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The Good, Bad, and Ugly of Watershed Management

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Chapter 8: The Good, Bad, and Ugly of Watershed Management

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Abstract

Efficient management of groundwater resource systems requires careful consideration of relationships — both positive and negative — with the surrounding environment. The removal of and protection against "bad" and "ugly" natural capital such as invasive plants and feral animals and the enhancement of "good" capital (e.g. protective fencing) are often viewed as distinct management problems. Yet environmental linkages to a common groundwater resource suggest that watershed management decisions should be informed by an integrated framework. We develop such a framework and derive principles that govern optimal investment in the management of two types of natural capital — those that increase recharge and those that decrease recharge — as well as groundwater extraction itself. Depending on the initial conditions of the system and the characteristics of each type of natural capital, it may make sense to remove bad capital exclusively, enhance good capital exclusively, or invest in both activities simultaneously until their marginal benefits are equal.

Introduction

Payment for Ecosystem Service (PES) programs, which incentivize private landowners to protect ecosystem services when making land use decisions, have grown rapidly in the past few decades (Daily et al. 2009; Nelson et al. 2009; Sanchirico and Springborn 2010). Forested watersheds in particular provide a wide range of services, including those related to water resources, species habitat, biodiversity, subsistence activities, hunting, aesthetic values, commercial harvest, and ecotourism, among others, and those services can have substantial value. For example, Kaiser et al. (1999) estimate that the 99,000-acre Koolau Mountain Range on the island of Oahu (Hawaii) provides forest benefits valued between $7.4 and $14 billion. Though the motivation for watershed conservation activities is clear, the abundance of potential conservation instruments – removal of any number of invasive species, reforestation or afforestation, construction of capital such as fencing or settlement ponds, etc. – creates a considerable challenge for resource managers: what type of conservation should be employed and in what order?

The dearth of quantitative information about the costs and benefits of alternative conservation instruments, combined with the lack of a specific measurable objective, often leads to ad hoc decisions regarding investment of limited resources for conservation in practice. The objective of this chapter is to develop a framework for making efficient decisions about employing available watershed conservation instruments. By building the management problem around the concept of present value, we provide a quantifiable objective, and hence a means to rank alternatives. Taking Oahu as a case study, we also find that more scientific research is needed to quantify the effects of various conservation activities on ecosystem services of interest.

General conservation framework

To maintain clarity in the discussion that follows, we focus on freshwater services, while keeping in mind that the framework could be extended to multiple ecosystem services. Groundwater recharge depends on a variety of factors including precipitation, evapotranspiration, soil type, and land cover. Although many of those factors are out of our control, land cover can be altered in a variety of ways. Particularly high transpiration rates have been documented for some invasive plant species. Such plants tend to capture a relatively high proportion of precipitation before infiltration to groundwater resources can occur. Other plants have been shown to extract existing water directly from the groundwater resource itself via deep taproots. Feral ungulates can similarly inhibit groundwater recharge by altering landscapes; digging, trampling, and consumption of existing vegetation creates stretches of bare land that are more conducive to runoff during rain events. Although each of these examples has a negative impact on water resources, the degree of impact varies, and managing each problem entails different costs.

As an alternative to or in addition to (bad) invasive species removal, watershed conservation can entail investment in (good) plant species that tend to augment the watershed's ability to recharge underlying aquifers. An advantage of investing in natural capital is the potential for growth in the future without further investment. However, quantifying the net recharge benefit of reforestation activities (relative to the existing or counterfactual land cover) is often very challenging, and limited data is available for Hawaii. Investment in (good) produced capital such as settlement ponds, injection wells, and fencing for feral animals can also be made to increase the percentage of rainfall converted to groundwater recharge, although unlike natural capital, produced capital typically requires higher levels of maintenance over time.

