Valuing Coastal Natural Capital in a Bioeconomic Framework

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Abstract: The wetlands of the Gulf Coast region of the United States are under pressure from relative sea level rise and subsidence pressures that threaten to alter fishery breeding grounds and increase expected damage from stochastic storm events, among other issues. Barrier islands, marshes, and swamps are thus forms of natural capital that serve both an intermediate role in supporting fishery stocks, as well as a final demand role in providing direct protection to infrastructure. In order to make good policy choices related to land loss, the values associated with these interacting stocks must be estimated. We extend the numerical approach of Fenichel and Abbott (2014) to illustrate the valuation both fish and wetlands stocks, allowing for the recovery of both final demand and intermediate service values, taking into account the scarcity value of each resource. We also present examples of policies which, when implemented, will change the subsequent valuation of each resource.

JEL Codes: C6, D6, H41, Q2, Q3, Q57

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Introduction

Natural capital is a key input into human well-being. Environmental stocks, and the ecosystem services that they enable and provide, provide both direct benefits (and potentially costs) to consumers and producers and intermediate services that contribute to other forms of natural capital, which in turn may provide other direct and indirect benefits. Direct benefits have been termed “final ecosystem goods and services” or “ecological endpoints” in the literature, and are defined as entering directly into the net benefit function of firms and consumers (Ringold, et al., 2013; Boyd and Krupnick, 2013). Those goods and services that act as inputs into additional goods are derivatives valued through their relation with the underlying final goods or endpoints. Of course, many forms of natural capital may serve multiple roles. For example, the land and trees that form a national park may provide recreational benefits (an endpoint) and provide habitat for wildlife populations (with habitat as an input that supports valuable populations).

Along the Gulf Coast of the United States, barrier islands, marshes, and swamps (hereafter “wetlands”) are forms of natural capital that are viewed as both valuable and vulnerable. Louisiana alone contains forty percent of the nation’s wetlands, which provide direct benefits through storm protection and intermediate benefits to the fishing industry by providing breeding grounds for a large percentage of valuable species (Restore or Retreat, 2012; CPRA, 2013; Browder, et al., 1985; Chesney, et al. 2000). However, over 1,900 square miles of land has been lost since the 1930’s, with subsidence and relative sea level rise expected to further contribute to loss into the future (CPRA, 2013).

A key question for policy-makers in the face of this threat is the value of the lost wetlands, both now and into the future. Prudent public policy that affects wetlands and/or the associated fishery, storm protection, and other sources of value would take the benefits and costs associated with this form of natural capital into account. Furthermore, policies such as infrastructure hardening that change the relationship between natural capital and the benefits it provides will affect the valuation of the resource, altering the benefit-cost calculus of future potential policies.

This paper presents a method and model that can be used to consistently value a system of interacting natural capital stocks; namely, wetlands and a fishery. The fishery is assumed to provide final/endpoint benefits to the fishing industry using a variation on the common model of a renewable resource. Wetland stocks are assumed to provide final/endpoint benefits in the form of storm protection to coastal residents, as well as habitat-augmenting or diminishing intermediate services to the fishery. As such, wetlands can be considered a “dual ecological commodity”, using the terminology introduced by Boyd and Krupnick (2013).

The method, extended to a two-dimensional case from Fenichel and Abbott (2014), provides a means of estimating values for this interacting system of natural capital in a theoretically-consistent manner that does not depend on the assumption of optimal behavior (nor the solution to a dynamic programming problem). We show how the model can be used to provide insight
into the sources of value for the dual ecological commodity, the importance of capital gains and losses in estimating the value of a marginal unit of capital stock, and how estimates of both natural wealth and welfare gains/losses can be calculated. We also present two examples of how policy changes can affect both the valuation of the capital stocks and the net present value of following a particular behavioral rule over the course of the planning horizon.

Model and Assumptions

Consider an ecosystem with valuable commercial fish species represented by \( x(t) \), such that

\[
\dot{x} = G(x(t); k) - h(t),
\]

(1.1)

where \( G(x(t); k) \) is natural growth and \( h(t) \) is harvest. The parameter \( k \) is assumed to be carrying capacity (i.e., \( G(0; k) = G(k; k) = 0 \)), but this ecological parameter depends on the “edge” of the wetland, defined as the perimeter between land and open sea. The stock of wetlands is represented by state variable \( s(t) \), and evolves according to the equation

\[
\dot{s} = -c,
\]

(1.2)

where \( c > 0 \) represents (exogenous) land loss due to subsidence or relative sea level rise. In accordance with recent theory (e.g., Browder, et al., 1985; Chesney, et al. 2000), we assume that carrying capacity is related to wetland stocks such that \( k'(s) > 0 \) for some \( s_0 > s > \hat{s} \), and \( k'(s) < 0 \) for \( s < \hat{s} \).\(^1\) Coupled with (1.2), this implies that ecological capacity for natural fish production is first increasing with habitat fragmentation, then decreasing as wetland edge is eroded. This relationship provides the intermediate relationship from wetlands to the fishery.

