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A Framework with Application to Elephants and Whales

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Abstract: We develop a framework for natural resource valuation that directly addresses the fundamental collective action problem in environmental protection. Our framework uses the lessons of behavioral economics to create values that individual decisionmakers find credible and relatable, in addition to stimulating excitement or concern that is essential to prompting action. We then apply this framework to value forest elephants in Africa and great whales that are found off the coasts of Brazil and Chile. The values we estimate for individual members of these species are significant: \$1.75 million per forest elephant and an average of \$2 million per whale. We discuss how our valuations lead to new designs for environmental preservation and restoration policies.

JEL Codes: D62, G12, G41, Q5, Q54, Q57

Keywords: Climate Change, Valuation, Carbon Capture, Behavioral Economics

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1. Introduction

In most economic and financial contexts, the tools of valuation are used to make resource allocation or capital budgeting decisions. In these situations, the prior decision of whether to expend resources in order to reach an objective has already been made in favor of doing so, so that the purpose of valuation is to determine how best to deploy resources to attain the objective. For example, an individual's portfolio allocation problem, solved by applying models such as the Capital Asset Pricing Model or Arbitrage Pricing Theory, presumes that a household has already decided to smooth consumption over time or save toward goals such as starting a business.

In environmental economics, however, the tools of valuation are used not only to answer the allocation question, but also to motivate agents to answer the prior question—whether to expend any resources at all in pursuit of environmental objectives—affirmatively. As an example, The Economics of Ecosystems and Biodiversity (TEEB) initiative describes its goals in this way on its website (http://www.teebweb.org/about/the-initiative/):

> **The Economics of Ecosystems and Biodiversity** (TEEB) is a global initiative focused on **"making nature's values visible**". Its principal objective is to mainstream the values of biodiversity and ecosystem services into decision-making at all levels. It aims to achieve this goal by following a structured **approach** to valuation that helps decision-makers ***recognize*** the wide range of benefits provided by ecosystems and biodiversity, ***demonstrate*** their values in economic terms and, where appropriate, suggest how to ***capture*** those values in decision-making.

The National Research Council (2005, p. 2) describes the role of valuation in this way:

> Despite growing recognition of the importance of ecosystem functions and services, they are often taken for granted and overlooked in environmental decision-making. Thus, choices between the conservation and restoration of some ecosystems and the continuation and expansion of human activities in others have to be made with an enhanced recognition of this potential for conflict and of the value of ecosystem services.

These examples show that environmental economists explicitly employ valuation tools in an attempt to persuade individuals, businesses, and governments to expend resources on environmental protection and restoration. These attempts are necessary in order to overcome the significant disincentives to taking action associated with externalities and collective-action problems.

Because of these additional demands being placed on valuation tools by the environmental economics profession, it is sensible and necessary to reflect on whether the valuation tools and strategies currently being employed are effective at motivating people to commit their scarce resources to pursuing environmental protection and restoration. Unfortunately, it would be both very difficult and highly controversial to evaluate the impact of environmental valuation efforts on the amounts of resources (both financial and physical) expended in the pursuit of environmental protection and restoration. Nonetheless, it is probably fair to say that there is room for improvement. For example, since 1997 TEEB has produced estimates of the total value of ecosystem services provided by all of the planet's biomes. These estimates, which consistently produce a value larger than global GDP, do not appear to have catalyzed a wave of new investments in environmental protection and restoration.

It is still possible to evaluate the effectiveness of valuation methods and strategies in motivating environmental investments, however, by considering their characteristics rather than attempting to measure their impacts. One key characteristic is the ability of the information produced by the method to motivate or inspire people to take action. Several types of agents exist who use the information from environmental economics to make different types of decisions: individuals, business leaders, and policymakers. In order for a valuation method to be effective, each type of agent must find that the information produced by the method motivates them to take action. Although making judgments about the motivational power of a valuation method may at appear subjective, there is an extensive literature from economics, psychology, and marketing that we can draw from regarding attributes that make information persuasive or effective in provoking action.

This literature suggests that the motivational power of information comes from its ability to stimulate excitement or concern in the recipient. Information interacts with human emotions and cognitive biases to exert powerful influence over behavior and decisionmaking. For example, Hesketh (2015) argues that information is persuasive when it enables people to satisfy important psychosocial needs, like the need to be loved. Crimmins (2016) discusses how information that works with people's cognitive biases, such as the many heuristics that humans use to make decisions, is more successful at motivating people to act than information that works against these biases.

