nature climate change

PERSPECTIVE

PUBLISHED ONLINE: 24 FEBRUARY 2016 | DOI: 10.1038/NCLIMATE2871

Wealth reallocation and sustainability under climate change

Eli P. Fenichel[1]*, Simon A. Levin[2], Bonnie McCay[3], Kevin St. Martin[4], Joshua K. Abbott[5] and Malin L. Pinsky[6]

Climate change is often described as the greatest environmental challenge of our time. In addition, a changing climate can reallocate natural capital, change the value of all forms of capital and lead to mass redistribution of wealth. Here we explain how the inclusive wealth framework provides a means to measure shifts in the amounts and distribution of wealth induced by climate change. Biophysical effects on prices, pre-existing institutions and socio-ecological changes related to shifts in climate cause wealth to change in ways not correlated with biophysical changes. This implies that sustainable development in the face of climate change requires a coherent approach that integrates biophysical and social measurement. Inclusive wealth provides a measure that indicates sustainability and has the added benefit of providing an organizational framework for integrating the multiple disciplines studying global change.

Income and wealth distributions, and the fact that a substantial fraction of society's wealth is held in the form of natural capital, are increasingly central to policy discussions[1–4]. Global climate change will profoundly reshape ecosystems, substantially impact the size and distribution of stocks of natural capital, dramatically alter the amount and distribution of wealth on the planet and compound the impacts on vulnerable human communities[5–10]. Moreover, human responses to climate change and associated impacts on ecosystems are likely to rival the direct effects of climate change[11,12]. Understanding the feedbacks among climate, human actions and ecosystems is imperative to charting a path towards sustainability[13]. However, policymakers are still largely 'flying blind' as traditional performance indices (for example, gross domestic product, GDP) do not provide long-term, forward-looking information[2,14]. Understanding what is and is not sustainable in the context of climate change and adaptation has been challenging[15–17]. Qualitative principles exist, but quantitative measures have been difficult to develop[15–17]. Quantitative measures are important because "we manage what we measure"[18]. Capital stocks, or wealth, provide the capability for future generations to meet their needs, and therefore changes in wealth are a measure of sustainability[19]. However, wealth must be broadly defined and properly valued to operationalize measurement[20,21].

The inclusive wealth (IW) framework (sometimes called genuine or comprehensive wealth)[3,19–22] was developed to measure national sustainability. IW is also appropriate for evaluating how past changes have influenced the sustainability of social–ecological systems (SESs) at a local scale, and can be used to forecast how changes could influence future sustainability. IW for a group of people is the sum value of capital assets — construed broadly to include natural, human and produced or built capital — for those assets that generate flows of valuable current and future goods and services to a group. The term 'group' defines a collection of people (that may be a single individual) who may or may not interact, in the sense of 'community', but who have some degree of shared use rights to the service flows from the assets in the system. There may be strong geographic associations among group members, shaped in part by the location of spatially immobile resources. Group assets can be measured at different scales (for example, at national to village levels) or for different interest groups (for example, indigenous groups to resource-based industries). Groups and their environments jointly constitute an SES.

A necessary condition for a sustainable SES at any level is non-declining IW[21,22]. Local or regional IW accounts can help planners anticipate how climate change will impact human well-being[14]. Developing IW accounts for groups at local levels (for example, municipalities, regions or local business sectors) is probably more tractable than developing country accounts. However, spillover across groups may yield sustainability in one location at the cost of sustainability elsewhere. Only one recent case study has attempted to use IW at the local level[23]. Tracking the reallocation of natural and other forms of capital through regional or local-level IW accounts could help super-regional governments or international agents assess appropriate transfer payments to address the distributional and equity impacts of climate change[8,24].

Here, we show how climate change directly and indirectly affects the value of capital assets — especially natural capital. We then show how changes in wealth can be analysed with an IW approach, and how IW tracks the distributional and aggregate impacts of climate change on local and global sustainability. We highlight cases where climate change shifts natural capital in space across political and cultural boundaries. Our analysis shows that biophysical indicators are unlikely to correlate with measures of natural capital value or IW. This lack of correspondence implies that policymakers concerned with the implications of climate change for sustainable development and distributional impacts can gain further insight by supplementing biophysical indices with IW-based indices. We illustrate the IW framework with a fisheries example, and suggest that IW also serves as an organizing interdisciplinary framework for studying global change.

[1]School of Forestry & Environmental Studies, Yale University, 195 Prospect Street, New Haven, Connecticut 06460, USA. [2]Department of Ecology & Evolutionary Biology, Princeton University, Princeton, New Jersey 08544-1003, USA. [3]Department of Human Ecology, Rutgers University, 55 Dudley Road, New Brunswick, New Jersey 08901, USA. [4]Department of Geography, Rutgers University, 54 Joyce Kilmer Drive, Piscataway, New Jersey 08854-8045, USA. [5]School of Sustainability, Arizona State University, PO Box 875502, Tempe, Arizona 85287-5502, USA. [6]Department of Ecology, Evolution, and Natural Resources, Rutgers University, 14 College Farm Road, New Brunswick, New Jersey 08901, USA. *e-mail: eli.fenichel@yale.edu

Climate change, natural capital and adaptation

Climate change physically reallocates natural capital[25], with no guarantee that the total quantities or values of natural assets are preserved. Chief among these natural capital resources are populations of plants, trees, fish and other species important to humans. Many of these organisms are shifting polewards, towards higher elevations or towards greater ocean depths in response to changes in the abiotic environment[6,26–29]. The demographic processes that proximally contribute to the shift of organisms include juvenile dispersal, adult movement and differential growth of existing populations. These biological shifts often have strong interactions with human responses, which are conditioned by institutions — the rules that structure human interactions. Different biological mechanisms may alter the claims that different groups hold in relation to common-pool resources, such as when an abundant anchovy population recently appeared in the North Sea, creating a new fishery[30]. Subsequent research revealed that this population resulted from growth of a local, previously unrecognized population, and not from movement of the regulated Bay of Biscay stock further south[30]. The biological reallocation mechanism and rules governing European fisheries suggest the need for a new fishing-quota allocation for the North Sea stock, rather than applying the same allocation as the Bay of Biscay stock, which is assigned to Spain and France.

