Measuring the value of groundwater and other forms of natural capital

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Edited by Stephen Polasky, University of Minnesota, St. Paul, MN, and approved December 31, 2015 (received for review July 13, 2015)

Valuing natural capital is fundamental to measuring sustainability. The United Nations Environment Programme, World Bank, and other agencies have called for inclusion of the value of natural capital in sustainability metrics, such as inclusive wealth. Much has been written about the importance of natural capital, but consistent, rigorous valuation approaches compatible with the pricing of traditional forms of capital have remained elusive. We present a guiding quantitative framework enabling natural capital valuation that is fully consistent with capital theory, accounts for biophysical and economic feedbacks, and can guide interdisciplinary efforts to measure sustainability. We illustrate this framework with an application to groundwater in the Kansas High Plains Aquifer, a rapidly depleting asset supporting significant food production. We develop a 10-y time series (1996–2005) of natural capital asset prices that accounts for technological, institutional, and physical changes. Kansas lost approximately $110 million per year (2005 US dollars) of capital value through groundwater withdrawal and changes in aquifer management during the decade spanning 1996–2005. This annual loss in wealth is approximately equal to the state's 2005 budget surplus, and is substantially more than investments in schools over this period. Furthermore, real investment in agricultural capital also declined over this period. Although Kansas' depletion of water wealth is substantial, it may be tractably managed through careful groundwater management and compensating investments in other natural and traditional assets. Measurement of natural capital value is required to inform management and ongoing investments in natural assets.

groundwater | sustainability | inclusive wealth | comprehensive wealth | genuine investment

Sustainability scholars and advocates are abuzz about natural capital (1). Natural capital is a powerful metaphor conveying the importance of Earth's biotic and abiotic natural resources as society's productivity base, capable of providing ongoing flows of socially valuable services. This rhetoric places natural capital on common conceptual terms with "traditional" produced assets, enabling policy makers to frame resource management and sustainability challenges as a form of "portfolio management." However, operationalizing natural capital requires that decision makers evaluate tradeoffs across capital stocks using a common currency. A lack of prices for valuing natural capital stocks continues to hamper progress toward including natural capital in social benefit–cost analyses or the accounts used to measure social progress (2–4). A major barrier for implementing "inclusive or comprehensive wealth," the United Nation's and World Bank's advocated sustainability metric, is measuring the value of natural capital (2, 5–7). Smulders (8) writes, "The Achilles' heel of the method [Inclusive or Comprehensive Wealth or Genuine Savings] is the determination of the shadow prices," where shadow prices refer to the appropriate natural capital prices. Polasky et al. (7) emphasize that in current attempts to measure inclusive wealth, "all measures included in natural capital were values for market commodities," but "evaluating sustainability via inclusive wealth . . . requires an assessment of the changes in value of all types of capital." Hanley et al. (9) review the theory of natural capital prices in wealth indices, and note the dearth of theory for measuring them. Moving beyond rhetoric to valuing natural capital is imperative for reforming national accounting and developing sustainability measures (2, 10–13), tracking the sustainable use of specific socio-ecological systems (14), and mainstreaming natural capital in a way that makes it comparable to other fiscal goals for policy analysis (15, 16).

We price natural capital in a manner fully consistent with economic capital theory (17). Our approach reflects real-world, "kakatopic" (18) institutional and management arrangements and encompasses the dynamics of the coupled socioecological system (19). This approach directly addresses the Achilles' heel of the inclusive wealth metric by responding to Smulders' (8) call for "good theorists and clever empiricists to . . . close the gap between theory and practice." Our framework generalizes the applicability of Jorgenson's (17) classic capital asset pricing approach—a pillar of economic capital theory—beyond marketed assets, thereby providing natural capital prices for rigorous policy analysis and enabling "apples to apples" comparisons with traditional capital assets (e.g., real estate, machinery, or financial assets). Specifically, we show that Jorgenson's asset pricing equation does not rely on the often questionable assumption of an optimizing economy, even for nonmarket natural capital. The pricing equation continues to provide the revealed marginal social benefit from holding an additional unit of natural capital. The framework is applicable to the full range of natural capital stocks and is scalable to capture greater socioeconomic and biophysical detail when data permit. Thus, we provide a pathway for resolving Polasky et al.'s (7) concerns about the omission of natural capital that does not form market commodities. Moreover, we bridge

