Valuing indirect ecosystem services: the case of tropical watersheds

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ABSTRACT. Mitigating the harmful effects of development projects and industries
(negative environmentalism) is inadequate, especially in resource-dependent economies
whose resources are at risk from other forces. While positive environmentalism includes
conservation projects, the non-market benefits of such projects are difficult to evaluate.
This paper provides and illustrates a method for evaluating the indirect, watershed ben-
efits of a tropical forest, without resorting to survey methods. The conservation of trees
prevents a reapportionment from groundwater recharge to runoff that would otherwise
occur. The value of the water saved is then valued at the shadow prices obtained from
an optimizing model. An illustration of the model shows that watershed conservation
projects may have very high payoffs, even before assessing existence values and other
forest amenities.

1. Introduction

The sub-field of development and the environment enriches both environ-
mental economics and development economics. Environmental economics
has evolved primarily in industrialized countries and is heavily pollution
based (that is oriented to 'P-issues'). Developing countries are relatively
more dependent on natural resources; accordingly, the sub-discipline is
more resource based ('R-issue' oriented). In particular, natural resources
are more prominently featured in the circular-flow description of the
economy. This means in turn that conventional methods of project evalu-
ation and measuring economic indicators such as NNP, which often
overlook natural capital, are more seriously flawed in developing coun-
tries. Finally, interactions and system-based analysis are important –
interactions between the environmental resource system and interactions
within the resources system.[1]

Sustainable development in resource-dependent economies may require
more than the 'negative environmentalism' of rejecting development

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[1] See Opschoor, Button, and Nijkamp (2000) especially the volume introduction.

projects that fail an environmental impact assessment. Environmental degradation may be occurring for many reasons besides development projects and 'positive environmentalism' including environment-enhancing projects may be appropriate.

Forests and forested watersheds are of particular interest among developing countries, whose governments are said to 'often look to their forests as a standing asset that can be liquidated to solve financial problems' (Abromovitz, 1998). Many in the environmental movement, on the other hand, see forest preservation as a moral imperative that should be exempted from hard-nosed economic analysis. A third perspective, that conservation may be consistent with economic efficiency, is hampered by the difficulties of measuring the non-market benefits of conservation. This paper develops and illustrates a methodology for evaluating forest conservation projects, more specifically the contribution that the forest makes to the water balance between run-off and groundwater recharge.

Conservation efforts can in principle be evaluated according to the value of the environmental resources they save. These environmental resources include not only end-user products like recreational opportunities but also indirect ecosystem services such as soil quality or groundwater replenishment. The valuation of these resources is complicated by the lack of markets for the goods and services involved. This paper explores the possibility of using concrete microeconomic foundations to value indirect environmental (ecosystem) services that lack market prices, or are not part of a composite market good for which hedonic pricing models might be used. Groundwater resources dependent on forested watershed quality on the island of Oahu provide a concrete example.

No markets exist for the indirect service a forest provides by increasing groundwater recharge. Measurement techniques in cases where market goods, or, alternatively, composite goods where the environmental service may be hedonically isolated, do not exist have traditionally been forced to rely on direct methods such as contingent valuation. This paper argues that a less controversial method for valuing certain services may be possible through the use of benefit–cost project analysis where an indirect ecosystem service changes the net present value of a renewable resource.

In the case of a coastal aquifer, optimal groundwater values themselves will fluctuate with the aquifer head level, as demonstrated in Krulce, Roumasset, and Wilson (1997). The head level is a function of groundwater recharge, which is in turn a function of forest quality. One aspect of determining the full value of a conservation project regarding forest quality is therefore the indirect service of groundwater recharge. The value of changes in forest quality can thus be measured in part by the corresponding change in the net present value of the groundwater.

A further complication in the valuation of indirect ecosystem services is that there may be a missing or imperfect market for the good whose production is enhanced by the service in question. Calculation of the net present value of the groundwater should take into consideration the market imperfections associated with the water supply. Imperfect markets for groundwater resources tend to over-utilize and undervalue the

resource (Young and Havemann, 1985). Here, first-best shadow prices are determined in order to accommodate the market's shortcomings. Changes in forest quality from the status quo are describable as conservation projects. This is in effect a benefit–cost analysis of the value of a conservation project where the benefits are indirectly transmitted to the marketplace through natural rather than human processes and the first-best prices are unknown due to market imperfections.