Human groups respond to uneven climate change impacts in multiple ways. Some, but not all, responses involve changes in ownership or spatial reallocation of capital. Groups may reallocate built capital to new locations, for example, transferring farming machinery and crop varieties[31,32]. People may move in response to climate change, reallocating human capital. People may also take steps to influence the spatial reallocation of natural capital. For example, reducing non-climate stressors can help to mitigate climate impacts on natural capital[33]. The ability to engage in adaptive, or perhaps mitigative, responses depends on the capital stocks appropriable by individuals as well as institutional arrangements. Successful management of common-pool resources often depends on the existence of 'clear boundaries' or rights to define the resources and the groups of users to be governed[34,35]. Rights, broadly defined, provide institutional security[36]. When people have clear rights to capital that can be transferred at low cost (is physically movable like a tractor, or is non-physical, like a transferrable right to use a common-pool resource, for example), the capital can be sold or traded, providing further scope for adaptation. However, some forms of capital are more costly or effectively impossible to move, in part because of physical or cultural constraints or because groups lack the rights or mechanisms to make the transfers. Climate change knows no human boundaries or system of rights, thereby violating the important clear boundaries design principle. The adaptation strategies that groups choose can feed back in important ways to influence natural resource dynamics[11,37].

Box 1 | A primer on accounting prices.

An accounting price measures the value of one more unit of a specific capital stock 'in place'. It is the time-discounted sum of the monetized flows of benefits to people and companies resulting from an extra unit of a resource. Accounting prices are:

The true costs of capital depletion. When a unit of capital is consumed, society sacrifices the benefits that this capital would have provided, had it been conserved. An accounting price reflects the value of this lost opportunity.

Social. Once the scale of the analysis is defined (for example, a region, nation or the entire world), the accounting reflects all human beneficiaries in the system. This implies that benefits that arise to one group through market distortions (for example, externalities or monopoly power, which can lead to 'distorted prices') must be matched with their associated social costs to others in the system.

Reflections of current, imperfect markets and governance. Accounting prices show the value of capital in the world as it is, not as we might wish it were. Grounding valuation in current institutions and their means of allocating resources provides operational insights to policymakers about tradeoffs and sustainability. Using optimized or idealized prices would prevent valuation of institutional reforms.

Forward-looking. Capital provides durable benefits. Therefore, capital's value must reflect assumptions about the future trajectory of the capital stock, the valuation of its benefits, human responses to changes in the capital stock and the appropriate discount rate for comparing current and future benefits.

Seldom reflected in markets. In principle, prices from an ideal asset market correspond to the accounting price. However, many forms of capital, particularly natural capital, have characteristics and systems of property rights that make the creation of asset markets difficult or undesirable. Other forms of capital (for example, fossil fuel deposits) generate social liabilities when used that are not reflected in their market price. In practice, accounting prices must be derived from adjustments to market prices or estimated based on first principles. Because accounting prices don't reflect actual market transactions, they are often called shadow prices.

Inclusive wealth and natural capital

IW is a coherent approach for measuring sustainability, in part because wealth is the suite of resources available for current and future human production and consumption. Wealth is 'inclusive' when it includes natural resources, environmental resources, human skills and health, in addition to financial and manufactured capital[20,21,38–41]. Dasgupta[21] measures wealth $W(t)$, at time t as

$$W(t) = \sum_i F_i(t)K_i(t) \quad (1)$$

where i indexes resources set A, $i \in A$ material to the group, $K_i(t)$ is an inventory or physical stock of a resource i, and $F_i(t)$ is the value society assigns to a unit change of resource stock i (its price)[21]. Material resources are those that are most important to the group's well-being or essential character.

Critical to measuring wealth is measuring prices. Price measures scarcity[42] — the value of a bit more of something — and therefore typically declines with extra quantity. Dasgupta calls appropriate prices for wealth accounting the accounting price (Box 1). He notes that prices should reflect current institutions, but accounting prices may not be identical to market prices if no market, and thus no price, exists or if subsidies or externalities skew the market price — a common occurrence for many forms of natural and human capital[20,21]. We assume that the capital stocks dynamics are autonomous in time, which Arrow *et al.*[43] point out is not a burdensome assumption. Time autonomy means that time only enters through the changes in the stocks — the calendar day does not matter. Therefore, we redefine the price as a function of capital stocks and institutional arrangements, for example, $F_i(t) = P_i(K_i(t), \boldsymbol{K}_{-i}(t);\phi)$, where ϕ is a parameter vector describing institutional arrangements that guide choices about the use and allocation of resources — referred to as the economic programme, and $\boldsymbol{K}_{-i}$ is a vector of the quantities of other forms of capital, other than stock i, which make up the current conditions.

Equation (1) provides the level of wealth, but changes in wealth are more important for sustainability. Changes in wealth are net investment or divestment, and sustainability requires that IW is stable or increasing. A stable or increasing trend suggests that the society can produce and consume as much in the future as it can today[14,22,44], which formalizes the Brundtland Commission's definition of sustainable development[45]. Furthermore, anticipating changes in the IW contribution of natural capital is a practical way to measure the investments required to offset productive base losses from climate change, which Sumaila *et al.*[25] refer to as an adaptation endowment fund. For small changes (that is, marginal change), net investment is well approximated by

$$\Delta W = \sum_i \bar{P}_i \Delta K_i \qquad (2)$$

where $\bar{\boldsymbol{P}}_i$ is a weighted average of prices of stock i before and after the change[21]. Equation (2) exactly measures net investment if $P_i(K_i, \boldsymbol{K}_{-i}; \phi)$ is linear in K_i, other capital stocks do not change, and $\bar{P}_i$ is the arithmetic mean of prices before and after the change (indicated by Δ, $\Delta K_i = K_i\,(t + \varepsilon) - K_i(t)$ and ε is the increment of time). For small changes, a linear approximation provides sufficient accuracy. More generally, however, the appropriate weighting of prices for $\bar{P}_i$ in equation (2) depends on the curvature of the underlying price function.

Climate change will probably shift natural capital stocks in unprecedented and large ways, and natural capital price functions are generally expected to be nonlinear[46]. Therefore, we require a more general approach than equation (2). Consider the case where climate change substantially shifts a natural capital stock $j \subset A$ and other stocks indexed by $-j$ change only slightly, such that $\Delta K_{-j} \approx 0\ \forall\ j$. In this case, stock j cannot be included in the sum as in equation (2), except in the unlikely case the price function is linear[46]. Instead, changes in wealth should be measured as:

$$\Delta W = \sum_{i \neq j} \bar{P}_i \Delta K_i + \int_{k_j(t)}^{k_j(t+\epsilon)} P_j(\xi, \boldsymbol{K}_{-j}(t); \phi)\mathrm{d}\xi \qquad (3)$$

where k_j is a specific quantity of capital stock K_j, $P_j = P_j(K_j(t), \boldsymbol{K}_{-j}(t); \phi)$ is the price function for stock j, and ξ is an infinitesimal increment of stock j. We suppress the dependences on $\boldsymbol{K}_{-j}(\boldsymbol{t})$ and ϕ when they are held fixed. For stock j the contribution to the change in wealth is the area under the price curve (Fig. 1). In Fig. 1, $k_j(t)$ and $k_j(t + \varepsilon)$ are k and $k \pm s$ (stock goes up or down by s). If $k_j(t + \varepsilon) = k - s$ then the integral in equation (3) can be visualized as $B + D + G$. If the price curve were linear, which is an increasingly good approximation as $s \to 0$, then equation (2) measures ΔW with $\bar{P}_J = (P_j(k) + P_j(k - s))/2$. In the linear case, error introduced by using too high a price at stock size k, $\bar{P}_J > P_j(k)$, is exactly offset by the error from using too low a price at stocks size $k - s$, $\bar{P}_J < P_j(k - s)$. Yet, for any level of climate change worth worrying about, it will probably be important to measure the changes in area B more accurately, and not rely on offsetting errors.