Significance

Economists have long argued, with recent acceptance from the science and policy community, that natural resources are capital assets. Pricing of natural capital has remained elusive, with the result that its value is often ignored, and expenditures on conservation are treated as costs rather than investments. This neglect stems from a lack of a valuation framework to enable apples to apples comparisons with traditional forms of capital. We develop such an approach and demonstrate it on Kansas' groundwater stock. Between 1996 and 2005, groundwater withdrawal reduced Kansas' wealth approximately $110 million per year. Wealth lost through groundwater depletion in Kansas is large, but in a range where offsetting investments may be feasible.

Author contributions: E.P.F. and J.K.A. designed research; E.P.F., J.K.A., J.B., W.B., E.M.K.H., and L.P. performed research; E.P.F. and J.K.A. contributed analytic tools; E.P.F., J.B., W.B., E.M.K.H., and L.P. analyzed data; and E.P.F., J.K.A., J.B., W.B., E.M.K.H., and L.P. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1513779113/-/DCSupplemental.

literature using ecological–economic production functions (20) and the macroeconomic literature on inclusive wealth by providing a framework for providing the necessary capital prices.

We link economic measurement of ecosystem service flows, a form of income dependent on nature (21), with models of biophysical dynamics and adaptive human behavior (shaped by policy and other institutional constraints), to value quantities of natural stocks, which are capital (21). This focus on natural capital's durable value in place differentiates our approach from the considerable progress made in valuing short-run flows of benefits deriving from natural capital—termed "ecosystem services" (20, 22–24). The value of ecosystem service flows affects the value of natural capital; however, they are not equivalent. Ecosystem service values must be integrated with other important social, economic, and biophysical data (25) to produce estimates of the long-run value of natural stocks as durable assets (i.e., natural capital). This integration has lagged considerably. Moreover, our work contrasts with approaches borne from accounting and mass balance (26) that suffer from a lack of a consistent framework for integrating environmental and social data to evaluate tradeoffs and that confuse stocks and flows.

We illustrate our approach with an application to the High Plains Aquifer in the American Great Plains. This aquifer is of critical importance to American agricultural production (27). Groundwater is a crucial asset globally, supporting 40% of the world's food production (28). However, its value as natural capital has not been credibly estimated (29–31). Indeed, the lack of values for water is lamented in the 2014 Inclusive Wealth Report (IWR) (2). Previous attempts have inventoried groundwater stocks, providing physical measurements of quantities without values (27, 32), or have valued the flows of ecosystem services associated with water use (30, 33, 34), which provides a poor approximation to the wealth contained in water. To value the groundwater capital stock, we focus on the regions of the aquifer associated with crop agriculture, which received 99% of the groundwater pumped (35) in western Kansas over a period of a major technological change, 1996–2005. We find that the incremental value of an extra acre-foot of water (1 acre-foot = 1,233.5 m^3), the present value of foregone future production by pumping an extra acre-foot at present, for the average farmland acre was between \$7 and \$17 (7% or 3% discount rate). The present value of profits attributable to the Kansas portion of the aquifer, the value as natural capital, declined from \$2.3 billion in 1996 to \$1.2 billion in 2005—a loss of \$110 million per year (2005 US dollars, 3% discount rate). To achieve sustainability, at minimum, Kansas would need to have offset these losses with equivalent investments in other forms of capital, i.e., used the Hartwick Rule (36). The annualized losses are more than twice the state's annual investments in school infrastructure (a precursor to human capital) (budget.ks.gov/publications/FY2005/FY2005_Governors_Budget_Report–Volume_1(rev2-09-2004).pdf). Moreover, Kansas's net investment in traditional forms of agricultural capital (e.g., farm machinery and financial assets) appears to have declined in real terms [www.ers.usda.gov/data-products/farm-income-and-wealth-statistics/us-and-state-level-farm-income-and-wealth-statistics-(includes-the-us-farm-income-forecast-for-2015).aspx]. These comparisons raise questions about the magnitudes and types of investment that can maintain public wealth and the sustainability of Kansas agriculture.