Forested watersheds certainly provide more amenities than groundwater replenishment. For example, net estimates of tropical non-timber benefits range from $1 to $420 per hectare per year (Godoy and Bawa 1993). Forests have complex interrelationships with other types of natural capital. The value of ecosystem services derived from the soil, the ocean, and beaches are all related to the forests and how they are utilized and managed. Thus one must interpret the economic benefits of forests with an understanding of the roles and values of these associated types of natural capital. Nonetheless, the value of the forested watershed in replacing groundwater may be used as a basis for finding the lower bound of a proposed conservation project. The robustness of the results indicates that such conservation actions which reduce the probability of forest deterioration may have extremely high benefit–cost ratios.

The following section provides methodological background showing how the method introduced here relates to alternative valuation methods. In particular we show that even though there is no market for the ecological services of trees and that the market for water is highly distorted, it is not necessary to resort to contingent valuation. Rather the shadow price of water can be calculated from an optimizing model and the value of conservation based on the corresponding present value of the water saved. The subsequent section provides the optimizing model and illustrates the present value calculation using an example of a tropical watershed that supports the resource-dependent economy of Hawaii. The final section provides concluding remarks.

2. Methodology

Background

Methods for the valuation of environmental amenities may be categorized as direct or indirect methods. Contingent valuation, that is the use of survey methods to elicit preferences, is the primary example of a direct method. This approach has met with several severe criticisms, most of which stem from hypothetical underpinnings (Kolstad, 2000; Burness, Cummings, and Harrison 1991; Cummings, Brookshire, and Schulze 1986). The additional burden of measuring the value of an indirect scientific process such as groundwater recharge, that is not well understood by those partaking in the surveys, makes direct valuation methodology particularly unreasonable for indirect ecosystem services (Smith *et al.*, 1990). Indirect methods, which use hedonic pricing and its variants to link environmental resources with existing market goods, are therefore preferable but can only be used when a market good can be associated with the use of the environmental amenity. This limitation also challenges the ability to measure indirect ecosystem services.

Indirect ecosystem services may in some cases be valued by investigating a change in the stream of benefits from the final good produced through the ecosystem services (Barbier, 1994). In many cases, however, the indirect environmental service is contributing to the production of a good that is itself not properly priced in the marketplace. Examples of this include public goods and open access natural resources. The indirect services of a tropical forested watershed provide a concrete example of a service whose economic value is associated with an imperfectly priced market good with public good attributes. This paper describes and demonstrates a potential methodology for determining values for such cases.

Indirect ecosystem services provide economic value by supporting the production of a directly consumed set of public and/or private goods. Their role as natural capital in this production is often overlooked because no markets exist for their services. Nor are reproducible perfect-substitutes likely to be available; the replacement of the service generally requires an inferior substitute because the replacement only addresses one aspect of the ecosystem service. For example, in the absence of natural forest filtration to groundwater resources, water purification will clean drinking water, but it cannot easily address siltation of streams or reefs supporting valuable aquatic habitat.

In what follows, we show that economic values from these services may be measured marginally as the present value of their contributions to a final good. These marginal contributions should be determined by including in the valuation process an understanding of the scientific properties of the environmental service. This must be done in order to correctly understand and model the change in value that a change in amenity quality or quantity would spawn.

Determining the economic value

Indirect ecosystem services act as intermediate goods in the biophysical production of natural and environmental resources consumed by humans. The scientific process, or 'technology' that nature uses must be understood in order to assess the relative contributions of interdependent assets. The effect of changes in the status quo levels of the environmental service's input into the final good must be estimable, as must, in some cases, the probability that such changes will take place. The scientific process provides the description of what a conservation project would need to preserve: here, groundwater recharge is the intermediate good provided in various levels determined by the forest quality. We first consider the case in which the conservation retains the *status-quo* resource quality with certainty and the amount of resource degradation without conservation is known. We later suggest how this can be generalized to account for uncertainty.

A conservation project that retards depreciation of a watershed may be thought of as analogous to an irrigation project and its present value reckoned according to the appropriate shadow prices (small project assumption) of water in different time periods. But while irrigation-project evaluation is typically based on a specific water management plan, water policy (for example, pricing) for an economy would be difficult to know in

advance as are the interrelated management decisions associated with multiple water sources. Moreover, since it is impossible to know how a water resource will be distributed across time and across users, it is impossible to calculate second-best shadow prices, based as they are on the concept of a distorted competitive equilibrium.