In many contexts, the motivational power of information is the sole measure of its effectiveness. But people whose decisions are publicly scrutinized, such as policymakers and business leaders, place additional demands on the information they use, in order to withstand this scrutiny. These include many qualities such as accuracy, reliability, and replicability, but we summarize them in a criterion we call credibility. Credibility of information reflects the difficulty of doubting or disproving its truth or accuracy: the more difficult it is to doubt or disprove a piece of information, the more credible it is. This is important to policymakers and business leaders because they need to defend their decisions in the face of public scrutiny. If a decision is based on credible information—ideally, the best information available at the time—it is difficult to attack or fault.

In addition to being credible, and able to stimulate excitement or concern, valuation information must also be relatable. Relatability describes the extent to which information is expressed in terms that humans find relevant and useful. For example, from the point of view of businesses, relatable valuation information is helpful in identifying and evaluating feasible business opportunities. People find information on costs and benefits expressed in monetary terms to be useful for making decisions. On the other hand, they generally find imprecise, complex or abstract information difficult to relate to their objectives and hence a much weaker motivation for making decisions or taking action.

As an example of environmental information that performs well with respect to all three criteria, consider a television advertisement for the World Wildlife Fund (WWF) that was widely broadcast in early 2020, which had the purpose of encouraging donations to fund efforts to protect polar bears. It featured video sequences of mother polar bears and their offspring, while the voiceover in the advertisement discussed how climate change was causing the ice floes that polar bears depend on to vanish. The advertisement mentioned scientific studies, which viewers would find credible, but expressed the implications of the studies in simple, concrete, relatable terms that people could understand: the disappearance of ice floes and the polar bears that need them for survival. The advertisement also took advantage of the emotional impact created by the video images, and the brain's tendency to jump to conclusions, to create the impression of polar bears desperately searching for ice floes, stimulating the viewer's concern.

Although we are not suggesting that the WWF advertisement should be a template for environmental valuation, it nevertheless offers some lessons for improving the ability of environmental valuation to motivate the recipients and users of these valuations to take action. In particular, we argue that the criteria discussed above and the example of the WWF advertisement suggest that the following valuation strategy would be more successful at inspiring action than current valuation approaches:

- Use only market-based methods of valuation.
- Value individual resources rather than groups of disparate resources or ecosystems.

Valuations based on these two broad guidelines will perform well according to the criteria discussed above. Market-based methods of valuation will tend to have high levels of credibility, as long as the markets from which prices are obtained are relatively free of distortions, because of the confidence that free-market prices are fully reflective of all social costs and benefits and thus reveal the "truth" regarding how society values a good or service. They will also have high levels of relatability because they express values in monetary terms, and because they will naturally identify the markets that are relevant to a particular natural resource.

Estimating the value of individual resources will also support the credibility of the valuations, since the linkages from the resource to its value should be transparent. This approach is also highly relatable, since an individual resource and the market-valued services it provides are both concrete and specific. Valuing individual resources also has high potential to work with human emotions and cognitive biases in order to create concern or excitement. Although the term "charismatic megafauna" sometimes carries negative connotations because these species tend to draw attention away from other natural resources, it nonetheless acknowledges that individual resources can take advantage of humans' affinity and availability heuristics in order to arouse excitement and concern. And the surprise that an unexpectedly high valuation of an individual resource engenders can also strongly stimulate excitement or concern.

There is a cost to this approach to environmental valuation, which is the fact that it omits any non-market and non-use values and therefore does not capture the total economic value (TEV) of a natural resource. Our approach thus necessarily represents a conservative approach to valuation, which places lower bounds on the values of individual natural resources. We argue that this is a contribution of our method rather than a drawback. By including only those services to which market prices can be readily assigned, we remove as much subjectivity as possible from the estimated values. Valuation will always be as much art as science, in which human judgement plays a key role in identifying the determinants of value as well as in selecting and applying valuation models. But our approach removes unsupported claims and cheap talk from the critical step of assigning monetary values to the service flows or to the resource itself. Therefore, we argue that the estimates produced by our method are reliable and convincing starting points for public discussion regarding whether—and how much—to invest in environmental protection[†].

