570 (no kiawe removed). The removal of kiawe significantly affects water price, head level, and consumption trajectories in a manner that increases benefits to society. Specifically, it allows the aquifer to build for a period before being drawn down to its steady state level. Because water is relatively abundant at the outset and demand is growing, the time path of the head level is nonmonotonic; the aquifer is allowed to replenish initially in anticipation of future scarcity. This is not to say that groundwater consumption is lower under kiawe management. On the contrary, the water salvaged from kiawe ensures a lower price and higher consumption in every period, in addition to delaying the need for a costly alternative such as desalination by nearly 40 years. The price, head, water extraction, and consumption paths are presented in **Error! Reference source not found.**.

Quantitatively, the benefits of kiawe management are calculated as the difference between the PVs of the aquifer with and without kiawe removed. While the PV benefits are net of the costs associated with extracting groundwater, they do not yet account for the cost of controlling kiawe. The NPV was calculated by subtracting the PV cost of kiawe treatment for each of the methods outlined in **Error! Reference source not found.**. The NPV is positive for each method, ranging from a low of USD 17.0 million for bulldozing to a high of USD 31.8 million for fire (**Error! Reference source not found.**).

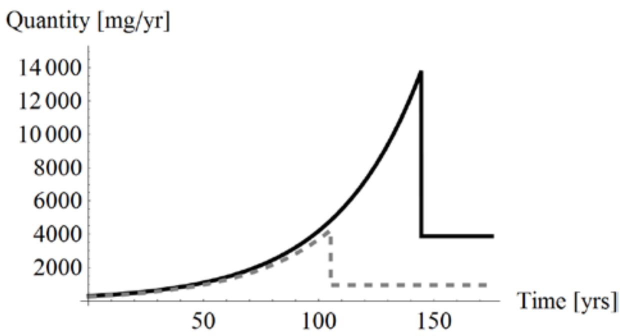
Figure 5-2. Price, head, extraction, and consumption trajectories for no kiawe management (dashed lines) and the case where all kiawe is removed (solid lines).



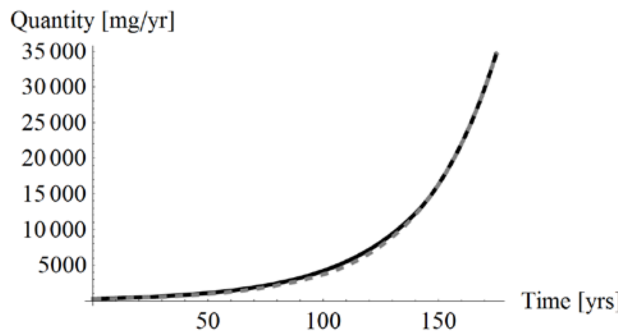
(a) Price paths



(b) Head paths



(c) Water extraction paths



(d) Water consumption paths

Table 5.3. NPV calculations for various kiawe management instruments

Method	PV benefit (million USD)	PV cost (million USD)	NPV (million USD)
Single pull	32.5	1.57	30.9
Double pull	32.5	3.36	29.1
Bulldoze	32.5	15.5	17.0
Aerial spray	32.5	6.98	25.5
Blade-plough	32.5	3.20	29.3
Hand spray	32.5	1.84	30.6
Spray + chain	32.5	2.83	29.6
Roller chopping	32.5	7.60	24.9
Root plowing + reseed	32.5	3.34	29.1
Fire	32.5	0.68	31.8
Grub	32.5	5.56	26.9

5. CONCLUSION

This study derived welfare-maximizing decision rules for the dynamic management of two interacting resources: groundwater and kiawe (*Prosopis pallida*). The optimal quantity of groundwater extraction satisfies the condition that the marginal benefit of water consumption is equal to the sum of extraction and marginal user cost, where the latter is a function not only of the groundwater stock but also of the kiawe stock via its ability for groundwater uptake. Analogously, the optimal decision rule for kiawe control is dependent on the stock of groundwater; kiawe should be removed until the marginal benefit in terms of water salvage is equal to the marginal cost of removal. At the optimum, which can be achieved only through joint management of the resources, the costs of conserving water via tree removal and consumption reduction are equal. One way of implementing the optimal solution is by setting the marginal water price equal to the cost of providing water through both mechanisms.

An application of the model to the Kona Coast of Hawaiʻi showed that the PV cost of removing existing kiawe trees is outweighed by the benefits, measured as the difference in PV welfare to water consumers with and without the trees removed. Among the 11 removal methods considered, management by fire yields the lowest PV cost (USD 0.68 million) and hence the highest net PV (USD 31.8 million), while management by bulldozing yields the highest PV cost (USD 15.5 million) and the lowest net PV (USD 17.0 million). However, the NPV estimates considered only the direct costs of management (e.g., wages, materials, equipment rental). Each removal instrument may generate additional costs that must be accounted when devising a management strategy. Fire, for example, does not require much labor or rental of expensive machinery, but the potential for spread to non-targeted areas may not be trivial, especially in dry leeward areas conducive to kiawe growth. The smoke generated might also cause discomfort to surrounding residents. Herbicide application is effective, but has the potential to affect non-target native species and to compromise the quality of underlying groundwater sources. Obtaining permits for aerial broadcast of herbicides may be prohibitively costly or difficult. Thus, **Error!**

Reference source not found. should be a viewed as primarily a starting point for the development of kiawe management policy.