To illustrate the tradeoffs between different conservation instruments, we consider two types of investment: fencing for feral pigs (*Sus scrofa*) and removal of invasive strawberry guava (*Psidium cattleianum*). In both cases, we assume that protection against new or recurring invasions is lumped into removal costs. More generally, one can imagine separate protection or maintenance costs incurred in periods following initial removal. The cost of removing one acre of (bad) strawberry guava (c_S) is assumed to increase as the current stock declines due to the loss of economies of scale and increasing unit search costs. However, the stock can only be reduced by removing more plants than natural growth (F). In the analytical model and the application that follows, we assume that the number of invasive plants removed is proportional to the number of acres cleared (x^S). One could imagine a model that tracks individual plant units with a non-uniform distribution over space, but implementation would require spatial details that are unavailable in our case. The dynamic behavior of the strawberry guava stock in terms of acres (S) is described by the following equation:[1]

$$\dot{S}_t = F(S_t) - x_t^S \tag{1}$$

By not explicitly modeling space, we are implicitly assuming that high priority areas, i.e. those that would generate the largest recharge gains, are targeted first. Consequently, the recharge function (R) is concave with respect to guava stock – as management shifts toward lower priority areas over time, gains in recharge are smaller, and removal costs may be higher for the reasons explained above.

Feral animal control also entails reducing or slowing a continuously growing stock but typically requires investment in (good) capital such as fencing, which may have large upfront costs for the initial fence construction and removal of pigs from the fenced-off area. The stock of

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[1] In the equations that follow, a dot over any variable indicates its derivative with respect to time, in this case, $\partial S/\partial t$.

produced capital, in this case fencing, could be modeled explicitly, including the initial

installation/removal costs and yearly maintenance expenditures. For the purpose of illustrating

the management principle of equimarginal benefits, however, we will assume that the cost of

fence installation (c_Z) includes the present value of maintenance, reckoned at the time an acre is

cleared. The population of pigs in terms of acres (Z) increases over time in accordance with its

natural growth function G and is reduced by investments in fencing (x^Z), which includes initial

removal:

$$\dot{Z}_t = G(Z_t, \sum_{\tau=0}^{t} x_\tau^Z) - x_t^Z \tag{2}$$

The growth function is dependent on not only the stock of feral animals but also on cumulative

removal up to the current period (implicitly the acres of fencing installed). Like for strawberry

guava, we assume that the location of future fence installations is predetermined, based on

existing knowledge of the watershed. Typically, one starts at a high elevation, builds additional

fencing to enclose previously fenced areas, then removes pigs between the fences. We also

assume a proportional relationship between the number of acres fenced and the number of pigs

removed. In a more general formulation, G would depend directly on growth-retarding capital

such as fencing. Then, fencing installation and existing fencing stock would enter the

management problem as additional control and state variables respectively.

Each type of capital – good, bad, natural, and/or produced – feeds into the groundwater

recharge function. The stock of groundwater, indexed by the head level (h) converted to volume,

changes over time according to recharge (R), stock-dependent natural leakage to adjacent water

bodies (L), and extraction (q):

$$\dot{h}_t = R(S_t, Z_t) - L(h_t) - q_t \tag{3}$$

where $R_S < 0$ and $R_z < 0$.

The objective of the management problem is to maximize the present value of net benefits from water use, taking into account both groundwater extraction costs and watershed-conservation costs, subject to Eqs. 1-3:

$$\underset{q_t,b_t,x_t^S,x_t^Z}{Max} \int_0^\infty e^{-rt}\left\{\int_0^{q_t+b_t} D^{-1}(\theta_t)d\theta_t - c_q(h_t)q_t - c_b b_t - c_S(S_t)x_t^S - c_Z x_t^Z\right\}dt \tag{4}$$

Gross benefits of water consumption are measured as consumer surplus, or the area under the inverse demand curve for water. The unit cost of groundwater extraction (c_q) is stock-dependent because the distance water must be lifted to the surface varies with the aquifer head level. In addition to groundwater extraction, we allow for the production of desalinated seawater (b) at unit cost (c_b) as a backstop resource. Desalinated water need not be used in every period, and in most cases, is likely to serve as a supplemental resource only in the very long run.

The dynamic optimization problem can be posited in an optimal control framework, and it is straightforward to derive the following efficiency price equation for optimal groundwater extraction from the necessary conditions (Roumasset and Wada 2013):

$$p_t = c_q(h_t) + \frac{\dot{p}_t - c_q'(h_t)[R(S_t,Z_t) - L(h_t)]}{r + L'(h_t)} \tag{5}$$

Eq. 5 says that water should be extracted until the marginal benefit, measured as the efficiency price (p), is equal to the marginal opportunity cost (MOC) of groundwater. The MOC includes the physical extraction cost, as well as the marginal user cost (MUC), which accounts for the forgone use of the marginal unit of groundwater when the price is higher in the future, as well as the effect of today's extraction on leakage and marginal extraction cost in the future. Along the optimal path, the MUC is equal to shadow price of groundwater, which is by definition, the increase in net present value resulting from an additional unit of groundwater stock.