Valuing Natural Capital

Capital assets are stocks with the potential to generate flows of current and future well-being through production of goods and services (21). All economies rely on a combination of produced, human, and natural capital for production (2). In the case of agriculture, soil, water reserves, machines, and human know-how are all capital assets. Wealth is the summed value of productive assets, valued at appropriate accounting prices (shadow prices), which measure the social worth of an additional unit of the asset (18). Wealth is "inclusive" if all assets, including nature, enter this sum (2, 12, 13). If a country, region, or project's ability to generate future well-being is stable or increasing over time, then it can be said to be sustainable, and nondiminishing inclusive wealth is a necessary condition for this sustainability (37). Thus, what matters for sustainability are changes in wealth, or net investment, across all capital stocks. Measuring changes in natural capital value is not sufficient for assessing sustainability, but it is necessary. For example, measuring the sustainability of a groundwater-dependent agricultural system requires measuring the wealth held in the aquifer. If the value of groundwater capital is declining, then substantial investment in other capital stocks may be required to achieve sustainability. Our goal is to demonstrate how natural capital asset prices for use in inclusive wealth accounting can be estimated—using a single, but important, asset as an example. Developing complete inclusive wealth accounts is beyond the scope of this paper; instead, we show how to compute natural capital prices to fill an important void in existing wealth accounts, including in the 2014 IWR.

To operationalize the inclusive wealth framework for a specific natural asset, it is essential to know the accounting price for valuing the stock. For these prices to guide real-world resource management decisions, they must be marginal prices grounded in capital theory (17), reflecting the change in current and future well-being from an incremental increase of the stock (38). These conditions require that accounting prices (Fig. 1, gray circle) connect human investment/consumption behavior (Fig. 1, yellow box), including use of natural resources with biophysical dynamics of the resource stock (Fig. 1, orange box and arrows), in an internally consistent fashion (14). Moreover, accounting prices need to account for projected feedbacks from natural assets to human behavior (Fig. 1, maroon circle and arrow to human behavior), which are often adaptive and always policy or institutionally conditioned. These behavioral rules are often called the "economic program" (12, 14). For accounting prices to be relevant to management, the economic program must reflect real-world institutions, technology, and management (Fig. 1, black box) rather than idealized, optimized policies.

Fig. 1 is more than a conceptual framework; it illustrates a concrete formula for computing the price of natural capital (large light gray box). The natural capital accounting price function, $p(s(t))$, can be expressed as a function of the stock of natural capital, $s(t)$, at an instant in time, t, and parameters characterizing biophysical dynamics, human behavioral feedbacks and the value of ecosystem service flows (14). (We suppress t in our notation when doing so does not cause confusion.) Importantly, the economic program, $x(s(t))$, is embedded within the price function, thus embracing the role of institutions and human behavior as well as ecological and economic dynamics.

$$p(s) = \frac{MD(s,x(s)) + \dot{p}(s)}{\delta - [MG(s) - MHI(s,x(s))]} \quad [1]$$

The equation for $p(s)$ is derived directly from economic capital theory following refs. 14, 17, and 39, and provided in *Supporting Information*. However, our derivation enables us to connect measurement of natural capital with applications in wealth accounting in a theoretically consistent way. Jorgenson (17) assumes a market allocation mechanism to derive Eq. **1**, making Jorgenson's formulation inappropriate for natural capital not traded in markets. Arrow et al. (39) develop theory for the nonoptimizing economy to derive the inclusive wealth measure of sustainability from first principles, but do not use this theory to inform the measurement of accounting prices. We contribute to the literature by providing the general link between Jorgenson's capital