Regardless of method, kiawe removal may disrupt other activities that generate benefits. For instance, although it is an invasive species in Hawai‘i, kiawe is valued for its role in honey production and as firewood. These industries are small relative to the state's economy, but the potential welfare loss should be incorporated into a comprehensive benefit-cost analysis of various management instruments under consideration. While a detailed analysis of the impact on the local economy is beyond the scope of this chapter, any losses suffered by those industries are believed to likely be outweighed by the potential recharge benefits of management, inasmuch as the kiawe under consideration in Kiholo composes only a fraction of the forest stands on the island and in the state.

The framework developed herein can be applied to a variety of settings around the world, where the presence of one natural stock affects the quantity, quality, or availability of another. Other appropriate applications include jointly managing upstream forests and downstream waterways, invasive pest control in agriculture, and groundwater management and linked nearshore marine ecosystems. To the extent that the relationships between natural stocks, as well as the implications of changing one or the other, can be characterized, optimal management trajectories for maximizing their joint benefit can be obtained.

From a policy perspective, one can draw several lessons from the framework developed. First, resource scarcity can be largely affected by interlinkages between different types of ecosystems or natural resources, so management decisions such as price reform should consider those interlinkages. Relatedly, managing resources independently – e.g., a groundwater aquifer and an invasive species such as kiawe that affects the aquifer – overlooks potentially large welfare gains that may be obtained from joint management. Lastly, even when currently available data are not sufficient to jointly optimize both resources, management scenarios such as removing all of the invasive species in the current period may serve as a useful approximation (or lower bound) of NPV benefits to justify financing a joint management approach.

The analysis presented can be extended in a variety of ways. The NPV calculations assume that kiawe reduction would occur immediately, when in fact it may make sense to delay the removal of the trees. If the discount rate is large (future benefits and costs are not valued highly from today's standpoint) and groundwater is initially relatively abundant, consumers may prefer to delay the cost of kiawe management. In that case, the problem becomes one of optimal timing: at what point in the future should kiawe trees be removed to maximize PV? An even more ambitious extension would involve determining the optimal dynamic path of kiawe reduction, provided that data are available to parameterize detailed uptake and growth functions.

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Appendix I

Recall that the objective is to maximize Eq. 3 subject to state Eq. 1 and 2. Optimal control is implemented to characterize the necessary conditions for the maximization problem. The corresponding current value Hamiltonian is

(A1) $$H = B(\bullet) - c_q(h_t)q_t - c_b b_t - c_r(K_t)r_t + \lambda_t \gamma^{-1}\left[R - L(h_t) - q_t - U(K_t)\right] + \mu_t\left[F(K_t) - r_t\right]$$

and the Maximum Principle requires that the following conditions are satisfied (Chiang, 2000):

(A2) $$\frac{\partial H}{\partial q_t} = B'(q_t + b_t, t) - c_q(h_t) - \gamma^{-1}\lambda_t \leq 0 \qquad \text{if} < \text{then } q_t = 0$$

(A3) $$\frac{\partial H}{\partial b_t} = B'(q_t + b_t, t) - c_b \leq 0 \qquad \text{if} < \text{then } b_t = 0$$

(A4) $$\frac{\partial H}{\partial r_t} = -c_r(K_t) - \mu_t \leq 0 \qquad \text{if} < \text{then } r_t = 0$$

(A5) $$\dot{\lambda}_t - \rho\lambda_t = -\frac{\partial H}{\partial h_t} = c_q'(h_t)q_t + \gamma^{-1}\lambda_t L'(h_t)$$

(A6) $$\dot{\mu}_t - \rho\mu_t = -\frac{\partial H}{\partial K_t} = c_r'(K_t)r_t + \gamma^{-1}\lambda_t U'(K_t) - \mu_t F'(K_t).$$

(A7) $$\dot{h}_t = \frac{\partial H}{\partial \lambda_t} = \gamma^{-1}\left[R - L(h_t) - q_t - U(K_t)\right]$$

(A8) $$\dot{K}_t = \frac{\partial H}{\partial \mu_t} = F(K_t) - r_t.$$

An efficiency price equation for water that is dependent only on constant parameters and the two state variables can be derived using the above conditions. First, define the price for which the marginal benefit and marginal cost of water extraction are equal as $p_t \equiv B'(q_t + b_t, t)$. Then assuming groundwater extraction is positive, Eq. A2 becomes

(A9) $$p_t = c_q(h_t) + \gamma^{-1}\lambda_t \Leftrightarrow \lambda_t = \gamma[p_t - c_q(h_t)].$$

Taking the time derivative of Eq. A9 yields

(A10) $\dot{\lambda}_t = \gamma[\dot{p}_t - c_q'(h_t)\dot{h}_t]$.

Next, replace $\dot{h}_t$ in Eq. A10 with the right hand side of the equation of motion (Eq. A7). Finally, substitute all λ_t and $\dot{\lambda}_t$ terms in Eq. A5 with Eq. A9 and A10:

(A11) $$p_t = c_q(h_t) + \frac{\dot{p}_t - \gamma^{-1}c_q'(h_t)\left[R - L(h_t) - U(K_t)\right]}{\rho + \gamma^{-1}L'(h_t)}.$$

Similarly, a condition can be derived to describe the optimal removal of kiawe over time. When removal is positive, $\mu_t = -c_r(K_t)$. Taking the time derivative of the costate variable yields

(A12) $\dot{\mu}_t = -c_r'(K_t)\dot{K}_t$.

Eq. A12 can be further simplified by replacing $\dot{K}_t$ with the right hand side of the equation of motion (Eq. A8). Substituting all μ_t and $\dot{\mu}_t$ terms in Eq. A6 results in the following equimarginality condition:

(A13) $$\gamma^{-1}\lambda_t = \frac{c_r(K_t)[\rho - F'(K_t)] - F(K_t)c_r'(K_t)}{U'(K_t)}.$$