Each of the invasive species stocks has an optimality condition for efficient removal. Strawberry guava should be eliminated until the marginal benefit of the last unit removed, measured as the shadow price of groundwater (λ), is equal to the MOC of control:

$$\lambda_t = \frac{c_S'(S_t)F(S_t) + c_s(S_t)[F'(S_t) - r]}{R_s} \tag{6}$$

The MOC of strawberry guava removal includes the effect on both the stock-dependent marginal extraction cost and the stock-dependent growth. An analogous condition can be derived for pig control:

$$\lambda_t = \frac{c_Z[G'(Z_t) - r]}{R_Z} \tag{7}$$

The assumption of a constant unit cost of fence installation eliminates costs related to changes in the marginal cost of control. Consequently the MOC of pig removal is driven primarily by the effect on the growth rate. Inspection of the two optimality conditions for watershed conservation reveals that optimal management is steered by the system shadow price of water (λ). The shadow price, in turn, is determined endogenously by the joint maximization problem (Eq. 4), which means that present value is only maximized if the watershed and aquifer are managed simultaneously.

For an internal solution, i.e. in which removal of both invasives is optimal, the above conditions imply an equimarginality condition for the two removal instruments. Control measures should be implemented until both MOCs are equal to each other and simultaneously equal to the shadow price or scarcity value of recharge. In certain periods, however, it may not be optimal to allocate any resources toward one or more watershed conservation instruments. For example, if the MOC of pig removal is higher than the shadow price of recharge for any level of

control in a given period but the MOC of strawberry guava is lower than the shadow price over some range of control, only strawberry guava removal is optimal and a corner solution obtains.

Generally, watershed conservation activities – enhancing good and removing bad or ugly watershed capital – can be arranged according to their effect on recharge. The supply cost of protective capital such as fencing is the implicit rental cost or user cost of capital. When protective and removal actions are treated separately, removal can also be thought of as capital, where depreciation is the maintenance required to keep new invasive species out of the controlled area. Interdependence between different instruments for increasing recharge – e.g. a fence complements reforestation and serves as a substitute for invasive tree removal – means that the integrated management problem must be solved in its entirety, i.e. not piecewise. For graphical purposes, however, we can assume that individual supply curves for recharge are drawn *mutatis mutandi*, i.e. with other inputs at their optimal quantities. Upon adding the supply curves horizontally, the resulting aggregate supply curve for recharge intersects the marginal benefit curve for water at the shadow price of recharge (Fig. 1).

The relative slopes of the supply curves will depend on the cost and effectiveness of each respective conservation instrument. If the land management authority can rank locations according to the cost per recharge saved, e.g. because of the location of plants in more or less critical watershed areas, then a least-cost approach implies an upward sloping supply curve of recharge via strawberry guava removal. The same applies to pigs, except that current conservation practices seem to suggest that a top-down approach is most cost-effective, presumably because the more critical watershed areas tend to be at higher elevations.
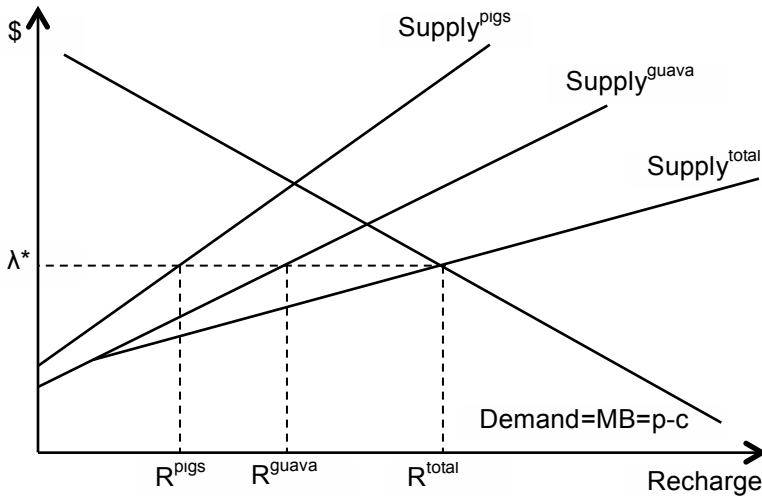
Figure 1. *Supply and demand for recharge*

The individual recharge supply curves for pig and guava removal are
added horizontally to determine the optimal total quantity of
recharge. The downward sloping demand for recharge is the net
price of groundwater.