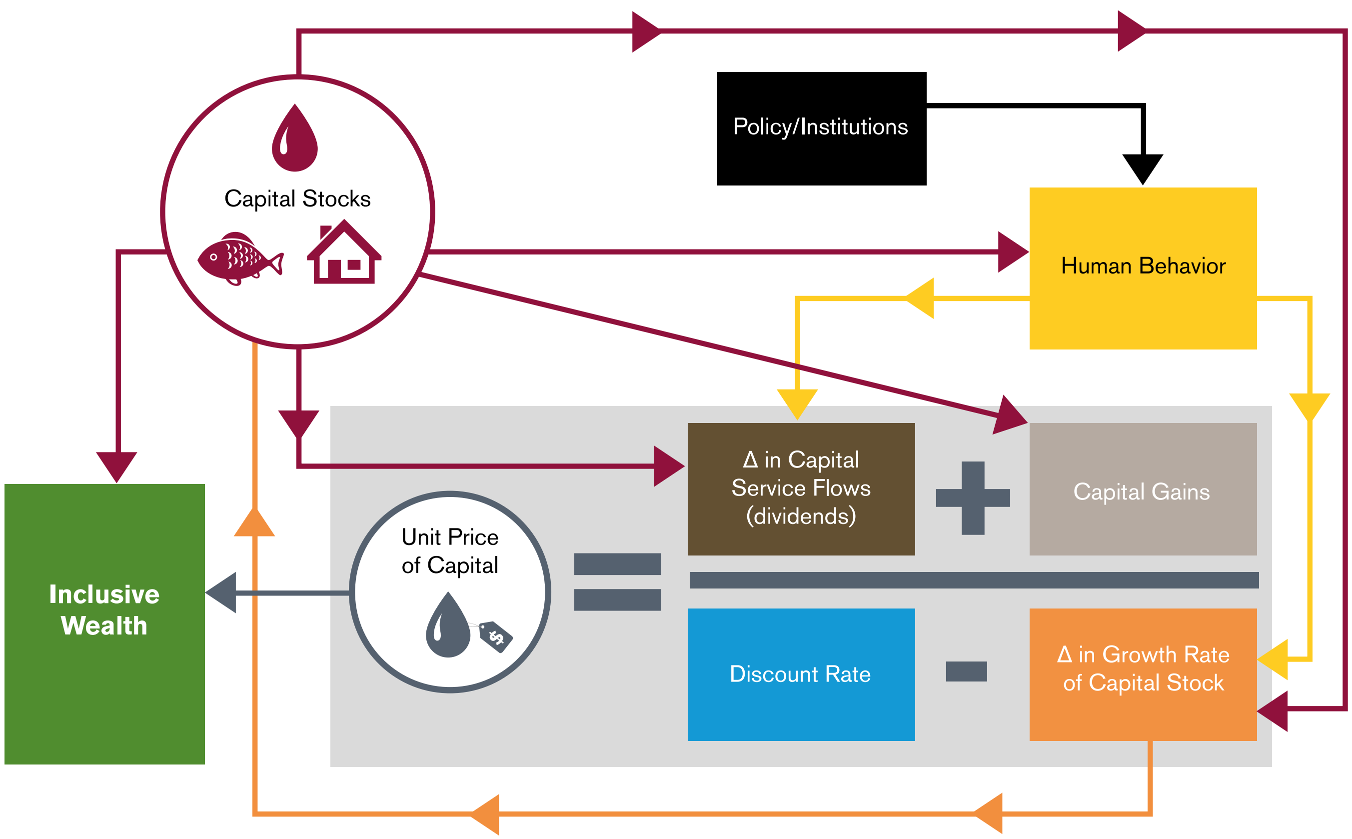

Fig. 1. Conceptual model and equation for valuing natural capital.

asset price theory and the theory of inclusive wealth accounting for economies that don't optimally allocate all resources.

Eq. **1** corresponds to Jorgenson's foundational equation (ref. 17, p. 249) for the value of invested capital. *MD* stands for marginal dividends and is the incremental flow benefit from a small increase in the natural capital stock—the value of the ecosystem services produced with slightly more natural capital (Fig. 1, brown box). The stock of natural capital can directly influence these dividends, or they can arise as a function of natural capital's influence on human behavior via the economic program. Ecosystem service values have received extensive attention in the literature but are often poorly distinguished from the value of natural capital (20, 22, 40, 41). Fig. 1 makes clear that, although related, natural capital and ecosystem services are not equivalent. There are several mitigating factors that prevent a one-to-one mapping. Ignoring these factors can be highly misleading, potentially suggesting value is increasing when it is in fact declining, and vice versa (14).