Measuring the value of capital stocks

Point estimates for accounting prices are insufficient, and prices as a function of capital stocks are needed to forecast changes in the accounting prices as stocks change. Approaches to measuring built capital are well developed[3,47], and could be downscaled to the community level. Inklaar and Timmer[47] and Fraumeni and Liu[3] offer internationally accepted approaches for valuing human capital. Valuing natural capital stocks has remained difficult[21,23,44]. The first step is to measure the quantity of natural capital stocks material to the long-term success of societies. Although this is a daunting task, scientists have made substantial advances. The second step is to determine the appropriate price. Fenichel and Abbott[46,48] recently

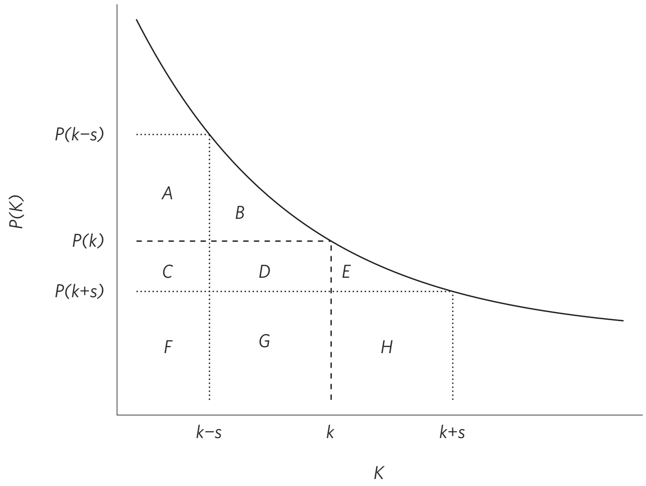

Figure 1 | The reallocation of natural capital wealth between two otherwise identical locations, when accounting prices reflect some degree of economic scarcity. Wealth is the region under the price curve to the right of a level of k. Dashed lines illustrate initial conditions, and dotted lines illustrate conditions after a climate-change-imposed change. Regions A–H represent additions or subtractions from wealth-associated change in natural capital.

developed an approach for recovering the accounting price for natural capital as a function of the stock and the broader socio-ecological setting. Their method, grounded in economic theory, enables the recovery of accounting prices for capital stocks conditional on current institutions.

The approach used by Fenichel *et al.*[46,48] enables the measurement of the entire price function, including the curvature. We present their pricing equation in the context of a single stock of natural capital with time-autonomous dynamics and suppress other stocks and the economic programme, which can be treated as parameters. The approach is generalizable to valuing other forms of capital[48] and to multiple stocks. The accounting price of natural capital, j, P_j, for a stock of natural capital, K_j, accounting for feedbacks in the coupled social-ecological system is[46,48]

$$P_j(K_j(t)) = \frac{\mathrm{MD}\big(K_j(t), x(K_j(t))\big) + \dot{P}_j(K_j(t))}{\delta - \big(\mathrm{MG}(K_j(t)) - \mathrm{MHI}\big(K_j(t), x(K_j(t))\big)\big)} \qquad (4)$$

where MD is the marginal dividend or marginal flow benefit from a small increase in the natural capital stock j — the marginal ecosystem service net benefit. In the case of commercial fisheries, this term is the change in net revenue with respect to a change in the fish stock size. MD depends directly on the stocks of capital, K_j, and indirectly on the stocks through the economic programme, $x(K_j(t))$, where the dependencies on other stocks and ϕ are suppressed. MG is the marginal change in growth rate (appreciation) of stock j from having an extra increment of stock. It could be positive or negative, depending on the level of the stock and environmental factors influenced by climate. The MHI is the marginal human impact that results from stakeholders' behavioural responses to changes in resource j, that is, whether people increase or decrease exploitation of the stock as the stock changes. The term δ is a discount rate that is often determined by public accounting authorities and reflects the degree to which people value benefits now versus in the future. The term $\dot{P}_j(K_j(t))$ reflects changes in the accounting price of asset j, and can be found using a collocation approach[49] given process-based models linking capital stock dynamics and human investment or consumption behaviour in these stocks[46]. Analogous equations are well known in other areas of capital valuation[50].

Natural capital prices and institutions. The economic programme, fully expressed as $x(K_j(t),\boldsymbol{K}_{-j};\phi)$, depends on institutions and resource allocation mechanisms. Therefore, equation (4) makes the importance of institutions explicit. This elevates the importance of measuring changes in IW using marginal values of natural capital and other forms of capital that are expressed as functions of the quantity (and perhaps quality) of resource stocks, with these values conditioned on the institutions that govern resource allocation. Indeed, understanding pre-existing institutions and socio-economic feedbacks is absolutely necessary, in addition to understanding biophysical processes. This understanding is particularly important when institutions vary between 'donating' and 'receiving' regions, which is likely to occur and influences the accounting prices of capital in each region[14,19,46]. Therefore, without analysis of pre-existing institutions, it is not possible to accurately measure the accounting price in a given setting, which makes it unclear how moving capital from one region to another will affect value. We highlight the importance of these institutions with four examples below.

A fisheries example

We use a fishery to illustrate how the IW approach can speak to distributional impacts while providing a framework to help organize interdisciplinary climate research. Fisheries are coupled SESs requiring natural, human, and built capital to produce human well-being and maintain their essential character. Our understanding of how climate change will alter and reallocate ocean wealth, impacting the sustainability of coastal communities, remains limited[25,51,52]. As a practical matter, IW accounting needs to begin by focusing on material assets, particularly because the stocks that are material for the success of that group may be easier to identify. For example, for a coastal fishery, stocks of fish, waterfront and processing infrastructure, boats and gear and local ecological knowledge may be the primary capital stocks material to success. For sake of space, we focus primarily on natural capital, but similar logic applies to human and built capital, which are necessary for true IW accounting.

Consider a stylized example with two ports (groups), Southport and Northport. Southport and Northport are divided along an environmental gradient. Southport's fish stock declines as the climate changes whereas Northport's stock increases. This situation reflects expected scenarios for areas such as the mid-Atlantic and New England regions of the US East Coast, where many fish stocks are moving rapidly in response to warming[27,52]. To develop intuition, we first discuss how climate change can affect the price function. Next, we discuss the case where only natural capital is reallocated. Then, we discuss how changes in natural capital may interact with other forms of capital to more drastically influence IW.