Application: Koolau Watershed

Watershed management can generally entail investment in a wide variety of conservation

activities, possibly including installation of both natural and produced capital. In the application

that follows, the problem is to remove and protect against *bad* strawberry guava and remove and

protect against *ugly* pigs. Protection against new strawberry guava (e.g. making sure the

herbicide reaches the roots and conducting occasional surveillance for new growth) is lumped

into removal costs. The cost of removing feral pigs is included in the construction cost of *good*

(preventative) fences. For reasons of tractability, investment in good natural capital (e.g.

reforestation) is not considered here.

Nonnative feral pigs (*Sus scrofa*) reproduce rapidly, starting from as early as 6-12 months in

age. Sows usually produce litters of 5-7 piglets and having two litters per year is common

(Pavlov et al. 1992). In Hawaii, survivorship of piglets is particularly high, owing to lack of predators and abundant food sources. A yearly production of ten piglets, with some mortality, accords with the notion that uncontrolled pig populations in Hawaiian rainforests are currently capable of doubling every four months (Katahira et al. 1993). Although reliable data is currently unavailable regarding both the existing population and growth rate of feral pigs in Hawaii, we make some simple assumptions to illustrate how the optimization framework could inform resource management decisions. Suppose that the initial stock of pigs in the Koolau watershed on the island of Oahu is 5,000 and that the carrying capacity of the approximately 100,000-acre watershed is 100,000 pigs. Because Katahira et al.'s (1993) estimate of the pig population doubling every four months was made over 20 years ago, the rate of growth has likely changed substantially as the stock of pigs has continued to expand. We assume that feral pig growth can be roughly approximated by a logistic growth function, and that the intrinsic growth rate is 25%, the upper range of an estimate for *Sus scrofa* annual intrinsic growth in Texas (Texas A&M, 2011). The natural growth of pigs is described by the following function:

$$G(Z_t) = 0.25Z_t(1 - Z_t/100000) \tag{8}$$

While there are many possible control methods, fencing is often considered the standard conservation instrument for removing and then excluding feral pigs from a watershed area. Kaiser et al. (1999) estimate that fencing would cost roughly $40,000 per mile in the Koolau watershed, not including monitoring and depreciation costs. Cost data from recently completed projects on Oahu suggest that costs have since risen substantially and are likely more in the range of $92,000-$159,000 per mile (M. Burt, Oahu Army Natural Resources Program, personal communication). Because these costs only include clearing, scoping, construction, and gear preparation, the total costs (including helicopter time and materials) may be much larger. For the

purposes of our illustration, we assume that fence construction costs $200,000 per mile. Given that one acre is equivalent to 43,560 square feet, installing a 165-foot by 264-foot (1-acre) rectangle with a perimeter of 858 feet (0.1625 miles) costs $32,500.[2] If additional rectangles are placed adjacent to the existing fencing, however, every rectangle except the one at the starting point in each row would only require two additional sides. We therefore assume that the average cost of fencing one acre is roughly $16,250. Pig removal (x^Z) in every period will be determined by investment in fencing (y^Z) and the stock of pigs (Z) in the following fashion:

$$x_t^Z = y_t^Z \left[\frac{Z_t}{100000 - \sum_{\tau=0}^{t} y_\tau^Z} \right] \tag{9}$$

In other words, the number of pigs removed in period t is equal to the number of new acres fenced, multiplied by the existing pig population, divided by the number of remaining unfenced acres in the watershed. The implied direct correspondence between fenced area and pigs and the assumption of uniform pig density over space are consequences of limited information in this particular application.