Because our estimated values are lower bounds, they still allow for additional discussion about how the non-market-valued attributes of a particular natural resource should factor into the investment decision. We believe such discussions should always take place when making decisions about environmental protection investments. But if agreement cannot be reached about these difficult to measure sources of value, then the baseline monetary value provided by our estimates can still form a basis for constructive action, effectively preventing the perfect from becoming the enemy of the good.

In this paper, we outline a valuation procedure that follows the guidelines introduced above. Then we implement this valuation strategy on two resources—elephants and whales—to demonstrate its feasibility and its ability to produce valuations that people find more persuasive or motivational than existing methods and strategies. Part of the reason these resources were chosen is that new research has identified additional services, of significant market value, that are provided by these animals. Integrating these additional service flows into the values of whales and elephants is a further contribution of this paper.

The remainder of the paper is organized as follows. Section 2 develops the valuation model and the discusses its parameter requirements. Sections 3 and 4 apply the valuation procedure to African forest elephants and cetaceans (the nine great whales), respectively. Section 5 concludes.

2. A Valuation Framework for Natural Resources

Valuation of natural resources is an important area of research in the environmental economics literature. Although some benefits that flow from individual natural resources are traded and priced on markets, many if not most are not, and moreover, many natural resources produce only non-market-traded benefits. Thus, one focus of valuation research has been to use economic fundamentals such as preferences to estimate values for natural resources that cannot be fully valued by markets. One of the primary valuation benchmarks in this literature is willingness to pay (WTP), which is the amount that an individual would pay to enjoy a natural resource or contribute toward an effort to preserve it.

[†] See Lew (2015) for a discussion of criticisms of standard estimation methods.

WTP is generally estimated using one of two methods [‡]. Revealed preference methods utilize data on purchases to estimate hedonic pricing models, or data on other related expenditures, such as travel costs incurred, to estimate WTP. These methods are suitable for estimating the amount that people would pay to enjoy a natural resource. The opportunities to apply revealed preference models to natural resource valuation, however, have proven to be limited. Most natural resources are not purchased (or consumed) by their users, and other revealed preference approaches such as travel cost models are limited in the types of service flows (such as recreational flows) they can value.

The vast majority of studies that estimate WTP, therefore, use stated preference methods. As the name suggests, stated preference methods employ different types of surveys in which respondents state their willingness to pay taxes or fees that will be used to invest in specific natural resource preservation or enhancement programs. Stated preference methods are used to estimate public willingness to pay for individual conservation programs and for ranking competing programs. And for programs that aim to increase the population of a living resource, stated preference estimates could be interpreted as the value of an increase in the population. But they generally do not attempt to estimate the total values of specific natural resources.

Stated preference estimates of WTP tend to have lower credibility than market-based valuations, because the respondents to surveys are not generally required to pay the fees or taxes they claim they would pay. And it should not be forgotten that the valuations obtained are technically those of the programs proposed in the experiments rather than the resources to be protected by the programs.

In some cases, market valuation of individual resources may be possible as a consequence of quota or cap-and-trade systems designed to limit harvesting. For example, Costello, Gerber and Gaines (2012) propose that the International Whaling Commission's whaling quotas be replaced by tradable harvesting rights. To the extent that such a market would be open to any willing purchaser, the resulting price would establish market values for whales that are more reflective of all of society's preferences. Such arrangements, however, presume that the case for preserving the resources has already been argued successfully, as reflected in the decision to implement a system of harvest limits. This method also begs the question of how to set the initial quotas and caps, which would presumably depend on the value assigned to the resource. And as in the case of revealed preference methods, only a very small subset of natural resources are harvested whole and could be valued in this way.

Most approaches to market valuation focus on the services produced by natural resources. These borrow the idea from financial economics that the value of a physical capital good is derived from the stream(s) of services that the good produces. Physical capital goods are created for the purpose of producing streams of services that have an explicit market value. Many natural resources also produce streams of services that are valuable to society, although this is not their primary goal or purpose. TEEB (2010) provides an overview of the types of services and the

[‡] See Freeman (2004) for an extensive discussion of the methods used to estimate WTP. Lew (2015) also gives an extensive review of these methods and their applications to marine resources.

market-based methods of valuing them. While some services are priced in markets, such as ecotourism, other services provided by natural resources are regulatory services (such as predator or flood control) that are not directly priced in markets. Market values can be assigned to these services, however, by estimating what it would cost to replace them. Natural resources may also provide services that are inputs into the production of other goods and services to which market values can be assigned. Market values may be assigned to these factor-of-production services if the contribution of the natural resource to production can be estimated.