Shifting natural capital values. Changes in the quantity of fish influence the accounting price (that is, the location on the price curve) in addition to the amount of resource available. But, climate-driven changes in biology, institutions, and SES interactions can also reshape the price curve.

Fish and shellfish have narrow limits of temperature and other factors in which they can thrive[53]. Climate change induces organisms to move or to experience differential mortality and reproductive success, resulting in population range shifts[54]. If temperatures exceed the thermal maximum of a stock, then the intrinsic growth rate of the stock may decline[53] (Fig. 2a, dotted curve). This reduces MG at the low stock sizes that characterize many fisheries[55] (Fig. 2b, dotted line). In Eq. 4, a lower MG increases the magnitude of the denominator (the effective discount rate) and reduces the accounting price at low stock sizes (Fig. 2c, dotted curve). The price curve itself changes, implying a lower value for the fish stock, even before a change in stock size is realized. In an economic sense, the drop in growth rates leads to faster 'depreciation' of the stock. Conversely, stocks may move closer to optimal temperatures for growth and experience increased intrinsic growth rates (Fig. 2a, dashed curve). An increase in marginal growth, holding the stock size constant, at least at low stock size (Fig. 2b, dashed line), increases the accounting price (Fig. 2c, dashed line) by reducing depreciation or allowing appreciation.

By a similar logic, declines in carrying capacity uniformly decrease the marginal growth (Fig. 2d, dotted curve) and shift the price curve downwards (Fig. 2f). Climate change could induce a reduction in carrying capacity if, for example, ecosystem primary productivity declined[56]. Current long-term projections of ocean primary productivity are uncertain, but generally indicate declines at low and mid-latitudes and potential increases at high latitudes[57]. There are also indications that extreme events will become more common in a warmer climate[58]. Greater variability in demographic rates implies a decline in long-term population growth rates, increasing the effective discount rate[59,60] (Fig. 2g, dashed curve). Such declines shift the price curve downwards and reduce prices at low stock size for both northern and southern populations (Fig. 2i, dashed curve). Furthermore, the risk of a climate-induced collapse in the stock may also increase, perhaps more so for the southern stock. An increased exogenous risk of collapse adds an additional term to the denominator of equation (3) (see ref. 37), and shifts the price curve downwards for highly variable or uncertain systems.

Given nonlinearities, symmetric changes in growth rates will probably lead to asymmetric shifts in the price functions. Thus, net effects on wealth are an empirical question that cannot be answered just with physical measurements.

Climate change and reallocating natural capital wealth. Changing climate could alter the distribution of wealth in many ways. Climate change could shift stocks asymmetrically, alter accounting price functions or lead to institutional change. However, these re-distributional forces are not necessary conditions for climate change to drastically reallocate natural capital wealth. We explore four cases to highlight the role of pre-existing institutions and allocation mechanisms.

Begin by considering a case where the total physical quantity of natural capital, that is, fish, is held constant, but the resource is reallocated across the system. Furthermore, hold all the institutions and allocation mechanisms constant. These assumptions are probably violated in the real world, but we maintain these assumptions to show how pre-existing institutions influence the way climate change reallocates wealth. Loosening these assumptions only serves to make climate change even more likely to reallocate wealth. Assume that Southport and Northport are identical, as are the individuals in each port, up to the climate change impacts they experience.

The case when both ports manage with pure open access. If Southport and Northport manage their fisheries with unrestricted open access, then $P_j(k,\boldsymbol{K}_{-j};\phi) = 0$ at the pre-change equilibrium in both areas (we suppress the dependences on time). Open access allocation implies zero marginal value to conserving fish because open access encourages fishers to continue to enter so long as revenue gain exceeds the cost of extra effort[61–64]. Under open-access allocation, climate change does not affect the fish stock's long-term contribution to wealth because the institutions managing the fisheries preserve no wealth in fish. However, Northport may experience a temporary windfall with the influx of new fish. Yet, the open-access institutions will not preserve the value of this capital. Worrying about environmental conditions or environmental changes requires that institutions manage the resource to preserve value[65], which means providing future users with some degree of security in the resource[41].

The case when the ports are symmetric and both have non-open-access management. If both ports restrict access to fisheries (symmetric, non-open-access management) — as is found in most developed countries and many developing countries — more