Economically, we assume a time-autonomous instantaneous social welfare function \( W(x(t), s(t), h(x(t))) \), where the harvest rule \( h(x(t)) \) is the “economic program”, including all market imperfections and behavioral constraints, that describes harvest of fish at levels of each stock of fish (Fenichel and Abbott, 2014).\(^2\) This can be “optimal” in the sense of maximization of the net present value of welfare subject to the evolution of the stocks, or it may be any other suboptimal (time-autonomous) path. Consistent with (1.2), we assume that the human system has no effect on land loss, but wetlands can provide final/endpoint storm protection benefits in \( W(\cdot) \).

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\(^1\) This is consistent with the “marsh-edge” theory presented in Browder, et al. (1985). Chesney, et al. (2000) provide a discussion of other potential changes in Gulf fishery habitat. For the purposes of this article, it is sufficient that the state variable representing wetlands affects the evolution of the fish stock in some manner in order for the wetlands to have intermediate ecosystem service value. The nature of this relationship determines the specific translation of physical processes to value.

\(^2\) In theory, there is no difficulty in the economic program depending on both state variables. However, in the absence of any empirical information about the fishing industry’s response to land loss, we maintain the specification that the industry responds to fish stock levels alone.
The objective is to estimate the (marginal) value of natural capital $x$ and $s$.\(^3\) These values, denoted $p_x(x,s)$ and $p_s(x,s)$, are the “accounting prices” that would be assigned to each unit of fish and wetland resource assuming management according to $h(x)$, values represented by $W(x,s,h(x))$, and ecosystems represented by the state transitions (1.1) and (1.2) (Dasgupta and Maler, 2000). The total value of natural capital, or “genuine wealth” (Dagupta, 2001; Arrow, et al., 2012), associated with a given state of the ecosystem is then $GW(x,s) = p_x(x,s)x + p_s(x,s)s$. Management that decreases this value over time does not meet a weak sustainability criterion within this ecosystem (Arrow, et al., 2003; Woodward and Bishop, 2003; Bond and Farzin, 2008).\(^4\)

Following Fenichel and Abbott (2014), the value of following the pre-defined, closed-loop harvest rule at time $t$ (and in period $t$ dollars) is

$$V(x(t), s(t)) = \int_{t}^{\infty} e^{-\delta(t-\tau)}W(x(\tau), s(\tau), h(x(\tau))) d\tau,$$

where $\delta > 0$ is the social rate of discount. Given this formulation, the marginal values, or accounting prices, of fish and wetland are given by $p_x(x,s) = \frac{\partial V(x,s)}{\partial x}$ and $p_s(x,s) = \frac{\partial V(x,s)}{\partial s}$, respectively. Differentiating (1.3) with respect to $t$ and solving for $V(x,s)$ yields

$$V(x,s) = \frac{W(x,s,h(x)) + p_x(x,s)\dot{x} + p_s(x,s)\dot{s}}{\delta}.\quad (1.4)$$

Equation (1.4) states that the value of being at states $(x,s)$ is equal to the net present value of instantaneous benefits plus the value of the change in each capital stock (i.e., the value of the investment in the natural capital stocks of fish and wetland).

Differentiation of (1.4) with respect to each stock results in the following set of equations:\(^5\)

$$p_x(x,s) = \frac{\partial W(x,s,h(x))}{\partial x} + \frac{\partial p_x(x,s)}{\partial x}\dot{x} + p_s(x,s)\frac{\partial \dot{x}}{\partial x} + \frac{\partial p_s(x,s)}{\partial x}\dot{s} + p_s(x,s)\frac{\partial \dot{s}}{\partial x}$$

\(^3\) We subsequently suppress the dependence of each state variable on $t$ when doing so does not cause undue confusion.

\(^4\) This is not to say that the larger regional economic system would necessarily be unsustainable if the gain in wealth from other natural and/or man-made capital stocks outstripped the decline in value of this subsystem.

\(^5\) As in Fenichel and Abbott (2014), the derivative of the instantaneous welfare function with respect to either state variable includes both the direct effect and indirect effect through the harvest function.
Note that \( \dot{p}_s(x,s) = \frac{\partial p_s(x,s)}{\partial x} \dot{x} + \frac{\partial p_s(x,s)}{\partial s} \dot{s} \) and \( \dot{\bar{p}}_s(x,s) = \frac{\partial p_s(x,s)}{\partial x} \dot{x} + \frac{\partial p_s(x,s)}{\partial s} \dot{\bar{s}} \), and via symmetry of the second derivative of the value function, \( \frac{\partial p_s(x,s)}{\partial x} = \frac{\partial p_s(x,s)}{\partial s} \). For the assumptions made herein, 