The valuation approach most similar to ours is embodied in the TEEB initiative as well as the Natural Capital Accounting method being developed by the U.K. Office of National Statistics (ONS) and Department for Environment, Food and Rural Affairs (Defra) (Philips 2017). As in our approach, Natural Capital Accounting seeks to recognize and quantify the goods and service flows arising from natural resources, so that a monetary value may be placed on them. For example, Natural Capital Accounting recognizes regulatory services such as greenhouse gas sequestration and market-valued services such as ecotourism, both which are also essential to our valuation analysis.

The aims of Natural Capital Accounting, however, are not well suited to the valuation of individual natural assets. This approach takes ecosystems as its unit of analysis, focusing on the valuation of entire biomes or ecosystems rather than their individual constituents. This method has also emphasized biodiversity, an ecosystem characteristic which has proven difficult to integrate into the Natural Capital Accounting framework as well as difficult to quantify and value (CIEEM 2019). Although there appear to be no theoretical obstacles to valuing individual natural resources using Natural Capital Accounting, no valuations of individual resources such as whales or elephants utilizing this framework have been published to date that we are aware of. To the extent that Natural Capital Accounting remains focused on valuing ecosystems, this approach does not perform well with respect to the relatability criterion. Biodiversity is too abstract, and ecosystems can be too large or too complex, to be helpful to individuals and businesses in making decisions. In addition, ecosystems do not appear to have a high ability to create excitement or concern, particularly in comparison to individual components of ecosystems.

Each of the above methods of valuation produces useful information for policymakers and the general public. But as our discussion indicates, none of them is well suited for estimating the value of individual natural resources. Therefore, we propose the following approach to natural resource valuation, which fills the need for this information. First, an individual natural resource is chosen. Then the services the resource produces are identified. These include only those services flowing from the natural resource that have been identified and measured in the academic and professional literature, and to which market values may be assigned.

Next, discounting is used to estimate the total market value of the services. The market value of an asset at any time is the discounted sum of the value of the services it is expected (or scheduled) to produce during all subsequent periods. Discounting the future values is necessary because these services are produced during many different future periods, and their value must be adjusted by the appropriate opportunity cost of waiting to receive these services. We initially assume for simplicity that only one type of service is produced by a physical capital asset. If we let ***s*** be the quantity of services produced, ***p*** be the market value (price) of these services, and ***r*** be the appropriate discount rate, then the value ***V*** of the physical capital asset is given by

$$V_t = \sum_{i=1}^{\infty} \frac{p_{t+i} s_{t+i}}{(1+r)^i}$$

This valuation equation is easily modified to accommodate multiple, distinct service streams because of the additivity of present values. If a physical capital good produces n distinct service streams with market prices $p_1, \ldots, p_n$, then the value of the capital good is given by

$$V_t = V_{1,t} + V_{2,t} + \ldots + V_{n,t} = \sum_{i=1}^{\infty} \frac{p_{1,t+i} s_{1,t+i} + p_{2,t+i} s_{2,t+i} + \ldots + p_{n,t+i} s_{n,t+i}}{(1+r)^i}$$

To summarize, the following procedure is used in this paper and can be used to estimate the money value of any individual natural resource:

1. Identify the services produced by the resource.

    a. Verifiable estimates of the quantities of services produced must exist in the academic or professional literature.

    b. If the quantity produced of a service is not measured in money, market prices must exist that can be sensibly assigned to the service.

2. Project the market values of each service ($p_{j,t+i}s_{j,t+i}$) into the future.

3. Assign a discount rate appropriate to the natural resource and the service(s) produced.

4. Using the values projected in Step 2, calculate the value of the resource using equation (2).

The best way to demonstrate the utility of this approach—and to recognize the issues it raises—is to move directly to extended examples in which we apply the above procedure to estimate the values of natural resources. In the following sections, therefore, we apply our framework to value African forest elephants, and to value great whales found off the coasts of Brazil and Chile.