The denominator of Eq. **1** functions as the effective discount rate—translating the flows of benefits in the numerator to a forward-looking value for an increment of the stock. Here δ is the "raw" discount rate before any adjustments for biophysical or anthropogenic processes of depreciation or appreciation. Discount rates (Fig. 1, blue box) for natural capital are controversial (42, 43). We follow refs. 14 and 43 and use two rates suggested by the US Office of Management and Budget (OMB) (44). OMB recommends a constant, conservative, consumption rate of 3% when a "social rate of time preference" is required and a higher rate of 7% when policy affects shifts in private capital. We treat the 3% rate as the base case and 7% as sensitivity analysis because the social rate of time preference is arguably most appropriate for accounting prices for public inclusive wealth accounts. *MG* is the marginal growth, appreciation, or depreciation arising from an additional unit of stock. This is the gross physical return to conserving the stock. This term can be positive, negative, or zero, depending on the characteristics of the resource (for example, whether the stock influences the rate of growth), its abundance, and its influence on its own regeneration. *MHI* is the marginal human impact on the capital stock (e.g., drawdown) resulting from an additional unit of stock. This term reflects the feedbacks between changes in resource stocks and human investment/consumption decisions. Together, these terms constitute the net physical appreciation or depreciation resulting from an additional investment in natural capital. This "socioecological rate of interest" (Fig. 1, orange box) is subtracted from the baseline discount rate, so that a stock with a positive net appreciation faces a lower effective discount rate (45), increasing its accounting price. Neglecting the ecological adjustment to the effective discount rate can result in dramatic errors in estimating the accounting price of natural capital, especially for self-renewing resources, e.g., fish or naturally regenerating forests (14).

The term $\dot{p} = dp/dt$ represents changes in price, reflecting capital gains or losses from the overall flux (net of human consumption driven through the economic program) in natural capital stocks (Fig. 1, dark gray box). This rate of price appreciation is often observed or forecasted for traditional capital. This is rarely possible for natural capital, because natural capital prices are seldom observable. However, the time path of natural capital prices, and hence $\dot{p}$, is implicit in a fully specified socio-ecological systems model (19), defining the remaining elements in Fig. 1. Function approximation methods (see *Supporting Information*) are used to recover values for $\dot{p}$ consistent with the maintained model of biophysical and economic dynamics and the service flow valuation assumptions. The accounting prices computed using Eq. **1** are conceptually the same as traditional capital asset prices (14).

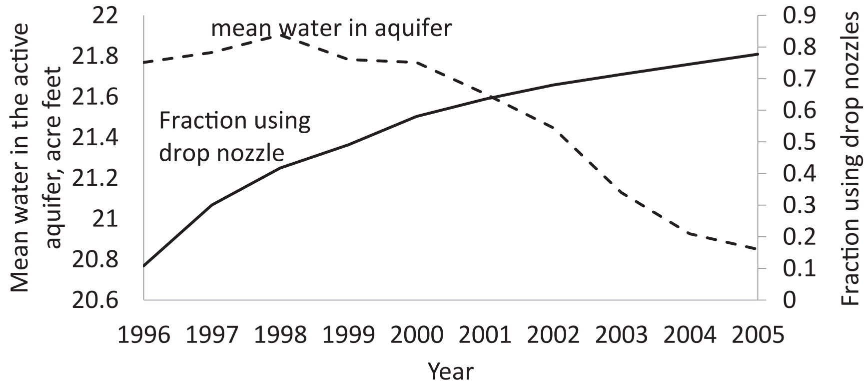

Fig. 2. The mean acre-feet of water per acre of land and fraction of fields using drop nozzles over time.

The unit price of natural capital and quantity of natural capital stock are multiplied to ascertain the stock's contribution to inclusive wealth (Fig. 1, green box). For small changes in the capital stock, it is acceptable to multiply changes in quantity by a constant price to calculate changes in inclusive wealth (2, 12, 13, 39). However, Eq. **1** dictates that, for large stock changes, allowances must be made for stock-driven changes in price (39, 46).