\[
\frac{\partial \bar{s}}{\partial x} = \frac{\partial \bar{s}}{\partial s} = 0 \text{ and } \dot{s} = -c,
\]

leading to

\[
p_s(x,s) = \left[ \delta - \left( G'(x;k(s)) - \frac{\partial h(x,s)}{\partial x} \right) \right]^{-1} \left[ \frac{\partial W(x,s,h(x))}{\partial x} + \dot{p}_s(x,s) \right] \\
\bar{p}_s(x,s) = \delta^{-1} \left[ \frac{\partial W(x,s,h(x))}{\partial s} + \dot{\bar{p}}_s(x,s) + p_s(x,s) \left( \frac{\partial G(x;k(s))}{\partial k} k'(s) - \frac{\partial h(x,s)}{\partial s} \right) \right] \\
\tag{1.5}
\]

The first equation shows that the marginal value of a fish in situ is equal to the net present value of the marginal annual net benefit from that fish plus any capital gains, \( \dot{p}_s(x,s) \), over an infinite horizon, using a discount rate adjusted for the effect of that fish on net marginal growth of the fish stock. The second equation shows a similar measure for wetlands, though the flow value is augmented by the value of the effect of an extra unit of wetland on net fish growth. Thus, the value of the wetland is a function of the value of the capital stock of fish. The discount rate used is not adjusted because wetland evolution is independent of the stock of total wetland area.

Fenichel and Abbott (2014) show\(^6\) that by parameterizing \( \dot{p}_s(x,s) \approx \mu_s(x,s; \beta_s) \), where \( \beta_s \) is a vector of parameters to be estimated and \( \mu_s(\cdot) \) is a member of a polynomial family, and taking the derivative of (1.5) with respect to time, a system of estimating equations can be used to identify the parameters and approximate the terms related to capital gains of each stock. All other functions in (1.5) should be available via other ecological or economic studies. A similar result could be derived by approximating the shadow price function itself, and using the derivative of the approximation to develop the estimating equation. As such, the accounting prices of each stock can be identified.\(^7\)

**Assumptions**

We assume the same basic parameterization for the fishery as in Fenichel and Abbott (2014), who calibrated their logistic-growth fishery model based on estimates of the Gulf reef fishery

\(^6\) The authors show the derivation for one state variable.

\(^7\) Numerical simulation could also be used to identify the appropriate accounting prices by approximating the value function using numerical dynamic programming.
estimates of Zhang and Smith (2011) and Zhang (2011) (see Appendix A). As such, this implies that commercial fishermen are not responsive, on average, to the effects of habitat edge loss on fishing effort, but do respond to changes in fish populations (i.e., $\frac{\partial h(x,s)}{\partial s} = 0$). This assumption could be easily relaxed.

To link land loss and the fishery, we assume a particular functional form for the relationship between carrying capacity and wetland based loosely on the relationship hypothesized in Browder, et al. (1985). Absent any additional information, we assume that the maximum carrying capacity is 20% greater than that estimated in Zhang and Smith (2011), and that the carrying capacity for fully intact wetland and fully lost wetland is 80% of current capacity. As such, we assume $k(s) = 287.2 \cdot 10^6 + 574.4 \cdot 10^5 s(1-s), \ 0 \leq s \leq 1$, with an implied current state of approximately $s(0) \approx .854$. Carrying capacity is thus increasing in land loss until the wetland state equals 0.5, and decreasing thereafter.

Finally, we assume $c = .01$ in (1.2), implying that from current wetland habitat state, complete land loss will occur in just over 85 years. We also assume a discount rate of 2%.

Methodologically, we use a two-dimensional Chebychev polynomial specification with 9 basis functions (plus intercept) in each of the state variables to approximate the price functions (Judd, 1998). The equations in (1.5) were evaluated at 50 Chebychev approximation nodes in each dimension, and the 100 coefficients were identified by minimizing the sum of squared errors on each equation, using the recursive formula for the derivative of the Chebychev polynomial with respect to each stock. Estimation of the wetland price function used the estimated price function associated with the fisheries stock. As polynomial approximation requires a closed and bounded state space, the bounds on the fishery stock were [60, 120] in millions of pounds of fish. This range allows for both positive and negative growth over assumed range of fish stocks at each level of the wetland stock. Bounds on the wetland stock were assumed to be [0.1, 0.9], where $s = 0$ representing complete conversion to open water and $s = 1$ representing an unfractured wetland area with minimum edge habitat. As such, $(1 - s)$ provides the proportional land loss from this unfractured state.

Maximum/minimum errors associated with price of the fish stock at were less than $10^{-6}$ (measured in dollars), while maximum/minimum errors associated with the price of the wetland stock were of the magnitude of $10^{-3}$ (measured in millions of dollars). Estimation was performed using Microsoft EXCEL’s standard non-linear solver.