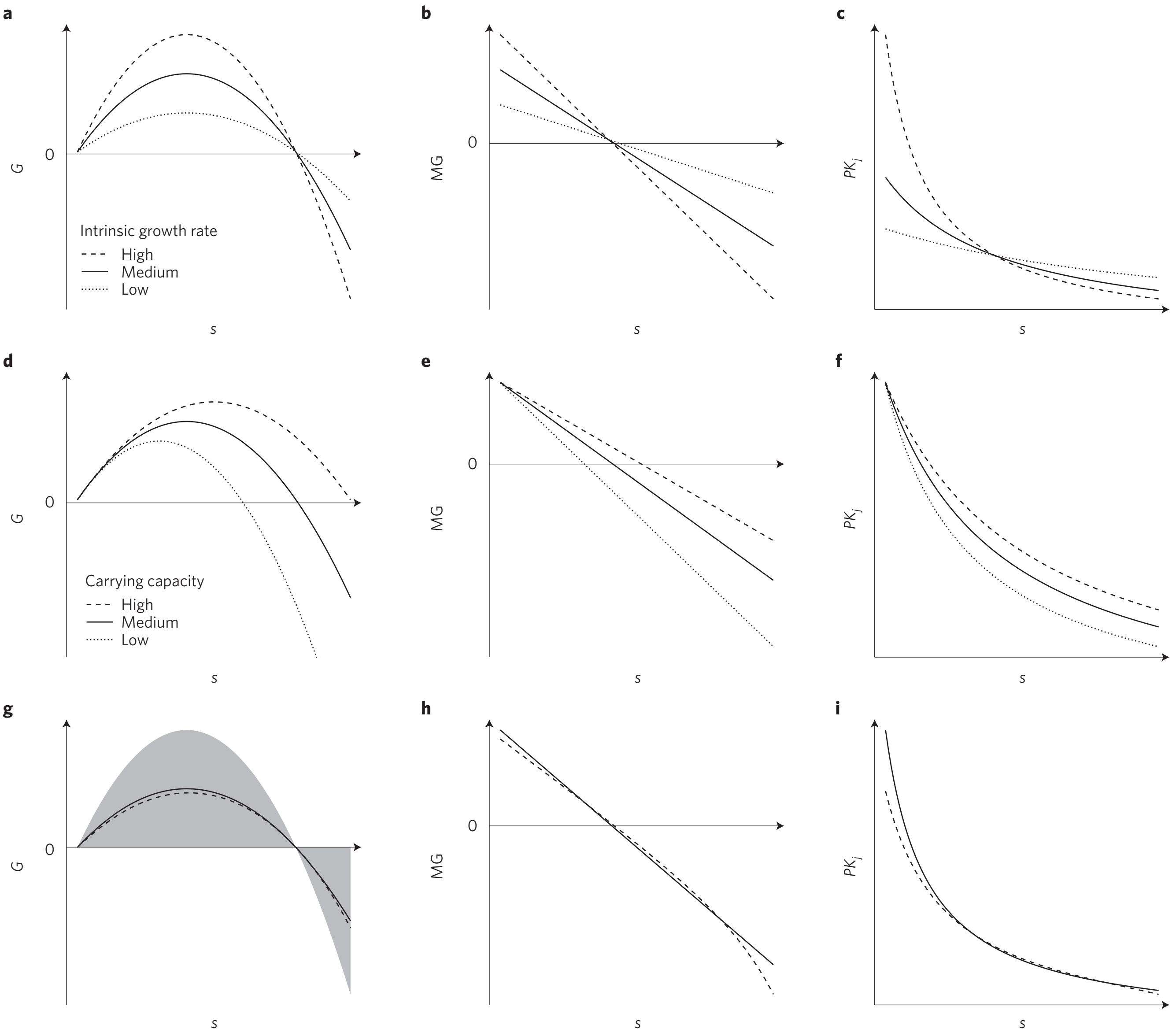

Figure 2 | The influence of demographic changes on marginal growth, and hence the accounting price of a fish stock. a–i, The left-hand column (**a**,**d**,**g**) shows population growth rate (*G*) as related to stock size (*s*). The middle (**b**,**e**,**h**) shows the marginal growth rate (MG), which is the marginal change in growth rate with a unit change in stock size. The right-hand column shows the effects on the accounting price (**c**,**f**,**i**). The scenarios include a change in the intrinsic growth rate, which is the growth rate at low population size (**a**,**b**,**c**); a change in the carrying capacity (**d**,**e**,**f**); and an increase in the variance of the intrinsic growth rate (**g**,**h**,**i**). In **g**, the grey region represents a range of realized growth rates that result from increased variance of the intrinsic growth rate. The stochastic growth rate is the equivalent long-term growth rate with this variance. Plots are made under the assumption that the fish stock follows logistic growth, $G = rs(1-s/C)$, where *r* is the intrinsic growth rate of the stock *s*, and *C* is the carrying capacity.

complex institutions, such as entry limits, exist to allocate resources. Even in the absence of formal policies, communities may cooperate to develop self-governing institutions to avoid a pure open access scenario. These institutions typically produce downward-sloping price functions, as in Fig. 1[46,62], and control fishing effort sufficiently to maintain a positive accounting price for the fish stock, $P_j(k,K_i;\phi) > 0$ in equilibrium. A downward-sloping price function implies that the resource is managed such that society places greater value on each extra unit of the resource as it becomes scarcer. If we maintain the assumption that the two regions are identical before climate change, climate change must create an aggregate loss in wealth even if the quantity lost by one region is exactly the quantity gained by the other. This result follows from a downward-sloping price function, which indicates that the group manages with a concern for scarcity (Fig. 1). If the institutions in both ports lead to the same price curve $P_j(k,\boldsymbol{K}_{-j};\phi)$, the initial stock for both ports is *k*, and climate change shifts *s* fish from Southport to Northport, then Southport's loss must exceed Northport's gain. The value of the gain (loss) is the change in area under the price curves for both ports associated with a physical change equal to *s*. Evaluated at post-climate change prices, Southport loses wealth of *G* in Fig. 1 whereas Northport gains an offsetting wealth of *H*. However, the addition to Northport (area *E* in Fig. 1) must be smaller than a rectangle with area $s \times (P_j(k + s) - P_j(k))$, because the $P_j(K)$ slopes down from $P_j(k)$. Conversely, Southport's loss contains two regions, area $D + B$ in Fig. 1. Area *D* alone is the rectangle with area, because $P_j(K)$ rises as *K* declines. The intuition is that because Northport and Southport were identical before the change, the scarcity effect makes Southport's losses greater than Northport's gains.

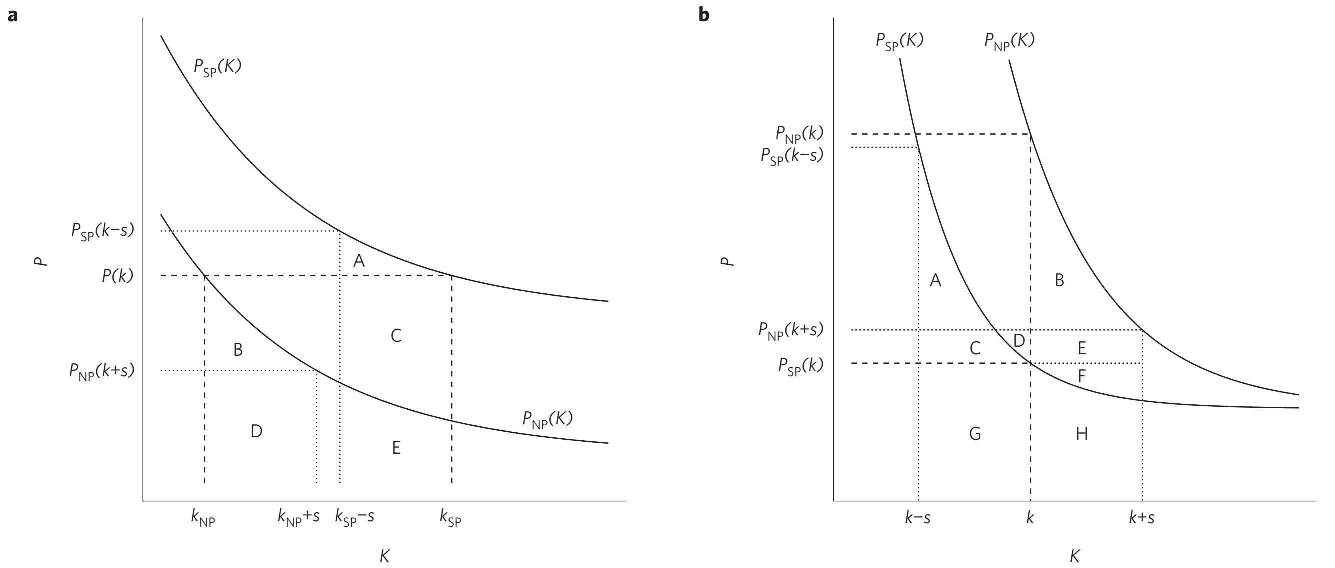

Figure 3 | The reallocation of wealth between asymmetric regions. a, The reallocation of natural capital wealth when Southport (SP) has greater quantity of natural capital stock and institutions that place a greater value on the natural capital stock than Northport (NP). Dashed lines illustrate initial conditions (note that initial price for both Southport and Northport is the same), and dotted lines illustrate conditions after a climate change imposed change. **b**, The reallocation of natural capital wealth when Southport and Northport have the same initial physical quantity of stock, but Northport's institutions place greater marginal value on stocks as they become smaller relative to Southport. Dashed lines illustrate initial conditions, and dotted lines illustrate conditions after a climate-change-imposed change. Regions A–E and A–H represent additions or subtractions from wealth-associated change in natural capital.