First-best shadow prices, however, may be feasible to calculate and may be justified in two ways. First, they are approximations of second-best prices, since the latter are themselves weighted averages of marginal social benefits and costs, one of which is higher and one of which is lower than the first-best prices. Second, iterative application of first-best prices will tend to lessen discrepancies between first- and second-best shadow prices. In the case that follows, first-best present values are used as the basis of estimating conservation benefits. In this illustration, conservation is assumed to preserve the present water balance between recharge and runoff, and failing to conserve would result in a greater runoff and a lower recharge to the aquifer. This benefit is quantified by calculating the optimal withdrawal pattern from the aquifer with and without conservation. The benefit of conservation is then given by the change in present value between the two scenarios.

First-best shadow prices (efficiency prices) also provide the basis for full-income accounting and nature-sector accounts. Aside from distributional considerations maximizing full-income, reckoned at first-best prices, is equivalent to maximizing both economic welfare and sustainable income (Weitzman and Löfgren, 1997). Thus valuing ecological services facilitates full income accounting and nature-sector accounting, as well as providing a basis for assessing the benefits and costs of conservation and related projects.[2] While both the calculation for the basis of the conservation project and that for full income accounting require the use of first-best prices, the appropriate benchmark for the two calculations is different. In the case of the conservation project, the benchmark is the amount of ecological depreciation that would occur in the absence of the project. In the case of full income accounting, the benchmark is no ecological service at all. For example, the benchmark for groundwater-recharge enhancement of a forested watershed is the recharge that would occur with no forest cover. Unfortunately, that benchmark is not necessarily well defined. Recharge without the forest cover will depend on what replaces the forest. It is possible that a non-forest, albeit 'green' cover can substitute for the recharge-generating attributes of a forest. A 'brown' cover, for example following a fire, would have quite different properties, as would encroachment of urban development.

Modelling the recharge value of watershed maintenance
Coastal groundwater is a renewable and replaceable resource. With an alternative technology for production available through desalination, the framework for determining the optimal prices and quantities used over time is shown in equation (1). This optimization maximizes the social

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[2] For a discussion of full income accounting and nature sector accounts, see, for example, Grambsch, Michaels, and Peskin, 1993 and Kaiser, Krause, and Roumasset, 1999.

welfare derived from the use of the resource using a demand function for
the resource over time.

Choose quantities of groundwater and desalinated water consumed, q_t
and b_t, respectively, and forest maintenance expenditures m_t, to maximize

$$\int_0^\infty e^{-rt}\left[\int_0^{qt+bt} D_t^{-1}(x)dx - c(h_t)q_t - b_t\bar{p} - m\right]dt \tag{1}$$

subject to $\dot{h}_t = w(s_t,h_t)$ s.t. , $q_t \geq 0$, $b_t \geq 0$, with h_0 given, where h_t is the time
denoted stock of groundwater and $w(s_t,h_t)$ is the net recharge to the
aquifer.

Here $\int_0^{qt} D_t^{-1}(x)dx - c(h_t)q_t - b_t\bar{p}$ is the consumer surplus associated
with water consumption in time t, $c(h_t)$ is the cost of providing the resource
given the indirect service $s(\sum_t m_t)$, D_t^{-1} is the inverse demand function for
the natural resource, and $\bar{p}$ is a backstop price in the form of another source
for an equivalent good (desalination). Here, the aquifer head level, h is a
function of net recharge, $w(s_t, h_t)$, which is a function of forest stock and
aquifer head level respectively. The forest stock is a function of cumulative
maintenance expenditures, $\sum_t m_t$.

Note that s_t enters the objective function only through its role as a con-
tributor to net recharge; the value for the forest as a good with end-user
demand of its own is not part of this model. Maximization of a joint
demand function would be required to incorporate the other aspects of the
forest source. In that case, maintenance expenditures m_t, would generate
benefits beyond their effect on groundwater recharge. This illustrates the
need for full-income accounting; in order to optimally determine expendi-
tures on forest maintenance, all aspects of the resource must be included.
The appropriate current value Hamiltonian and necessary conditions for
an optimal solution can then be derived.