**Wetland Value as an Intermediate Input**

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8 This is in keeping with the empirical observation that land loss has not severely depleted fish stocks, and, in fact, there is some evidence that they have increased slightly over time (Browder, et al., 1985; Chesney, et al. 2000).
We begin the results section by first assuming that the value of wetlands is derived only through its relationship to the fish stock, such that \( \frac{\partial W(x,s,h(x,s))}{\partial s} = 0 \). In this case, wetland is solely an intermediate input into the production of (marketable) fish, rather than a “dual” ecosystem good that directly enters the instantaneous utility function (Boyd and Krupnick, 2013). This assumption will be relaxed in later subsections.

**Accounting Price of Fish Stocks**

As seen in the first equation of (1.5) and in Figure 1, the value of fish stocks in situ depends not only on the fish population, but also the habitat conditions determined by the level of land loss. With approximately 85% of original wetland remaining intact, the accounting price of a fish at the steady state level (approximately 86 million pounds) is just over $3.15 per fish, or a total capitalized value (defined by \( p_s(x,s) \cdot s \)) of near $271 million. As in the single stock case presented in Fenichel and Abbott (2014), the marginal value is declining with increased abundance; the accounting price drops to just over $2.76 at a population of 120 million pounds.

As land loss increases, however, the marginal fish at a stock level of 86 million pounds\(^9\) first becomes more valuable due to the potential for a greater contribution to growth given the increased edge habitat. Given the nature of the land loss, this value is not maximized at 50% land lost, but rather prior to this point (around 46%), as the decrease in habitat due to shrinking edge causes depreciation of the values. Thereafter, the marginal value begins to decline at an increasing rate, with the land loss effect resulting in a lower accounting price at 90% land loss than at 10%. The total drop from the maximum level to the value at 90% land loss for the same sized stock is about $0.37, or about 10.6% of maximum value. At these levels, the effects of land loss can decrease the capitalized value of the 86 million pound fish stock by $31.4 million.

<Insert Figure 1 here>

**Accounting Price of Wetland Stock**

As can be seen in (1.5) with our imposed assumptions, the marginal value of wetland depends on two major terms, both placed into net present value terms via dividing by the discount rate. The first term, \( p_s(x,s) = \frac{\partial p_s(x,s)}{\partial x} \dot{x} + \frac{\partial p_s(x,s)}{\partial s} \dot{s} \), represents the capital gains (or losses) in the value of wetland, and depends on both fish and wetland stocks, as well as their evolution. It represents the pure scarcity value associated with this stock. The second term, \( p_s(x,s) \left( \frac{\partial G(x;k(s))}{\partial k} k'(s) \right) \), represents the value of the increment to growth of fish (through carrying capacity), or the value

\(^9\) Note that given the estimated economic program, the stock would not be expected to remain constant as marshland is eroded, as the dynamics of the problem would cause stocks to first increase and then decrease as the carrying capacity changes.
of the habitat change, given a marginal change in wetland contiguity. The sign of this term depends on $k'(s)$, which can be positive or negative depending on the level of land loss.

If there was no land loss and a constant stock of fish (i.e., $\dot{s} = \dot{x} = 0$), then the sign of $k'(s)$ would completely determine the marginal value of wetlands in the ecosystem. On the other hand, if land loss is very rapid, then the value of the marginal unit of wetland stock will be high, as that marginal unit provides augmented fishery production capacity relative to, say, a completely fractured landscape. For more modest land loss rates, the possibility exists that wetlands that are mostly intact are negatively valued, as the short-term losses from a decrease in carrying capacity given even less edge habitat (the second term) dominate the longer-term (discounted) benefits associated with the increasing, then decreasing carrying capacities (the capital gains term). Note that in order for the wetland to suffer capital losses at any moment in time, $\frac{\partial p_x}{\partial x} \dot{x} + \frac{\partial p_x}{\partial s} \dot{s}$ must be negative, which suggests that at a steady-state fish stock level, $\frac{\partial p_x}{\partial s} > 0$.

At a rate of $c = 0.01$, however, the marginal value of wetland will always be positive. As such, the (positive) capital gains term must dominate the value of the habitat change when $k'(s) < 0$, and thus will constitute the majority of the value of the wetland. Figure 2 shows this relationship for an 86 million pound stock.

The exponentially increasing nature of the capital gains term is a Hotelling-like result driven by the non-renewable nature of the land loss process.\(^{10}\) This term is adjusted by the value of the habitat increment, which is positive only for land loss levels greater than 50% (where additional wetland would add edge habitat). This result complements the findings in Fenichel and Abbott (2014) that ignoring capital gains in any valuation exercise could severely bias the estimate. In this case, ignoring capital gains would result in a negative valuation of wetland for losses below 50 percent, ignoring the effect that extra land has on the time dimension of the problem (namely, that any increase in wetland will still ultimately lead to increased habitat in the future given the equation of motion).

Figure 3 uses these terms, in conjunction with the discount rate, to show the capitalized value of wetland at varying levels of fish and land loss levels.