A unique strength of the framework in Fig. 1 is that it can be applied to natural, produced, or human capital—inviting "apples to apples" comparisons. Consider housing as a stock of produced capital. *MD* (brown box) is the net value of housing services arising from the "marginal" house—effectively, the rent the house could generate after deductions for costs, e.g., for maintenance and insurance. The economic program in this case includes the owner's decisions regarding insurance, maintenance, and general use of the house. The discount rate is the owner's rate of return on other investments. Wear and tear, which is partially a function of living decisions, made as part of the economic program, physically depreciates the house over time. This marginal depreciation is partially offset through maintenance, also a function of the economic program, but likely yields a net positive $MHI(s)$, which results in an increase in the effective discount rate. Houses do not renew themselves, so $MG(s)=0$. This is a key difference between most produced and some natural capital. Capital gains, $\dot{p}$, are forecasted based on observed price data. Estimates of these terms can all be found on housing price websites (e.g., Zillow), and the interested reader will see that combining them will typically yield a reasonable estimate for the market price of a house. Although capable of explaining prices for produced capital, the real power of our framework is that it can impute prices for natural capital in a symmetric fashion.

Case Study: Groundwater

To illustrate the power of the framework for natural capital, we examine an application to groundwater. We focus on first-order hydrological concerns to illustrate how groundwater and other natural capital assets can be valued. We define the stock of groundwater as the thickness of the saturated zone, which is mostly rock, multiplied by an estimate of specific yield to convert the saturated thickness of rock to the water held in the aquifer (47, 48). This allows us to value a marginal increase in the water volume contained under one surface acre. We provide an initial estimate for the Kansas High Plains for 1996–2005. There were many changes in agriculture over this decade. For example, farmers adopted high-efficiency center-pivot drop nozzles (Fig. 2). Over this same period, the stock of water contained under the average acre fell ~1 foot, a rate of 0.4% annually.

The Value of Water. Using Eq. **1**, we estimate an accounting price for an additional acre-foot of water, $p(s)$ (Fig. 3). This price function shows that the marginal value of an additional acre-foot of water declines with increases in the stock of water. The average acre overlies 21.5 acre-feet of water, and has an accounting price of \$17 per acre-foot using a 3% discount rate. This implies that water underlying the average Kansas acre with access to the aquifer contributes \$396 in value, approximately a third of 2005 price of irrigated farmland in western Kansas (49). Using a 7% discount rate, the accounting price falls to \$7 per acre-foot, implying an average value contribution of \$173 per acre. OMB's upper discount rate is 2.33 times greater than its lower rate. Using the lower rate yields an accounting price at mean water quantity 2.4 times the accounting price associated with the higher rate—highlighting the importance of discount rate choice.

Changes in Water Wealth. Changes in wealth, rather than absolute wealth, matter for measuring sustainability. The changes in groundwater levels that occurred in Kansas between 1996 and 2005 are of significant magnitude, involving nontrivial changes in the quantity and scarcity of the stocks. Small changes in quantities have minimal impact on marginal values, and can be valued at a constant price times the change in quantity. In such a case, the accounting price, $p(s)$, function can be approximated as a horizontal line. For

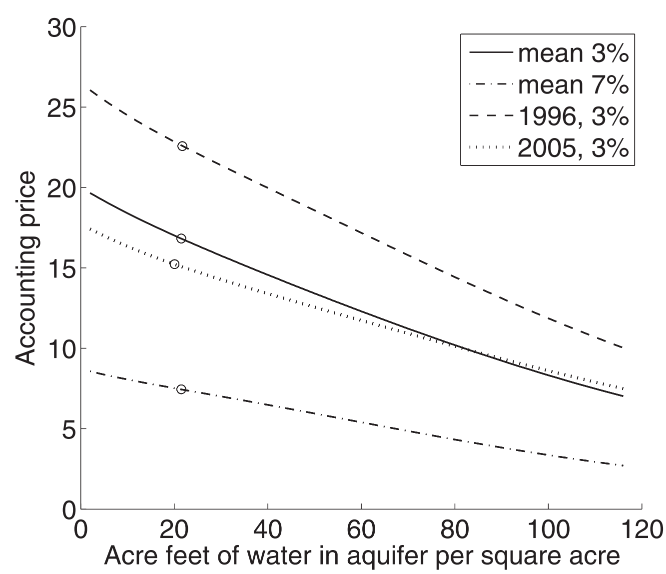

Fig. 3. Accounting price function for 1996, 2005, and the mean of those and all years in between using a 3% discount rate. The accounting price function for the mean of all years using a 7% discount rate is also shown. Circles show the price at the mean water stock.

example, firm market capitalization is computed as price times the number of shares. However, this is a poor approximation of the change in value arising from significant changes in natural capital stocks, which are often localized in nature with few readily available substitutes. In these cases, the scarcity of the natural capital stock dictates its marginal value. To account for scarcity effects, the change in value of the aquifer is best measured as the area under the accounting price curve between any two quantities of water in the aquifer (Fig. 3). Fig. 3 makes it clear that, in the neighborhood of the mean amount of water held in the aquifer (indicated by circles), the accounting price functions are not horizontal lines.