The current value Hamiltonian for this problem is

$$H = \int_0^{qt+bt} D_t^{-1}(x)dx - c(h_t)q_t - b_t\bar{p} - m + [w(s_t,h_t) - q_t]\lambda_t \text{ where } \lambda_t \geq 0$$

Following Kamien and Schwartz (sections 8 and 10), the necessary con-
ditions for an optimal solution are

$$\dot{h}_t = \frac{\partial H}{\partial \lambda_t} = w(s_t,h_t) - q_t \tag{2}$$

$$\dot{\lambda}_t = r\lambda_t - \frac{\partial H}{\partial h_t} = r\lambda_t + c'(h_t)q_t - \frac{\partial w}{\partial h_t}(s_t,h_t)\,\lambda_t \tag{3}$$

$$\frac{\partial H}{\partial q_t} = D_t^{-1}(q_t + b_t) - c(h_t) - \lambda_t \leq 0, \text{ if } < \text{ then } q_t = 0 \tag{4}$$

$$\frac{\partial H}{\partial b_t} = D_t^{-1}(q_t + b_t) - \bar{p} \leq 0, \text{ if } < \text{ then } b_t = 0 \tag{5}$$

$$\frac{\partial H}{\partial m_t} = -\frac{\partial w}{\partial s}\frac{\partial s}{\partial m}\lambda_t = 1 \tag{6}$$

Equation (2) gives the change in aquifer head level over time as a function of net recharge, $w(s_t, h_t)$, and withdrawal, q_t. The aquifer head level rises with increased recharge and falls with increased withdrawal rates.

Rearranging equation (3) yields

$$\lambda_t - \frac{\dfrac{\partial w}{\partial h_t}(s_t, h_t)}{r}\lambda_t = \frac{\dot{\lambda}_t}{r} - \frac{c'(h_t)q_t}{r}, \tag{7}$$

which can be interpreted as an extended Hotelling condition wherein the left- and right-hand sides are the marginal benefit and the marginal opportunity cost of extracting water respectively. The first term on the left-hand side is the direct marginal benefit of extracting water today, while the second term is the indirect marginal benefit ($\dfrac{\partial w}{\partial h_t}$ is negative) to net recharge from lowering the aquifer head level and thereby decreasing leakage from the aquifer. The first term of the right-hand side is the decrease in the present value of the aquifer from forgoing the potential capital gains associated with the next period's price increase. The second term is the present value foregone ($c'(h_t)$ is negative) as future extraction rates increase due to lower aquifer head levels. Alternatively, if (7) is rearranged such that the second term on the LHS appears on the right, then the RHS is the marginal user cost of water.

Equations (4)–(6) are the co-state equations describing the change in the current value Hamiltonian from the choice of extraction, q_t, desalination b_t, and forest maintenance expenditures, m_t.

The cost of a change in the production capability of the natural capital, here the contribution of forest quality to groundwater recharge, is measurable as a change in net social welfare as calculated above. The optimal resource allocations and prices are calculable for the current level of natural capital as well for future potential levels. The change in net social welfare between the scenarios serves as an estimate of the present value of the indirect environmental service. Any conservation project evaluation could determine a benefit–cost ratio for the contribution of the project to the final good by using this change in net social welfare to indicate the benefit (loss) of a conservation project (or lack thereof). This value may also be inserted into nature sector accounts or full income accounts whose purposes are to accurately reflect the values produced from natural capital ignored in traditional accounting methods.[3]

3. An illustration: the Ko'olau Watershed
Despite its relatively high per capital income. Hawaii has many characteristics of a developing country, including a high degree of economic dependence on natural resources. In our example, the interlinked natural

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[3] For a complete description of the optimal managament model used here, albeit without conservation expenditures and endogenous recharge, see Krulce, Roumasset, and Wilson, 1997.

resources are the Ko'olau Watershed and the Pearl Harbor Aquifer. The aquifer underlies much of Oahu, and the watershed on the leeward side of the Ko'olau mountains contributes significantly to the recharge of this aquifer. Current withdrawal rates are such that the State Water Commission estimates that all renewable island resources will be fully developed within 25 years. This means that any additional growth in water usage after this time will need to come from external sources such as desalination or depletion of aquifer levels.[4]

The Ko'olau mountain range runs roughly parallel to Oahu's southeastern shore, separating the island into its windward (rainy) and leeward sides. Over one hundred years ago, citing concerns that wild cattle would destroy the forests of the Ko'olau mountains, the State placed most of the mountain range into a conservation district [97,760 acres]. There are hundreds of inches of rain each year in some locations, and the general trend is for higher levels of rainfall along the crest of the range, declining with elevation. This conservation district accounts for virtually all the forested watershed that recharges the Pearl Harbor Aquifer.