As seen in panel a), for higher land loss levels, the value of wetland is increasing in fish stocks, while for lower levels, the value is decreasing in total biomass. The intuition for the latter is that

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\(^{10}\) The reader is cautioned that Hotelling’s Rule assumes optimizing behavior, while no such assumption is made here.
when wetland is relatively abundant, the increase in capital gains from an increase in fish stocks, 
\( \frac{\partial \hat{p}_s(x,s)}{\partial x} \), is less (in absolute value) than the decrease in the (negative) value of the habitat change, 
\( \frac{\partial}{\partial x} \left[ p_s(x,s) \left( \frac{\partial G(x,k(s))}{\partial k} k'(s) \right) \right] \). This relationship is reversed for higher levels of land loss, as the scarcity value of wetland is more responsive to changes in fish stock levels.

Panel b) shows that the capitalized value of wetland is first increasing and then decreasing as land is lost, despite its exponentially-increasing marginal value. Total land values range from just under $3 billion for largely intact wetland habitat, rising to just over $4 billion at land loss levels of 50%, and falling to under $2 billion as land loss reaches the 90% threshold. As suggested by the analysis of capital gains and the value of habitat change, total land values are thus much more sensitive to land loss than they are to fish stocks, despite deriving all of their value in this example from marketable fishery biomass.

**Total Capitalized Value of Ecosystem**

Figure 4 shows the total capitalized value, or genuine wealth, of the ecosystem (i.e., of the fish and wetland stocks) by land loss for three stocks of fish. Given the magnitude of the relative values of wetland and fish stocks, the total ecosystem value tends to be driven by wetland, with greater discrepancies in total ecosystem value across stock levels near maximum carrying capacity. Given the assumptions made here, incremental land loss is thus weakly sustainable up to a point, but the process as a whole, of course, is not.

<Insert Figure 4 here>

**Wetland Value as a Final Ecosystem Good or Ecological Endpoint**

In this section, we present results assuming that wetlands are directly valued in \( W(\cdot) \), rather than serve as an intermediate input into another ecosystem process. More specifically, barrier islands and wetlands serve as barriers against wind and storm surge from large storms such as hurricanes, providing valuable protection services. For example, Fischbach, et al. (2011) estimate that expected annual storm surge flood damage for the Louisiana coast in 2012 was approximately $2 billion (in 2010 dollars), but that could increase by 100 to 200 percent in 25 years and by 250 to 1000 percent (up to $20 billion per year) in a “future without action” due to uncertain land loss and subsidence processes.

We assume that land loss is not controllable and that the benefits from storm protection are represented by the function \( U(s) \). Focusing solely on storm protection benefits, (1.4) becomes

\[
V(s) = \frac{U(s) + p_s(s) \delta}{\delta},
\]

with differentiation resulting in 
\( p_s(s) = \left( U_s(s) + \hat{p}_s(s) \right) / \delta \). The marginal
value of capital stock due to storm protection, $p_s(s)$, can be estimated using the orthogonal polynomial approach described earlier.

For illustrative purposes, we assume that current expected annual storm protection benefits (at $s \approx 0.85$) are approximately twice the annual net profit from the fishery, so that $U(0.85) \approx $50 million. Roughly mimicking the results of Fishbach, et al., (2012), we parameterize the benefits from storm protection as $U(s) = a^{s} - 1$, with $a = 5.6$ and $\gamma = 2.7$ (measured in millions of dollars). The benefits of storm protection are measured in dollars relative to the storm protection level associated with a complete conversion of wetland to open water, such that $U(0) = 0$.

Figure 5 shows the contribution of the marginal benefits of storm protection and capital gains at each land loss level. Figure 6 shows the total capitalized value of remaining wetlands from storm protection services.

Figure 5 shows that once again, capital gains are a significant portion of the overall marginal value of wetland. When the wetland is relatively unfractured, providing significant protection benefits on an annual basis, capital losses cause the accounting price of wetland (the sum of the two curves) to decline as loss proceeds. This occurs when the change in the marginal value of storm protection is positive, or $\frac{\partial p_s}{\partial s} > 0$. In other words, the value function is convex with respect to the wetland stock over this region of the state space, suggesting that the net present value of fractured habit is quickly declining with fragmentation. Ultimately, however, the decline in the marginal benefits of protection causes the overall marginal value of wetland to rise.

Figure 6 shows that the total capitalized value of existing wetland for storm protection is steadily declining, though the rate of change is greatest at small (due to large instantaneous marginal benefits from protection) and large (due to large capital gains and small marginal instantaneous benefits) levels of overall land loss.

**Wetlands as a Dual Ecosystem Good**

In this section, we relax the assumption that wetlands serve only as an intermediate input or a final ecosystem good/ecological endpoint, and combine both values into a complete dual ecosystem service model that includes both derived fishery values and storm protection benefits (Boyd and Krupnick, 2013). Specifically, instantaneous benefits are now defined as $W(x, s, h(x)) + U(s)$, while the equations of motion are unchanged.