We compute year-specific accounting price functions (examples in Fig. 3) for water by adjusting year-specific means for all variables, including nozzle adoption. Combining the changes in the accounting prices with the changes in water volume, we create a time series for the value of the Kansas High Plains Aquifer. Between 1996 and 2005, the value of the Kansas portion of the aquifer fell at an annualized rate of 6.5% or approximately $110 million per year, using the preferred 3% discount rate, and 6.5% or approximately $31 million per year, using the 7% discount rate. Kansas had a projected budget surplus of $113 million in 2005. If this level is representative, then Kansas appears to have had the financial means to have invested in a "sovereign wealth fund" to enable offsetting capital investment—a sort of "Hartwick fund." It is an empirical question beyond the scope of this paper as to whether Kansas made such durable investments or consumed its surplus.

Fig. 3 illustrates that price curves shifted downward through time (only results for the 3% discount rate are shown). This downward shift corresponded with a rise in water-efficient drop nozzle technology, substantially accelerated by state subsidies for irrigation upgrades. Prior research (50) found that the adoption of this technology actually increased water use, as increased irrigation efficiency reduced the cost of an effective unit of water, inducing farmers to irrigate a greater proportion of their acreage and plant more water-intensive crops. The downward shift of the price function reflects the fact that the technological shift actually made water appear less scarce, reducing the value of a greater water stock (or the apparent cost of depleting water today). The adoption of new technologies often requires institutional adaptation to maintain wealth—adaptations that Kansas failed to make as the new nozzles emerged. The shift in price curves illustrates the joint importance of institutions and technology in determining the value of natural capital. As a thought experiment, imagine that the same amount of water had been withdrawn between 1996 and 2005, but there had been no technological or other shift to move the price curve downward from the 1996 level (i.e., the realized drop nozzle adoption did not occur). In this case, Kansas would have lost $10 million ($4 million) per year using the 3% (7%) discount rate, and the rate of decline in value would have been close to the rate of physical withdrawal.

Discussion

The phrase "natural capital" permeates current sustainability discussions. US federal agencies were recently instructed to account for ecosystem services and natural capital in policy planning (51). However, the idea of treating nature as capital is old (52) and well accepted. Fisher (21) clearly classifies fish stocks and public lands as capital in his foundational 1906 book on income and capital. The conceptual problem has been how to value nature as capital such that the prices used are comparable to capital prices observed in markets when few natural assets are allocated through efficient market mechanisms. Prior efforts to measure the value of natural capital stocks in situ have required assuming a competitive market for the stock and efficient allocation or that the value of the asset is zero (53, 54). However, public policy and informational institutions have led to nonmarket allocation mechanisms that make the Pareto efficient allocation assumption untenable for many important natural resource stocks, including groundwater. For at least the last 20 years, ad hoc empirical approaches attempting to relax the efficient allocation assumption have been suggested (26) and discredited (25). Others have made valiant efforts to measure stocks of resources and track ecosystem dividends (1, 22, 23). By returning to the first principles of capital theory, we present a bottom-up approach that explicitly shows how to integrate social, economic, and biophysical modeling and data to yield appropriate forward-looking accounting prices rooted in the particular biophysical, social, economic, and institutional conditions of specific natural capital stocks. Such a bottom-up approach is necessary in many cases, given the widespread lack of asset markets for natural capital, formidable physical barriers to arbitrage, and the inherently specialized and local nature of many of the services provided by natural capital.

Beyond providing an equation for valuing natural capital, Fig. 1 presents a framework to guide interdisciplinary efforts for generating natural capital prices for measuring and monitoring sustainability. Economists must continue to improve methodologies for valuing ecosystem services, but these efforts must be coordinated with measurements of other parts of the system. Biophysical scientists already play an important role in quantifying natural capital and understanding the production functions for ecosystem services; biophysical science also needs to contribute to establishing the effective discount rate for natural capital pricing. Measurements of marginal human impact will likely require collaboration among biophysical scientists, economists, and other social scientists, and broad collaboration across the social sciences (including economics) is needed to understand the economic program that links institutions and natural capital states to human behavior. The strength of Fig. 1 is that it shows exactly what interdisciplinary teams need to measure and how to integrate those measurements.