Current estimates of the total recharge to the aquifer vary somewhat; this analysis uses a recharge level of 281 million gallons per day (mgd) (Mink, 1980). Based on Giambelluca (1983) and Shade and Nichols (1996) we assume that approximately 133 mgd, or about 45 per cent of the groundwater recharge to the Pearl Harbor Aquifer, comes from the Ko'olaus.[5] Estimated levels of recharge for the island make it apparent that the Ko'olaus are significant contributors to recharge. Maintaining high levels of recharge from the Ko'olaus will lessen the need for alternative water sources. The upland forest plays an important role in this maintenance.

Vegetation cover determines much of the process of groundwater recharge, and virtually all the mutable portion of the process. A healthy, multiple tiered forest will collect more raindrops through its leaves, protect the soil from erosion, and will keep the soil permeable through its roots system. Each of these services of the forest increases groundwater recharge levels. These are the services that a conservation project focused on the forest's contribution to groundwater must evaluate. Threats to these services exist in many forms: invasive alien plant species, urban development, logging, destructive mammals (for example pigs, goats, cattle), and fire.

Expenditures to reduce the probabilities of these events should be weighed against the contributions the *in-situ* vegetation cover makes to net

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[4] Roy Hardy, Water Commission, personal communication, 24 July 1998.

[5] From Giambelluca's research on the Ko'olau mountains, USGS researchers have estimated that for the leeward side of the mountain range, precipitation is divided very generally into approximately 45 per cent recharge, 40 per cent evapotranspiration, and 15 per cent runoff. Since these estimates may vary significantly, primarily with climatic zone, and there exists significant scientific uncertainty about the hydrological process in the Ko'olaus, including incomplete soil surveys, rainfall and hydro-geologial data, and evapotranspiration rates, these numbers should be interpreted as only a rough starting point.

social welfare. This is measured by estimating the lost value (replacement cost) accrued from a decline in environmental quality. This value also accounts for the market imperfections by calculating present values for the resource based on the first-best prices.

Valuation
Using the model presented above, we calculate the net present value of the Ko'olau forested watershed's contribution to groundwater recharge at $1.42 billion to $2.63 billion. The parameters used to reach these figures are presented here.

The demand function is modelled as a constant elasticity demand function that grows over time at a constant rate. The elasticity of demand used in our example is 0.3 and the growth rate of demand is 0.01, as chosen for Krulce, Roumasset, and Wilson (1997). The extraction cost, c, is a positive, decreasing, convex function of the head, h. The aquifer head level is not only depleted by extraction, but also through saltwater seepage, which increases as the weight of the fresh water in the aquifer decreases. Removal of groundwater should continue until a steady state is reached where the recharge from rainfall is equivalent to the withdrawal rate. At this point, surplus demand will be met through desalination, so the price of desalination will be the same as the true price of groundwater extraction.

It is assumed that the water from the aquifer can be substituted for with desalinated water at a wholesale price of $3.48 per thousand gallons,[6] which provides an upper limit to the price that can be charged for the water from the aquifer.

The above conditions set up the optimal control problem outlined above. From these results, we can calculate the net present value of the aquifer by discounting the sum of scarcity rents calculated for each time period. The discount rate is intended to measure the time preference for money across periods; considerable debate exists regarding the appropriate level of discounting (Tietenberg, 1996; Kahn, 1995). The lower the discount rate, the greater the value placed on future time periods. This analysis uses discount rates of 1 per cent and 3 per cent to provide a range of value that highlights the importance of intergenerational preference weighting.

The optimal price for groundwater from the Pearl Harbor Aquifer given the current forest quality level will rise over time reflecting the increasing demand for the resource and its increasing scarcity. This scarcity rent (*in situ* shadow price) can be seen for any given time period in figure 1 as the difference between the optimal price path and the extraction cost path.[7] (Figures 1 and 2 show costs and prices in dollars per gallon).