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11 Given the additive separability in the two sources of value and the structure of the ecosystem models, summing the values is identical to incorporating both into the model.
We first discuss capitalized values of the existing stock, which is identical to the manner in which the national income and product accounts value man-made capital (or net national product is calculated). We then discuss the welfare effects of stock changes, which is the appropriate measure to use when performing benefit-cost analysis.

**Capitalized Value of the Dual Wetland Stock**

Figure 7 shows the total marginal value, or accounting price, of wetland including both ecosystem service benefits. We denote this value as $P(x, s)$.

<Insert Figure 7 here>

Overall, the marginal value of wetland is increasing as the land loss process proceeds, largely due to the pure scarcity effects represented by capital gains. At 15 percent land loss, the marginal value of wetland is approximately $12.5$ billion, meaning that the benefits of increasing wetland by 1 percent (a marginal increase in the land stock) are approximately $125$ million. As wetland becomes more scarce, however, the willingness to pay for a marginal unit of land increases.

These marginal values can be used to estimate the capitalization value of wetland at various stock sizes, akin to the treatment of capital assets in national product accounts. Figure 8 shows the total land value at various levels of land loss for an 86 million pound stock of fish.

<Insert Figure 8 here>

Figure 8 shows that the loss in capitalized wetland value from 10% to 90% land loss is approximately $7.2$ billion, taking into account the biophysical processes that drive both sources of value. The importance of the capital gains term can be seen through calculation of the loss in wealth using accounting prices at 10% and 90% land loss. In the former, the wealth lost would be overestimated by 39.2% by undervaluing the remaining land. In the latter case, the loss would be overstated by 352.7% via vastly overvaluing the initial wetland.12

**Welfare Effects of a Change in Dual Wetland Stock**

While the capitalized value calculation is consistent with the treatment of man-made capital in the national income and product accounts and in wealth accounting, it is not appropriate for valuing the benefits of policies which augment or decrease capital stock levels. Capitalized value is calculated as $P(x, s)$, which assumes that each unit of stock is valued at $P(x, s)$. The resulting value can be interpreted as the value of a capital stock as sold on a hypothetical “open market” with equilibrium price at $P_s(x, s)$.

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12 This conclusion stems from the fact that prices at 10% land loss are less than prices at 90%. In the opposite case (for, e.g., differing ecosystems), the sign of the difference would be reversed.
However, this does not account for the total benefit, or willingness to pay, for each unit of wetland, which we have seen is increasing as the stock gets more scarce. Instead, the appropriate value to use for this purpose (assuming a fixed level of fish stock) is

\[ TB(\bar{x}, a, b) = \int_{a}^{b} P_{s}(\bar{x}, s) ds, \]  

(1.6)

where \( a \) and \( b \) are some interval of land lost or gained.\(^{13}\) Because \( P_{s}(\bar{x}, s) = \frac{\partial V(\bar{x}, s)}{\partial s} \), the welfare gain is \( TB(\bar{x}, a, b) = V(\bar{x}, b) - V(\bar{x}, a) \), which can be calculated using (1.4) as

\[
TB(\bar{x}, a, b) = \frac{1}{\delta} \left[ \left( W(\bar{x}, b, h(\bar{x}, b)) - W(\bar{x}, a, h(\bar{x}, a)) \right) + \left( p_{s}(\bar{x}, b) \dot{x}(\bar{x}, b) - p_{s}(\bar{x}, a) \dot{x}(\bar{x}, a) \right) \right. \\
\left. + \left( P_{s}(\bar{x}, b) \dot{s}(\bar{x}, b) - P_{s}(\bar{x}, a) \dot{s}(\bar{x}, a) \right) \right].
\]  

(1.7)

Using (1.7) to calculate the welfare gains of moving from 90 percent to 10 percent land loss, the total gain for a fish stock of 86 million pounds is $17.2 billion, which is greater than the calculation of the loss of natural wealth at appropriate prices, but lies in between the valuation given by \( P_{s}(\bar{x}, b) b - P_{s}(\bar{x}, a) a \).\(^{14}\) Thus, any restoration project with a net present value cost of less than this figure (and that would keep fish stocks constant) would be welfare-improving.

**Value of Environmental Policy**

The shadow prices of natural capital stocks, and the resulting demand schedules (as a function of capital stocks), can both inform policy decisions and be affected by them. In this section, we examine the potential effects of implementation of two hypothetical policies on accounting prices and welfare: one that hardens infrastructure, thus changing the relative benefits of storm protection services of the land, and one that slows the rate of land loss by half.

**Hardening Infrastructure**

If the infrastructure at-risk in this scenario were to be protected from expected future damages, at least in part, then this change would directly affect the instantaneous benefits obtained from the wetlands, and thus the marginal value of them. Of course, such an action would also result in a differential in the net present value of managing the system according to the assumed behavioral rules, and thus the willingness to pay for additional wetlands capital.