3. Applying the Framework to the Valuation of Forest Elephants in Africa

Our first application estimates the value of African forest elephants (*Loxodonta cyclotis,* Matschie, 1900), a sub-species of the African elephant (*Loxodonta africana,* Blumenbach, 1797*)*. Forest elephants live in the rain forests of central and western Africa and are genetically and morphologically different from the ones inhabiting savannas. Further differences between savanna and forest elephants are their ecosystem engineering role. We focus on forest elephants as their ecosystem services (described below) have recently been quantified (Berzaghi et al. 2019).

Step 1: Identify the services produced by the resource

Elephants produce several types of services that could be valued using market prices. First, in some places such as south- and southeast Asia, elephants are employed commercially as beasts of burden. Forest elephants are generally not used for this purpose. Elephants also undoubtedly generate ecotourism revenues, since they are one of the “big five” species that tourists wish to see when they visit African game preserves and parks. It is difficult to separate ecotourism revenues into those due specifically to elephants, however. Moreover, the majority of African ecotourism takes place in the savannahs rather than in the rainforests, where tourism is still underdeveloped. Because of these difficulties with measurement, we do not include these services in our elephant valuations.

On the other hand, forest elephants do produce carbon-capture services that can be valued. Elephants contribute to carbon capture and long-term storage in two ways. First, as large animals, elephants store nontrivial amounts of carbon on their bodies. Considering the average body mass of a mature forest elephant is 3000 kg (Grubb et al. 2000), we estimated that each individual body is composed of 24 percent carbon, or 720 kg (see methods).

Although an individual elephant will eventually die and the carbon carried on its body will be released back into the ecosystem or the atmosphere in the form of CO_2, a stable population of elephants will continually store some amount of carbon. We can therefore value the carbon currently stored on the bodies of the existing population of elephants as if it were sequestered, assuming that current populations are maintained. In addition, any permanent increase in the population (that is, increase to the equilibrium or steady-state population) implies that an additional amount of carbon can be added to the total amount sequestered in elephant bodies.

The second way in which African forest elephants sequester carbon is through their impact on the forest ecosystem. Large herbivores and megaherbivores are known to have significant impacts on their ecosystems, and by extension on the biogeochemical cycles taking place in these ecosystems. Recent research by Berzaghi et al (2019) has shown that the activity of forest elephants contributes to the net accumulation of aboveground biomass (carbon) stored in trees. While moving through the forest and foraging for food, elephants reduce the density of trees smaller than 30 cm in diameter. This reduction in tree density changes light and water availability in the forest leading to an increase in the proportion and the average size of late-succession trees. Compared to other type of trees, late-succession trees are longer lived, require less light and water to survive, and become dominant once they reach the canopy. Late-successional trees store more carbon than other types of trees (given the same volume), so as their average size and abundance increase, there is a net increase in the amount of carbon stored in the forest.

Step 2: Project the market value of services provided into the future

An important question that arises when valuing living organisms is how to model future populations. The services provided by future offspring can be a significant source of the current population’s value, which implies that both over- and undervaluation are possible. In addition, the projected future population embeds assumptions about conservation and restoration that should be made transparent. Therefore, a population growth model is needed for each species. How population growth affects the production of services must also be specified.

In this paper, we project that future populations of both elephants and whales will grow from their current levels and eventually return to their estimated sizes before the advent of large-scale poaching and industrial whaling, respectively. We have two reasons for doing so. First, the current populations of elephants and whales are far below—on the order of ten percent of—their historical numbers. We argue that assuming a return to what scientists believe are their equilibrium populations strikes the right balance between over- and undervaluation. Second, estimates of the services provided by elephants and whales found in the literature are often based on the assumption of a return of the species to their previous population sizes.

We construct a model of population growth for elephants that utilizes data on birth rates, survival rates of calves and adults, ages at first reproduction, and intervals between births (Turkalo et al. 2017, 2018). A logistic function is used to model the birth rate, which converges to the death rate as the population reaches its steady-state value equivalent to the estimated pre-poaching population. Free parameters of the growth model are calibrated so that the initial numbers of births imply a constant ratio of births to population. Details of the construction of the population growth models are given in Appendix 1.