The present value of the groundwater resource is the discounted sum of the scarcity rent in each period times the optimal water consumption in that period. For the existing level of forest quality, optimal pricing would

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[6] Figure from Krulce, Roumasset, and Wilson (1997) was $3 per 1,000 gallons for 1991. $3.48 is inflation adjusted to 1997.
[7] Extraction costs are expected to increase with decreasing aquifer head levels.
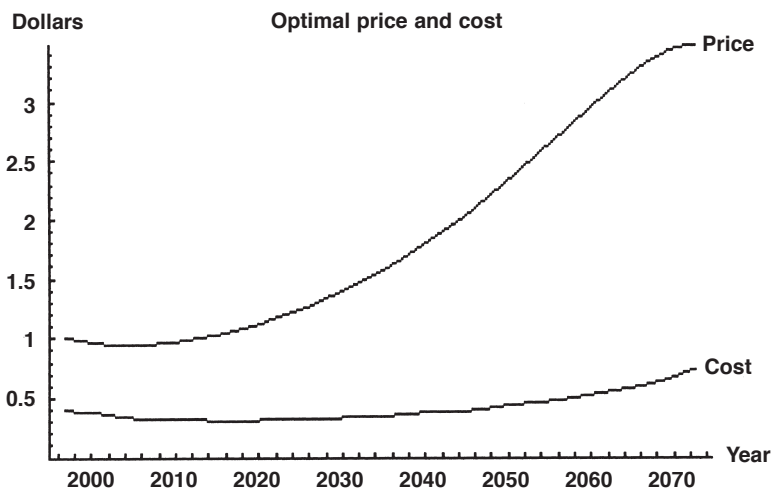
Dollars   **Optimal price and cost**

Figure 1. *Optimal price and cost for Pearl Harbor Aquifer groundwater, current forest quality*
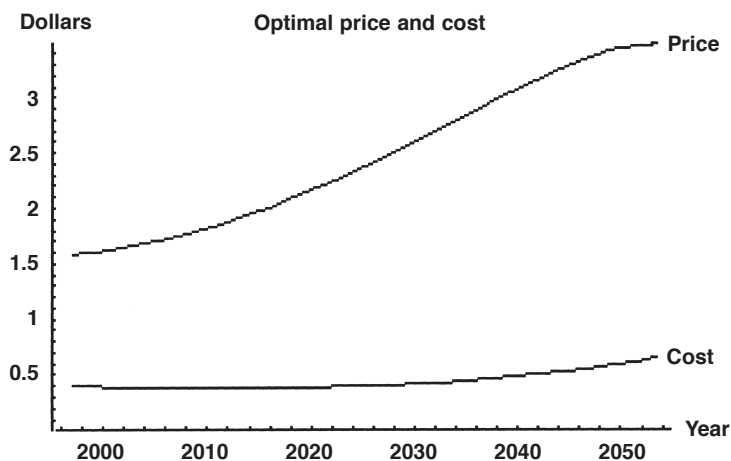
Dollars   **Optimal price and cost**

Figure 2. *Optimal price and cost for Pearl Harbor Aquifer Groundwater, Deteriorated Forest Quality*

delay the need for desalination until the year 2072, approximately 50 years after the Water Commission's estimate.

   To value the effect of a decline in forest quality, we consider a 31 per cent reduction in recharge from the Ko'olaus, that is, 41 mgd. Such a major disturbance could result from neglect of invasive and non-indigenous species of plants, animals, and insects, such as *Miconia calvescens*, feral pigs, and leaf hoppers respectively.

The results of this level of forest quality deterioration can be seen in figure 2. Notice that the area between the optimal price and the extraction cost is smaller, and that the switch to desalination must occur earlier, in 2057. Figures 1 and 2 trace the optimal price and cost for a representative gallon of water. To calculate the change in net present value between the two forest quality scenarios, we calculate the present value of the scarcity rent for the relevant qualities of water extracted across time. In the case of the higher forest quality, there are larger quantities of water than can be extracted for longer periods of time (given these conditions, an extra 25 years, from 2057 to 2072) before the island must meet new growth in demand from desalination, and the present value will accordingly be higher. The difference between the net present values for the two levels of forest quality is estimated at between $1.42 billion and $2.63 billion, corresponding respectively to a 3 per cent and 1 per cent social discount rate.