\(^{13}\) The interpretation here is that \( TB(\bar{x}, a, b) \) is the maximum amount of welfare (as measured by the instantaneous benefit function) that could be sacrificed in moving from \( s = a \) to \( s = b \) instantaneously (i.e., without a change in fish stocks) without being worse off. A relaxation of the fixed fish stock is straightforward.

\(^{14}\) In other words, demand slopes down. Just seeing if you were paying attention 😊.
In essence, the hardening of infrastructure (at some cost) introduces a substitute for the storm protection services previously supplied by wetlands. In the most extreme (hypothetical) case, the substitution is perfect, and the instantaneous benefits derived from wetlands for storm protection are driven to zero. The value of wetlands would then be as shown in Figure 3b, derived solely as an intermediate ecosystem good that supports fisheries.

A more realistic scenario is one in which some damage is avoided through the hardening, but a portion of the benefits of storm protection services from wetlands remains. For example, in Fishbach, et al. (2012), the reduction in expected annual damage (depending on the scenario) due to implementation of the 2014 Louisiana Master Plan is expected to decrease by 38-44% in 25 years, and by 62-77% in fifty years. In the bioeconomic model, this can be modeled by changing function that describes instantaneous benefits, $U(s)$. Specifically, to more or less match this pattern, we model a scenario in which $U(s) = 15s$.

Given the linearity of the storm damage benefits function, the accounting price associated with this benefit is a constant $750 million (15/0.02), with no capital gains or losses across the wetland space. Figure 9 shows the resultant value of capital stock (akin to Figure 8) with the new storm damage values.

This example shows not only that policies can affect accounting prices of natural capital, but also that the shape of the marginal instantaneous benefits function helps determine any capital gains or losses accrued across the planning horizon.

*Slowing Land Loss by Half*

Policies which slow the rate of land loss (perhaps through diversions designed to transport sediments and build land in desirable areas) directly affect (1.2), which subsequently affects the capital gains/losses for both the fish stock and the land stock, changing the marginal value of an additional unit of wetlands stock at each point in the state space. Because of the effective lengthening of the time horizon before all wetlands are lost (and thus an ability to benefit from both storm protection and fisheries over a longer time period), the overall value of the marginal unit of wetland fracturing is lower than in the more rapid loss case. This manifests itself in the capital gains terms for wetlands (and to a lesser extent, that of the accounting price of fish stocks), which also affects the shape of this term.

Figure 10 shows the difference in overall capitalized value for marshland for a fishery stock of 86 million pounds.
While the overall capitalized value of wetlands is still decreasing with land loss given the (assumed instantaneous) policy change, the slowdown of the land loss process decreases and flattens the capital gains terms. This causes a more pronounced U-shaped price curve for storm protection, as capital losses at low levels of loss pull down marginal values, and more of a downward shift in the value associated with fisheries (not shown). The result is less variation in total capitalized values after the policy, with an accounting price function that drops off more rapidly during early stages of the land loss process, but that is relatively flatter when wetlands are highly fractured. Ultimately, accounting prices are identical when \( s = 0 \).

The fact that the accounting price for wetlands at each state is lower with slower rates of land loss does not necessarily mean that the policy decreases overall welfare; in fact, the opposite is true. For example, from a starting point of 15% land loss and 86 million pounds of fish, the total reduction in the capitalized value of the (identical) fish and land stock levels is nearly $5.9 billion, while the net present value of the benefit gain from the policy is nearly $4.9 billion. At the other end of the spectrum, the gain from the policy the same stock of fish at a land loss of 85% is larger by almost factor of 4, at $16.2 billion, but the reduction in the capitalized value of the stock is $4 billion.\(^{15}\)

Conclusions

Whether the objective is to calculate the value of the existing capital stock (natural wealth) as in the national income and product accounts or to estimate the total benefits of a change in the underlying natural capital stock, the bioeconomic-based methodology provides the means of estimating values of capital stocks related to both final demand of ecosystem services/ecological endpoints and intermediate services, and does so in a theoretically-rigorous manner that appropriately accounts for scarcity values through capital gains/losses in a dynamic setting. This can be done without solving a dynamic programming problem, but does require information on the (expected) biophysical processes, the response of the human system to changes in natural capital stocks, and the instantaneous flows of benefits and costs from final ecosystem goods and services.