Feral pigs negatively impact native flora and fauna in Hawaii's forested watersheds and cause soil compaction. Although much more work needs to be done to fully understand the relationship between pigs and runoff, results from a recent study in the Manoa watershed on the island of Oahu suggest that exclusion by fencing may reduce pig-induced runoff (Dunkell et al. 2011). Of the seven study sites observed over a one-year period, runoff was roughly 10% less in fenced areas at two plots, 20% less at one plot, no different at three plots, and 10% higher at one

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[2] Assuming that fencing of the watershed starts from the highest elevation, one can imagine constructing a semi-circle of fence part way down one side of the mountain. A one-acre semi-circle has radius of 166 feet, and can be roughly approximated by a rectangle with dimensions of 165-feet by 264-feet. One could then move further down the mountain and install another semi-circle that encloses the original fence and remove the pigs in between. This process could be repeated to cover the entire watershed. Additional iterations would require more fencing, however, and thus be more expensive than the previous steps. For our purposes, we suppose that fences are installed in one-acre rectangular units that would roughly follow a semi-circular pattern down the mountain.

plot. On average, fencing appears to have reduced runoff by approximately 4%. Given that the carrying capacity of the 100,000-acre Koolau watershed is assumed to be 100,000 pigs, we suppose that removing one pig effectively reduces runoff within a one-acre area. Further, assuming that pig-induced runoff would have instead recharged the aquifer and that the recharge function is multiplicatively separable, i.e. $R(S,Z) = R^{max}·R(S)·R(Z)$, the last term in the recharge function can be written as follows:

$$R(Z_t) = 1 - 0.04\left(\frac{Z_t}{100,000}\right) \qquad (10)$$

When the population of pigs is zero, recharge is equal to the maximum level of recharge, adjusted only for the effect of strawberry guava, $R(S)$. If the population of pigs reaches the carrying capacity, R^{max} is reduced by 4% in every period, in addition to the effect of strawberry guava. For pig stocks between those levels, total maximum recharge is reduced, but not by the full 4%.

Psidium cattleianum is a small tree (2-6 m) that tends to form dense monotypic stands. The red-fruited variety, commonly known as strawberry guava, is native to Brazil. In Hawaii, strawberry guava is a highly invasive species that is very difficult to eradicate, due to lack of natural predators and imperfect biological control agents. Growth rates of strawberry guava in native Hawaiian forests can be very high. At 3,000 feet on Hawaii Island, average annual increases of over 12% in stem density and 9% in total basal area have been measured (Geometrician Associates LLC, 2010). Statewide, it is estimated that roughly 38% of forested areas have "likely dense infestation" of strawberry guava (Geometrician Associates LLC, 2010). Although tracking individual trees would provide the best estimate of the effect on watershed services, doing so would be infeasible given currently available data. We assume that the unit of

measure for strawberry guava is one acre – which implies that S_0 is equal to 38,000 – and growth

is described by a logistic function with an intrinsic growth rate of 10 percent:

$$F(S_t) = 0.1S_t(1 - S_t / 100000) \tag{11}$$

Controlling strawberry guava requires cutting of stems and application of herbicide to

prevent resprouting. Because many areas in Hawaii's upper watersheds are not easily accessible

by road, costs can increase dramatically if equipment needs to be transported over rugged terrain.

For example, if the target area is more than 1.5 miles away from a road, working crews typically

camp onsite, and a helicopter is used to transport equipment and camping gear. In East Hawaii

conservation areas, it is estimated that controlling dense infestations cost $10,500/acre near

roads, $12,200/acre at moderate distance from roads, and $23,315/acre in remote areas

(Geometrician Associates LLC, 2011). Assuming that the easiest-to-access infestations are

removed first – i.e. $10,500 is the cost of removing the first acre when the entire area is infested

and $23,315 is the cost for the last remaining infested acre – we fit a quadratic function to the

three data points to describe the stock/area-dependent cost function:

$$c_S(S_t) = 23315.2 - 0.230275S_t + 1.02122 \times 10^{-6} S_t^2 \tag{12}$$

Strawberry guava reduces groundwater recharge because of very high evapotranspiration

rates. Compared with forests dominated by native ohia (*Metrosideros polymorpha*), areas

densely infested by strawberry guava have a lower proportion of net rainfall reaching the forest

floor – 110 versus 123% of rainfall (Takahashi et al. 2011). In other words, replacing a stand of

strawberry guava with ohia would increase the amount of water available for groundwater

recharge by up to 12%. Given that the study was conducted on a different island, however, and

that invasive removal in our model does not include reforestation thereafter, we view the 12%

estimate as an uncertain upper bound. For our application, we assume that strawberry guava