Two cases when the ports manage asymmetrically with non-open-access management. Relax the assumption that the two ports begin with the same stock. First consider case three, where Northport's stock is smaller than Southport's, but Northport's institutions are less effective at preserving the value of the fish asset or the resource provides less value to Northport, for example, poorer market access (Fig. 3a). This shifts Northport's price function down $P_{NP}(K) < P_{SP}(K)$. In this case, a transfer from Southport, where stocks are relatively plentiful (k_{SP}), to a Northport, where stocks are relatively rare (k_{NP}), does not enhance the aggregate IW. Southport's loss of $A + C + E$ exceeds Northport's gain of $B + D$ (Fig. 3a).

In the fourth case it is possible that a transfer of s stock from Southport to Northport (all else equal) enhances aggregate wealth. This can happen if Northport's pre-climate change institutions are more conservation-oriented (assuming that climate does not influence these institutions). Figure 3b shows a case where the marginal value of fish stock rises more quickly in Northport as the stock declines $P_{NP}(k) > P_{SP}(k)$) — the fish stock is 'scarcer' in an economic sense. Southport loses the value $A + C + G$, and Northport gains the value $B + E + F + H$. If Northport's accounting price function is steep enough, then $G = F + H$ and $C + D = E$. Therefore, $C < E$, and it becomes an empirical question whether $A - D$ or B is larger, which determines if climate change leads to an aggregate loss or gain.

An important feature of the reallocation of wealth by climate change is that the donating and receiving institutions matter, as do other factors affecting value, including market and cost factors. If climate change reallocates natural capital from areas facing institutional failures (for example, open access) to areas that place a premium on scarce resources, for example, through management institutions that create positive and downward-sloping price curves, then climate change could increase aggregate IW. For example, if the regulatory institutions of a high-latitude region more effectively preserve stock value than lower-latitude institutions, then if climate change reallocates stocks polewards, aggregate IW could increase, holding all else equal. Of course, the reverse is also true: if the receiving institutions do a poorer job preserving value than the donating institutions, then the decline in IW will be even greater than if sustainability is only measured on the basis of the preservation of physical quantities (for example, footprints). The direction and magnitude of change is influenced by the degree to which institutions differ across the donating and receiving institutions.

Beyond natural capital

Climate change can affect the prices of more than natural capital. In general, each capital asset's price could be represented as $P_i(N,H,R;\phi)$, where the vector of capital stocks, $\mathbf{K}$, is divided into natural, N, human, H, and reproducible (built) R capital. Therefore, a critical question is what is $\Delta P_i \Delta N$, particularly when $i \neq N$? Deacon *et al.*[62] suggest that regulations, especially those on reproducible fishing capital, influence the value of natural and human capital. They show the potential for non-monotonic relationships between the intensity of regulation and the dividends from natural capital. Muller and Albers[66] discuss how labour and product market conditions jointly influence the accounting prices of natural, human and built capital. Changes in human capital that enable alternative marketing strategies could also affect the values of natural and reproducible capital.

Changes in the stocks of fish may not directly influence the quantity of boats (at least on the short term and especially under limited entry conditions), but may strongly influence the value of the boats. If the quantity of fish declines, individuals have fewer incentives to maintain fishing-related capital. Fewer people may train in fishing and acquire fishing skill, decreasing the stock of human capital; alternatively, maintenance on boats may be deferred, accelerating depreciation. A hypothesis consistent with Nadiri and Rosen[67] is that accounting prices for fishing capital and fishing skill fall as the fish stock declines. For non-diversified resource-dependent areas, climate change may not only reduce natural capital stocks; it could also have secondary effects through the impacts on value and investment decisions related to human and reproducible capital. For areas that receive new endowments of natural capital the effects may be reversed. Institutions governing these complementary forms of capital greatly matter.

Climate change will create winners and losers, and some forms of wealth will be reallocated. Theory provides no predictions about the aggregate outcome and biophysical models tell a very incomplete story. If climate change results in reallocations of natural resources from areas with weak institutions to those with strong, wealth-preserving institutions, then climate change could generate an aggregate increase in wealth. However, losses could still be highly impactful locally, jeopardizing equity and sustainability at local scales. Furthermore, how groups define themselves, and hence the idea of local impacts, could be influenced by climate change. In the fishing example, how society invests resources that would have gone into fishing boat maintenance or training fishers matters for the local impacts. Wealth-enhancing investments could instead be made in assets not material to the fishery (for example, schools and built infrastructure). Thus although the local fishery might not be sustainable, a broader group could be.

Conclusion

The physical changes exacted by a changing climate are unlikely to be proportional to the wealth changes that result. It is not possible to account for the impact of climate change without considering how the wealth effects work their way through the social–ecological system, potentially changing couplings. For example, how climate change will impact the contribution of 'the commons' to IW depends as much on management institutions and allocation rules as on biophysical dynamics.

Interest in climate change has catalysed many interdisciplinary efforts, but climate change is not an organizing framework for research. IW, however, can provide a framework for interdisciplinary collaborations[48]. Measuring IW requires deeper collaboration among natural and social scientists than standard climate integrated assessment models, because measuring IW must capture multiple feedbacks[68–70]. Using IW to measure sustainable development in the face of climate change highlights the importance of natural science in the measurement of social and economic well-being. Equation (4) provides guidance at the resource scale, and equation (3) provides guidance at the social–ecological system scale. To measure accounting prices, parts of equation (4) require scientific contribution from natural and socio-economic scientists. The equation suggests how these pieces need to come together and provides an organizational framework for interdisciplinary activities around climate change.

The links among climate change, physical and ecosystem change and sustainable development are challenging to identify and disentangle, and yet social concern about climate change is ultimately about the role that climate change has in directing, enabling or challenging sustainable development. IW provides a useful approach locally and globally. The greatest climate-driven reallocations of wealth are likely to be in the form of natural capital, which accounts for at least 28% of global wealth[3]. Markets for natural capital are largely missing or highly distorted[21], making market-driven adaptation unlikely. If climate change shifts resources from regions with weak resource governance to more capable regions, then it is possible that even if physical quantities of natural capital stocks decline, global wealth could increase. The reverse is also true — and seemingly more likely. Without more accurate measures of the value of natural capital and better measures of IW, it is not clear if climate change will increase or decrease global wealth.