As documented herein and in Fenichel and Abbott (2014), decision-makers should be aware that capital gains (and losses) may play a major role in the total valuation of an underlying environmental asset, and that ignoring these values when marginal benefits and costs change with the level of the capital stock can lead to poor decisions regarding natural resource management. Furthermore, policies that alter the instantaneous net benefits from final ecological goods/ecological endpoints, the biophysical processes that control the evolution of the natural capital stock, and/or the overall rate of discount will feed back into the valuation, implying that values post-policy may be significantly different than those used to evaluate the policy on an ex

\(^{15}\) Note that these values can be obtained by converting the value of the Hamiltonian (the numerator in (1.4)) at these stock levels for each parameterization to an annuity by diving by the discount rate (Fenichel and Abbott, 2014).
ante basis. This suggests caution in implementing sequential policy decisions, especially when relying on static data collected at a particular point in time and under particular conditions.

There are several implications for future research. First, although not explicitly modeled here, non-market values could easily be incorporated into the framework via the instantaneous net benefits function. However, the framework suggests several points to keep in mind in order to effectively integrate the two methods. First, non-market valuation researchers should pay particular attention to how willingness to pay changes as stocks of interest change; if these values are assumed constant when in reality they are not, scarcity values will not accurately be reflected in the accounting prices of the resources, and stocks might end up being undervalued as a result. Second, when mathematical or empirical models of ecosystems are available, researchers can focus on the final demand/endpoint ecosystem goods, and rely on the bioeconomic framework to recover values related to intermediate services. This should eliminate the cognitive burden on stated preference respondents to quickly process and understand complex ecological process, and lead to more precise valuation results.

Second, the method illustrated here relies strongly on understanding at least the basics of the dynamic relationships within an ecosystem, in addition to the state-dependent flow of ecosystem benefits and costs from the natural to the human system. In many cases, such as the example presented here, these relationships may be fairly straightforward, and the computational burden relatively low. However, in other cases, quantified relationships may not be readily available or estimable. In such cases, it may be worthwhile to qualitatively posit the likely signs of the first, second, and cross-derivatives of the instantaneous benefits function and state transition equations with respect to each stock, and perform sensitivity analyses to identify the parameters that most influence the results. Furthermore, very complex ecosystems are likely subject to a great deal of parametric uncertainty, and similar sensitivity results could be derived. Advances in function approximation techniques could also be explored in order to efficiently handle ecosystems of increased dimension.

Finally, practitioners should be aware that the valuation results depend on the assumed reactions of the human system to changes in the state variables, and that current actions in one part of the (observable) state space under consideration may not generalize to other portions of that space. In other words, while the valuation methodology developed by Fenichel and Abbott (2014) does not require and assumption of rationality or optimizing behavior, it is subject to bias when fixed behavioral rules are extended to situations in which responses to changes in natural capital stocks differ.
References


Figure 1. Marginal Value of Selected Fish Stock In Situ by Land Loss Percentage

![Figure 1](image1.png)

Figure 2. Instantaneous Capital Gains and Value of Habitat Change, 86 million lb. stock ($ mil)

![Figure 2](image2.png)
Figure 3. Capitalized Value of Wetland at Varying Fish Stock and Land Loss Levels

Panel a).

Panel b).
Figure 4. Total Value (Genuine Wealth) of Wetland/Fishery Ecosystem by Land Loss Percentage ($ mil)
Figure 5. Marginal Benefits of Storm Protection from Wetlands and Capital Gains

Figure 6. Total Capitalized Value of Wetlands for Storm Protection ($ mil)
Figure 7. Total Marginal Value (Accounting Price) of Wetland Providing Fisheries and Storm Protection Services by Land Loss at Fishery Stock of 86 million ($ mil)

Figure 8. Total Wetland Capitalization Value at Various Land Loss Levels, 86 million pound Fish Stock ($ mil)
Figure 9. Total Wetland Capitalization Value at Various Land Loss Levels, 86 million pound Fish Stock and Reduced Benefits of Storm Protection ($ mil)

![Graph showing total wetland capitalization value at various land loss levels.]

Figure 10. Effects of a Change in Land Loss Rates on Capitalized Value of Wetland, Fish Stock = 86 million pounds ($ mil)

![Graph showing effects of land loss rates on capitalized value of wetland.]

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Appendix A: Parameterization used in the Fishery Model

We adopt the specification in Fenichel and Abbott (2014), which originated with Zhang and Smith (2011) and Zhang (2011). Specifically, the fish stock $x(t)$, measured in pounds, is assumed to grow logistically as follows:

$$\dot{x} = 0.3847x\left(1 - \frac{x}{3.59 \cdot 10^8}\right) - qx\left(yx^\gamma\right)^\alpha,$$

where $q = 0.000317$, $y = 0.157$, $\gamma = 0.7882$, and $\alpha = 0.544$. In this specification, the reduced-form harvest function is the second term on the right-hand side, or $h(x) = qx\left(yx^\gamma\right)^\alpha$, with behavioral effort specified as $e(x) = yx^\gamma$.

Economically, the price of fish is assumed to be $2.70 per pound, and the price of effort is assumed to be $153 per crew-day. Instantaneous profitability of the fishery is thus represented by $\pi(x) = 2.70qxe(x)^\gamma - 153e(x)$. 