removal increases recharge by 8%, twice that of pig removal. Recalling that the recharge function is expressed as $R(S,Z) = R^{max} \cdot R(S) \cdot R(Z)$, the last term in the recharge function can be written as follows:

$$R(S_t) = 1 - 0.08\left(\frac{S_t}{100,000}\right) \tag{13}$$

When the population of strawberry guava is zero, recharge is equal to the maximum level of recharge, adjusted for the effect of feral pigs, $R(Z)$. If the entire area becomes invaded by strawberry guava, R^{max} is reduced by 8% in every period, in addition to the effect of pigs. For strawberry guava stocks between those levels, total maximum recharge is reduced, but not by the full 8%.

Assuming a (real) discount rate of 2 percent and plugging in specific functions to describe costs, growth, and recharge, the marginal opportunity cost of pigs – equivalently the supply curve for recharge via pig removal – from equation (7) can written as follows:

$$MOC_t^Z = \frac{-9.34375 \times 10^9 + 203125 Z_t}{R^{max}(1 - 8 \times 10^{-7} S_t)} \tag{14}$$

For R^{max}=220 million gallons per day, the initial point on the recharge supply curve for pig removal is -$0.039 per thousand gallons, which means that pig removal is optimal at the outset. Because the marginal benefit of recharge, equivalently the net price of groundwater, is currently positive, the demand and supply curves for recharge will intersect to the right of the initial point. The marginal opportunity cost of strawberry guava removal from equation (6) can similarly be written as

$$MOC_t^S = \frac{5.10612 \times 10^{-6}(-29793.7 + S_t)(1.53258 \times 10^{10} - 209323 S_t + S_t^2)}{R^{max}(1 - 4 \times 10^{-7} Z_t)} \tag{15}$$

Again assuming R^{max}=220 million gallons per day, the initial point on the recharge supply curve for strawberry guava removal is $0.002 per thousand gallons, which means that removing strawberry guava may also be optimal at the outset. When the recharge supply curves for pig removal and strawberry guava removal are added horizontally, the resulting aggregate recharge supply curve, in conjunction with the marginal benefit curve for water, determine how much of each conservation activity is warranted in the initial and future periods. Although the contemporaneous cost of strawberry guava removal is slightly lower than that of pig removal initially, pig removal may be preferable because optimality is driven by dynamic growth and cost effects. In this particular example, the pig population grows much more rapidly and the unit cost of removal is static. Strawberry guava, on the other hand, grows relatively slowly and removal cost increase dramatically as the stock is reduced. Ultimately, the scarcity of groundwater determines exactly if and when each of the conservation instruments is optimally implemented.

The example detailed in this section is meant to be illustrative, and adjustments to any of the parameter values may have large impacts on the optimal timing and ordering of the conservation instruments. In particular, the growth rates and initial populations of both invasive species are highly uncertain. Suppose, for example, that the initial population of pigs was 50,000 instead of 5,000 and the intrinsic growth rate was 10% instead of 25%. In that case, the initial point on the recharge supply curve for pig removal is $0.004 per thousand gallons, higher than the initial point for strawberry guava removal. At that population level, the marginal pig contributes less to future growth (moving into the concave portion of the growth curve), and therefore the growth effect in the MOC term is smaller. Moreover because the intrinsic growth rate is lower, the incentive to choose pig removal over strawberry guava removal is also lower in future periods, thus affecting the optimal transition path to the watershed's steady state.

Concluding remarks

Increasing water scarcity warrants greater attention to managing watershed resources. Multiple instruments of watershed conservation can be managed according the *equimarginal* principle, to wit: positive investments in different instruments should satisfy the condition that the marginal dollar invested in each instrument should yield the same increase in the present value of recharge benefits (holding any non-recharge benefits constant). Instruments that yield lower marginal benefits even for the first dollar invested should not be exercised. But increased investment in watershed conservation may be wasted unless the downstream groundwater is well managed. The principles of integrated water management are straightforward. In addition to the equimarginal principle just described, the marginal benefits of increasing recharge must be equal to the marginal user cost of groundwater. A decentralized method of implementation is to charge consumers the marginal opportunity cost of groundwater (extraction cost plus MUC) for the marginal unit consumed and to give landowners payments for watershed services (PWS) according to the (same) marginal value of recharge. Note however that these charges and payments need not apply to inframarginal units, thereby rendering PWS fiscally feasible and conferring maximum benefits to consumers.