Kansas experienced a nontrivial loss in water wealth from 1996 to 2005. The annualized rate of loss of physical water stock, 0.4%, severely underestimates the rate at which wealth was lost, 6.5%. However, these losses are not so great as to be insurmountable, if care is taken to balance resource depletion with sufficient compensatory investments. Our framework for measuring the value of groundwater specifically, and natural capital generally, is readily transferable to other systems. However, our prices are not. Measuring the value of groundwater in more-complex settings may require different approaches to measuring the marginal dividends, recharge, and marginal human impact. Indeed, not all groundwater is as valuable as our estimates, but much groundwater flows to high-valued residential use and is likely considerably more valuable, as in California and the Desert Southwest.

Our example illustrates the importance of how institutions, technology, and other factors shape the dividend flows from natural capital and the economic program. Natural capital prices are not immutable natural parameters to be discovered. They are functions of the way society interacts with the resource as mapped through the economic program and marginal dividends. The large loss in aquifer-associated wealth that Kansas actually experienced resulted from a combination of the physical drawdown of the stock and a state-subsidized shift toward an economic program that was less conservation oriented, even though it, paradoxically, involved a shift toward "highly efficient" nozzles. By failing to anticipate and mitigate the perverse consequences of the technological transition, statewide "investments" in improved technology actually destroyed wealth.

Measuring the value of natural capital and assessing whether or not resource use is sustainable go hand in hand. However, while measuring the value of natural capital is necessary, it is not sufficient for measuring sustainability. In addition to changes in wealth, changes in population can also be important; under certain circumstances, sustainability can be assessed via changes in per capita (or perhaps median) wealth (39). However, care may need to be taken in measuring the value of services flows and *MHI*, which may be a function of population size. Coordinated efforts to generate credible accounting prices are needed if the concept of natural capital is to be actionable, rather than a trite reminder to decision makers to "please remember the environment." Our framework provides a rigorous, integrative, and scalable approach to transition natural capital from a rhetorical device to a practical tool for fostering the sustainable management of our planet.

Methods

We parameterize the case study for the period 1996–2005 (see *Supporting Information*) using a 10-y data series from the Kansas Water Information Management and Analysis System, the United States Department of Agriculture Economic Research Service, and the Kansas State University Agricultural Extension, in conjunction with an annual time series of saturated thickness (32).

We estimate $MD(s,x(s))$ and $MHI(s,x(s))$ based on the market conditions, technology, and management in place at the time (35), where the economic program $x(s)$ reflects decisions of crop choice and irrigation pumping as a function of the groundwater stock under an acre (Tables S1–S4). $MD(s,x(s))$ links the change in the water in the aquifer with the change in field-level net revenues. $MHI(s,x(s))$ is influenced indirectly through the economic program by the irrigation requirements of various crop choices. $MHI(s)$ was computed as the change in water in the aquifer resulting from water withdrawal. We assume the aquifer recharges at a rate of 1.25 inches per year, and that the only losses are through agricultural withdrawals—a reasonable assumption for the High Plains Aquifer. We abstract from lateral flow and neighbor effects on pumping, which are, at most, secondary drivers of groundwater volume (55). We find that groundwater withdrawal increases at an increasing rate with more water in the West Kansas High Plains Aquifer. $MG(s) = 0$ because hydrologic theory does not support stock-dependent recharge rates.

In our base analysis, we model the average acre in Kansas. However, when we compute aggregate values for Kansas, we use the changes of all fields in the dataset rather than the change in the average field. This provides the most accurate measurement.

ACKNOWLEDGMENTS. D. Skelly and S. Yun provided helpful comments. K. Krause assisted with graphic design of Fig 1. E. Addicott provided research assistance. R. Llewlyn helped us access historic crop budgets. The Knobloch Family Foundation supported this research. E.M.K.H. was supported by National Science Foundation WSC 1039180.

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