Equally important, without clearer measures of wealth changes, it is not clear who will be the losers, who will be the winners and just how much wealth climate change will reallocate. Indeed, it is possible that reallocation of wealth will prove more disruptive than simple losses or gains, particularly in a globally connected and competitive world. In addition to better tracking aggregate changes in wealth, a better accounting of how climate change reallocates wealth will help to expose the implications for equity and distribution[71] — potentially leading to more fruitful regional and international agreements that include transfers between groups and countries.

Received 21 August 2015; accepted 21 October 2015; published online 24 February 2016

References

1. *Does Income Inequality Hurt Economic Growth?* (Directorate for Employment, Labour and Social Affairs, OECD, 2014).
2. Stiglitz, J. E., Sen, A., Fitoussi, J.-P. *Mis-measuring Our Lives: Why GDP Doesn't Add Up* (New Press, 2010).
3. UNU-IHDP and UNEP *Inclusive Wealth Report 2014: Measuring Progress Toward Sustainability* (Cambridge Univ. Press, 2014).
4. Agarwala, M., Atkinson, G., Baldock, C. & Gardiner, B. Natural capital accounting and climate change. *Nature Clim. Change* **4,** 520–522 (2014).
5. Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J. & Hanson, C. E. (eds) *Climate Change 2007: Impacts, Adaptation and Vulnerability* (IPCC, Cambridge Univ. Press, 2007).
6. Nelson, E. J. *et al.* Climate change's impact on key ecosystem services and the human well-being they support in the US. *Front. Ecol. Environ.* **11,** 483–893 (2013).
7. O'Brien, K. L. & Leichenko, R. M. Double exposure: assessing the impacts of climate change within the context of economic globalization. *Glob. Environ. Change* **10,** 221–232 (2000).
8. O'Brien, K. & Leichenko, R. Climate change, equity and human security. *Die Erde* **137,** 165-179 (2006).
9. Adger, W. N. *Fairness in Adaptation to Climate Change* (MIT, 2006).
10. Cheung, W. W. L., Close, C., Lam, V., Watson, R. & Pauly, D. Application of macroecological theory to predict effects of climate change on global fisheries potential. *Mar. Ecol. Prog. Ser.* **365,** 187–197 (2008).
11. Turner, W. R. *et al.* Climate change: helping nature survive the human response. *Conserv. Lett.* **3,** 304–312 (2010).
12. Quaas, M. F., Reusch, T. B., Schmidt, J. O., Tahvonen, O. & Voss, R. It is the economy, stupid! Projecting the fate of fish populations using ecological-economic modeling. *Glob. Change Biol.* **22,** 264–270 (2016).
13. Tavoni, A. & Levin, S. A. Managing the climate commons at the nexus of ecology, behaviour and economics. *Nature Clim. Change* **4,** 1057–1063 (2014).
14. Dasgupta, P. *Human Well-Being and the Natural Environment* (Oxford Univ. Press, 2007).
15. Adger, W. N., Arnell, N. W. & Tompkins, E. L. Successful adaptation to climate change across scales. *Glob. Environ. Change* **15,** 77–86 (2005).
16. Eriksen, S. *et al.* When not every response to climate change is a good one: Identifying principles for sustainable adaptation. *Clim. Dev.* **3,** 7–20 (2011).
17. Denton, F. *et al.* in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects* (eds Field, C. B. *et al.*) 1101–1131 (IPCC, Cambridge Univ. Press, 2014)
18. Heal, G. Reflections—defining and measuring sustainability. *Rev. Environ. Econ. Policy* **6,** 147–163 (2012).
19. Hanley, N., Dupuy, L. & McLaughlin, E. Genuine savings and sustainability. *J. Econ. Surv.* **29,** 779–806 (2015).
20. Dasgupta, P. The welfare economic theory of green national accounts. *Environ. Resour. Econ.* **42,** 3–38 (2009).
21. Dasgupta, P. Measuring the wealth of nations. *Annu. Rev. Res. Econ.* **6,** 17–31 (2014).
22. Arrow, K. *et al.* Are we consuming too much? *J. Econ. Perspect.* **18,** 147–172 (2004).
23. Pearson, L. J., Biggs, R., Harris, M. & Walker, B. Measuring sustainable development: the promise and difficulties of implementing Inclusive Wealth in the Goulburn-Broken Catchment, Australia. *Sustain. Sci. Pract. Policy* **9,** 16–27 (2013).
24. Miller, K. A. & Munro, G. R. Climate and cooperation: a new perspective on the management of shared fish stocks. *Mar. Resour. Econ.* **19,** 367–393 (2004).
25. Sumaila, U. R., Cheung, W. W. L., Lam, V. W. Y., Pauly, D. & Herrick, S. Climate change impacts on the biophysics and economics of world fisheries. *Nature Clim. Change* **1,** 449–456 (2011).
26. Chen, I.-C., Hill, J. K., Ohlemüller, R., Roy, D. B. & Thomas, C. D. Rapid range shifts of species associated with high levels of climate warming. *Science* **333,** 1024–1026 (2011).
27. Pinsky, M. L., Worm, B., Fogarty, M. J., Sarmiento, J. L. & Levin, S. A. Marine taxa track local climate velocities. *Science* **341,** 1239–1242 (2013).
28. Poloczanska, E. S., Hoegh-Guldberg, O., Cheung, W. W. L., Pörtner, H. O. & Burrows, M. T. in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects* (eds Barros, V. R. *et al.*) 123–127 (IPCC, Cambridge Univ. Press, 2013).
29. Lin, H. *et al.* Spatio-temporal dynamics on the distribution, extent, and net primary productivity of potential grassland in response to climate changes in China. *Rangeland J.* **35,** 409–425 (2013).
30. Petitgas, P. *et al.* Anchovy population expansion in the North Sea. *Mar. Ecol. Prog. Ser.* **444,** 1–13 (2012).