In our illustrative application, we found that pig removal may be preferable to strawberry guava initially, even though the contemporaneous unit cost of strawberry guava removal is slightly lower. The seemingly counterintuitive result can be explained when one considers the dynamic growth and cost effects underlying the model. While the pig population grows rapidly and the cost of fencing an acre remains constant, strawberry guava grows relatively slowly and removal costs increase dramatically as the stock is reduced over time. Consequently, allowing strawberry guava to grow initially while focusing resources on the explosive pig population is

the most cost-effective approach. However, the results discussed in the application are largely dependent on the accuracy of underlying cost, growth, and recharge parameters. More research is necessary to quantify initial populations, intrinsic growth rates, and the effect that various invasive species have on reducing potential recharge.

While the focus of the developed framework is to characterize optimal investment patterns for a variety of conservation instruments over time, real-world decisions may be constrained by limited budget allocations for conservation or other issues with financing potentially large projects. For example, if all investments in watershed conservation were completely financed through taxes, the model would need to be adjusted to account for the rising marginal cost of public finance. In that case, one could imagine that the proportion of conservation instruments with large initial outlays (e.g. fence construction) would be reduced in favor of options with low upfront cost but possibly higher maintenance costs (e.g. invasive plant removal). The result would be more uniform expenditures on conservation and lower taxes over a longer period of time.

A natural extension of the basic model would include reforestation and other methods of enhancing natural and/or produced capital to increase recharge. For example, consider the installation of settlement ponds that convert runoff into recharge. These facilities should be expanded until the marginal present value of increased recharge is equal to one, the marginal cost of investment. The same principle applies to investments in natural capital such as reforestation. In the latter case, however, one should add the marginal value of other ecosystem services to the marginal recharge benefits. Implementation of such a model may require detailed watershed-hydrological modeling in order to estimate the effects of different land cover scenarios on recharge.

References

Daily et al. (2009) 'Ecosystem services in decision making: time to deliver', Frontiers in Ecology and the Environment, vol 7, no 1, pp. 21–28.

Dunkell et al. (2011) 'Runoff, Sediment Transport, and Effects of Feral Pigs (*Sus scrofa*) Exclusion in a Forested Hawaiian Watershed', Pacific Science, vol 65, no 2, pp. 175-194.

Geometrician Associates LLC (2011) 'Biocontrol of Strawberry Guava by its Natural Control Agent for Preservation of Native Forests in the Hawaiian Islands', Draft Environmental Assessment prepared for the State of Hawaii Department of Land and Natural Resources.

Kaiser et al. (1999) 'Environmental Valuation and the Hawaiian Economy', University of Hawaii Economic Research Organization Working Paper, http://www.uhero.hawaii.edu/assets/HawaiiEnviroEvaluation.pdf.

Katahira et al. (1993) 'Eradicating feral pigs in montane mesic habitat at Hawaii Volcanoes National Park', Wildlife Society Bulletin, vol 21, pp. 269-274.

Nelson et al. (2009) 'Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales', Frontiers in Ecology and the Environment, vol 7, no 1, pp. 4-11.

Pavlov et al. (1992) 'Feral Pigs, Rainforest Conservation, and Exotic Disease in North Queensland', Wildlife Research, vol 19, no 2, pp. 179-193.

Roumasset, J. and Wada, C.A. (2013) 'A dynamic approach to PES pricing and finance for

    interlinked ecosystem services: Watershed conservation and groundwater management',

    Ecological Economics, vol 87, pp. 24-33.

Sanchirico, J.N. and Springborn, M. (2011) 'How to get there from here: Ecological and

    economic dynamics of ecosystem service provision', Environmental and Resource

    Economics, vol 48, no 2, pp. 243-267.

Takahashi et al. (2011). 'Rainfall partitioning and cloud water interception in native forest and

    invaded forest in Hawaii Volcanoes National Park', Hydrological Processes, vol 25, no 3,

    pp. 448-464.

Texas A&M Institute of Renewable Natural Resources (2011) 'Feral Hog Statewide Population

    Growth and Density', AgriLIFE Research & Extension Fact Sheet,

    http://feralhogs.tamu.edu/files/2011/05/FeralHogFactSheet.pdf