The potential seriousness of the impacts should not be underestimated. For example, *Miconia calvescens* is a rapidly growing, quickly spread tree that can produce dense, monotypic stands with shallow root systems. The tree stands have replaced 70 per cent of Tahiti's forests and are thought to promote landslides as well as reduce vegetation biomass (Meyer and Malet, 1997). It has already established a presence in Hawaii, and budget allocations for eradication of the incipient population have already exceeded $100,000 in recent years. In many cases, the cost of prevention of the establishment of such invasive species appears to be much lower than the cost of controlling these species once they become established (see Kaiser *et al.*, 1999). Developing nations accruing significant economic gains from indirect ecosystem services may benefit at considerably lower expenses through early detection and prevention mechanisms for invasive species than previously considered.

Conservation expenditures on management and control of these invasive species can be weighed against the benefits accrued from preserving the level of groundwater recharge to the aquifer. If destruction of the forest were imminent, one could estimate that the value of the lost recharge would be the full charge in net social welfare calculated above. Alternatively, one could approximate the present value to the aquifer by specifying a plausible time path of deterioration.[8]

A more general, albeit rather complicated approach, would involve specifying the net probability distribution of damages in various years. In some cases, however, even simple calculations may be quite compelling. Consider, for example, that $1 million dollars in conservation projects[9] might quantifiably reduce the existing probability of significant forest

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[8] It is important to note, however, that there are fundamental non-convexities in the costs of preventing the spread of 'alien species'. Once the populations of these invaders are large enough to cause considerable damage, it may be prohibitively expensive to control them.

[9] This is approximately the current level of expenditures on maintaining forested watersheds for the state of Hawaii. Source: Mike Buck, Director, Forestry Division of the Hawaii Department of Natural Resources. (Personal Communication, 31 July 1998)

destruction within the next ten years from 10 per cent to 5 per cent. The expected value of the case without the conservation project can be weighed against the expected value of the case with the project to determine the benefit–cost ratio for the project. The benefit–cost ratio in this case is above 50,[10] and does not include on the benefits side any of the direct services provided by the forest. Significant returns to maintenance of natural capital can therefore be expected even under more pessimistic scenarios.

For purposes of full-income accounting ('green' net national product), similar calculations can be made to reckon the additions to income provided by the watershed and the subtractions associated with the depreciation of natural capital. The former requires simply valuing the additional recharge being provided by the watershed (41 mgd in our illustrative case) at the current *in situ* shadow price of water as provided by the optimization model. Natural depreciation corresponding to a changed forest cover condition can be calculated as the loss in present value associated with the loss of the corresponding recharge. The present value of the additional recharge provided by the watershed is the present value of losing 100 per cent instead of 31 per cent of the Ko'olau-generated recharge, that is $4.6 billion. The sustainable income generated thereby is that amount of capital times the discount rate, for example 3 per cent of $4.6 billion or $138 million (Weitzman and Löfgren, 1997). Even without calculating the benefits of conservation, these figures suggest that there is much to gain by prudent stewardship of nature's bounty.

4. Concluding remarks

Conservation of tropical forests and other natural capital may be motivated by hard-nosed economic analysis after all. One of the difficulties associated with measuring the benefits provided by environmental resources is the indirect nature of some of their services. The description and illustration of capitalization with and without the indirect service in question can be widely applied. The example of the Ko'olau watershed illustrates that a small investment in conservation may protect a natural asset of rather enormous value.

Our findings required developing a mechanism for valuing an indirect ecosystem service through its contribution to another natural resource. The indirect benefits of conservation are modeled according to the increase in maximum present value of the recipient resource. Attempts to integrate the scientific relationships that interlink ecosystems and the natural resources humans consume from these ecosystems into the valuation process should be considered as viable and valuable approaches to measuring economic value for non-market environmental services.

We find significant returns to investment in the conservation of existing natural capital, with an example of a benefit–cost ratio exceeding 50:1 for a project that reduces the probability of significant forest destruction in the Ko'olau watershed from 10 per cent to 5 per cent over ten years. Such a return highlights two important findings. First, it serves as a concrete

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[10] Using the 3 per cent social discount rate. For the 1 per cent discount rate the benefit–cost ratio may be incrased to above 100.

example of the great returns that small amounts of conservation effort might generate due to the unrealized value of existing natural capital assets. Second, it demonstrates the great need for fuller national accounting systems, particularly in more resource-dependent developing communities that might otherwise forego such value-laden projects for the more immediately visible returns to leveling tropical forests to gain foreign exchange.

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