31. Mendelsohn, R. O. The economics of adaptation to climate change in developing countries. *Clim. Change Econ.* **3,** 1250006 (2012).
32. Mendelsohn, R. & Dinar, A. *Climate Change and Agriculture: An Economic Analysis of Global Impacts, Adaptation, and Distributional Effects* (Edward Elgar, 2009).
33. Lawler, J. .J. *et al.* Resource management in a changing and uncertain climate. *Front. Ecol. Environ.* **8,** 35–43 (2010).
34. Ostrom, E. *Governing the Commons: The Evolution of Institutions for Collective Action* (Cambridge Univ. Press, 1990).
35. Stavins, R. N. The problem of the commons:still unsettled after 100 years. *Am. Econ. Rev.* **101,** 81–108 (2011).
36. Libecap, G. D. *Contracting for Property Rights* (Cambridge Univ. Press, 1994).
37. Reed, W. J. & Heras, H. E. The conservation and exploitation of vulnerable resources. *Bull. Math. Biol.* **54,** 185–207 (1992).
38. Dasgupta, P. & Maler, K.-G. Net national product, wealth, and social well-being. *Environ. Dev. Econ.* **5,** 69–93 (2000).
39. Barbier, E. B. Wealth accounting, ecological capital and ecosystem services. *Environ. Dev. Econ.* **18,** 133–161 (2013).
40. Barbier, E. B. Account for depreciation of natural capital. *Nature* **515,** 32–33 (2014).
41. Fisher, I. *The Nature of Capital and Income* (Norwood, 1906).
42. Hotelling, H. The economics of exhaustible resources. *J. Polit. Econ.* **39,** 137–175 (1931).
43. Arrow, K. J., Dasgupta, P. & Maler, K.-G. Evaluating projects and assessing sustainable development in imperfect economies. *Environ. Resour. Econ.* **26,** 647–685 (2003).
44. Arrow, K. J., Dasgupta, P., Goulder, L. H., Mumford, K. J. & Oleson, K. Sustainability and the measurement of wealth. *Environ. Dev. Econ.* **17,** 317–353 (2012).
45. World Commisson on Environment and Development *Our Common Future* (Oxford Univ. Press, 1987).
46. Fenichel, E. P. & Abbott, J. K. Natural capital from metaphor to measurement. *J. Assoc. Environ. Res. Econ.* **1,** 1–27 (2014).
47. Inklaar, R. & Timmer, M. P. *Capital, Labor and TFP in PWT8.0.* (Groningen Growth and Development Centre, University of Groningen, 2013); http://www.rug.nl/research/ggdc/data/pwt/v80/capital_labor_and_tfp_in_pwt80.pdf
48. Fenichel, E. P. *et al.* Measuring the value of groundwater and other forms of natural capital. *Proc. Natl Acad. Sci. USA* http://dx.doi.org/10.1073/pnas.1513779113 (2015).
49. Miranda, M. J. & Fackler, P. L. *Applied Computational Economics and Finance* (MIT, 2002).
50. Jorgenson, D. W. Capital theory and investment behavior. *Am. Econ. Rev.* **53,** 247–259 (1963).
51. McCay, B.J., Brandt, S. & Creed, C. F. Human dimensions of climate change and fisheries in a coupled system: the Atlantic surfclam case. *ICES J. Mar. Sci.* **68,** 1354–1367 (2011).
52. Pinsky, M. L. & Fogarty, M. J. Lagged social-ecological responses to climate and range shifts in fisheries. *Climatic Change* **115,** 883–891 (2012).
53. Pörtner, H. & Knust, R. Climate change affects marine fishes through the oxygen limitation of thermal tolerance. *Science* **315,** 95–97 (2007).
54. Bates, A. E. *et al.* Defining and observing stages of climate-mediated range shifts in marine systems. *Glob. Environ. Change* **26,** 27–38 (2014).
55. Worm, B. *et al.* Rebuilding global fisheries. *Science* **325,** 578–585 (2009).
56. Behrenfeld, M. J. *et al.* Climate-driven trends in contemporary ocean productivity. *Nature* **444,** 752–755 (2006).
57. Bopp, L. *et al.* Multiple stressors of ocean ecosystems in the 21st century: Projections with CMIP5 models. *Biogeosciences* **10,** 6225–6245 (2013).
58. Sillmann, J., Kharin, V. V., Zwiers, F. W., Zhang, X. & Bronaugh, D. Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections. *J. Geophys. Res. Atmos.* **118,** 2473–2493 (2013).
59. Caswell, H. *Matrix Population Models: Construction, Analysis, and Interpretation* 2nd edn (Sinauer, 2001).
60. Gutierrez, A. P. & Regev, U. The bioeconomics of tritrophic systems: application to invasive species. *Ecol. Econ.* **52,** 383–396 (2005).
61. Homans, F. R. & Wilen, J. E. A model of regulated open access resource use. *J. Environ. Econ. Manag.* **32,** 1–21 (1997).
62. Deacon, R. T., Finnoff, D. & Tschirhart, J. Restricted capacity and rent dissipation in a regulated open access fishery. *Resour. Energy Econ.* **33,** 366–380 (2011).
63. Fenichel, E. P., Gopalakrishnan, S. & Bayasgalan, O. in *Handbook on the Economics of Natural Resources* (eds Halvorsen, R. & Layton, D. F.) 165–205 (Edward Elgar, 2015).
64. Clark, C. W. *Mathematical Bioeconomics: the Optimal Management of Renewable Resources* 2nd edn (Wiley, 2005.)
65. Horan, R. D., Fenichel, E. P., Drury, K. L. S. & Lodge, D. M. Managing ecological thresholds in coupled environmental–human systems. *Proc. Natl Acad. Sci. USA* **108,** 7333–7338 (2011).
66. Muller, J. & Albers, H. J. Enforcement, payments, and development projects near protected areas: how the market setting determines what works where. *Resour. Energy Econ.* **26,** 185–204 (2004).
67. Nadiri, M. I. & Rosen, S. Interrelated factor demand function. *Am. Econ. Rev.* **59,** 457–471 (1969).
68. Nordhaus, W. D. Rolling the 'DICE': an optimal transition path for controlling greenhouse gases. *Resour. Energy Econ.* **15,** 27–50 (1993).
69. Nordhaus, W. D. *The Climate Casino* (Yale Univ. Press, 2013).
70. Manne, A., Mendelsohn, R.O. & Richels, R. MERGE: a model for evaluating regional and global effects of GHG reduction policies. *Energy Policy* **23,** 17–34 (1995).
71. Stanton, E. A. Negishi welfare weights in integrated assessment models: the mathematics of global inequality. *Climatic Change* **107,** 417–432 (2011).

Acknowledgements
Research support by NSF awards OCE-1426700, OCE-1426746 and OCE-1426891, NJ Sea Grant award R/6410-0011, the Knobloch Family Foundation, and the project Green Growth Based on Marine Resources: Ecological and Socio-Economic Constraints (GreenMAR), funded by Nordforsk.

Author contributions
E.P.F. and M.L.P. conceived the paper; E.P.F., M.L.P. and J.K.A. conducted analyses; E.P.F. led writing and all authors contributed to edits.

Additional information
Reprints and permissions information is available online at www.nature.com/reprints. Correspondence should be addressed to E.P.F.

Competing financial interests
The authors declare no competing financial interests.