Carbon Capture and Sequestration Through Elephant Biomass

In order to value carbon capture, an estimate of the market price of this service is needed. The most developed markets for carbon capture deal in carbon dioxide rather than pure carbon, since these markets were created in order to limit carbon dioxide emissions from industrial production, power generation, and transportation. Thus, all estimates of carbon capture and sequestration must be converted to their CO_2 equivalent by multiplying the amount of carbon by 11/3. Although many carbon-trading markets exist globally, the most liquid is the European market ETS. We argue that this market provides the best estimate of the market price of carbon.

We estimate the value of carbon sequestration on elephant bodies by first calculating the amount of carbon sequestered by current and future elephant populations. Then the carbon is converted to its CO_2 equivalent and multiplied by the price of $24.72 per tonne of CO_2.[§]

From above, the amount of carbon on the average elephant's body is 720 kg, which is multiplied by the current population of 100,000 individuals to obtain the starting amount of carbon sequestered. Additional carbon is sequestered each period equivalent to the change in elephant population implied by the growth model, multiplied by 720 kg. The amount of carbon on each elephant is equivalent to 720*11/3 = 2640 kg or 2.64 tonnes of carbon dioxide.

[§] The price of CO_2 per tonne is the average daily value during 2019 on the EU ETS. See https://markets.businessinsider.com/commodities/historical-prices/co2-european-emission-allowances/eur/1.1.2006_2.5.2020

Carbon Capture and Sequestration Through Stimulating Forest AGB Increase

Our approach is to first value the carbon capture contributed by the current elephant population and then add the carbon sequestered by each additional elephant as the population increases. We assume that the changes made to the forest by elephant activity are permanent, so that the increase in carbon capture is effectively permanent.

Berzaghi et al (2019) estimate that if forest elephant populations were to recover to their historic population, each forest elephant would stimulate a net increase in carbon capture in central African rain forests of 26 tonnes of C per hectare. Given the historic density of 0.5 elephants per km^2, this implies an actual increase in carbon capture of 13 tonnes of C per hectare. This increase in carbon capture will take place over a long period, however, for two reasons. The change in forest composition due to elephant activity will take decades to be completed, and the increase in the elephant population from their current number of approximately 100,000 individuals to their historic level of 1.1 million will require centuries to occur.

In order to make the carbon sequestration calculations simple and manageable, we make the following assumptions. First, we assume that the existing elephant population currently occupies only 200,000 km^2 of their historic range of 2.2 million km^2 at a population density of 0.5 elephants per km^2(but see Maisels et al. 2013 as the current population is highly fragmented across central Africa). This enables us to estimate the current carbon sequestration services of the existing elephant population by assuming that these individuals have already increased carbon capture of forests by 13 tonnes per hectare in this area.

For each new cohort born, we assume that the cohort moves to an unoccupied portion of the forest elephants' historic range and lives there at a density of 0.5 elephants per km^2. The area of the plot occupied is therefore determined by the size of the cohort and the assumed population density of 0.5 elephants per km^2. On each newly occupied plot, we assume that the initial amount of carbon captured is 3.25 tonnes, and this increases due to the elephants' activity at a constant rate over the next 150 years until the full 13 tonnes per hectare is reached, which is equivalent to 9533 tonnes of carbon dioxide per km^2. Once the carbon capture has increased by 13 tonnes per hectare, the increment goes to zero so that no further services are contributed to the valuation by the cohort. The annual increments are multiplied by the price of carbon dioxide.

This assumed process of new cohorts settling unoccupied portions of the historic range and increasing carbon capture within these new settlements continues until the elephant population has grown to its pre-poaching population, at which time they will fully occupy their historic range. According to the parameters of the population growth model we developed, this will require about 9 centuries.

Step 3: Assign a discount rate appropriate to the natural resource and the service(s) produced.

According to financial economic theory, the discount rate used to value an asset consists of two components. The first is the risk-free interest rate, which is better understood as the return required to overcome human impatience and induce a person to wait for a future payment. The second component is a risk premium, which compensates the holder of an asset for the systematic or nondiversifiable risk that the asset incurs. The identifying feature of systematic risk is that it is common to many assets, making their payoffs fluctuate in concert. Thus, the most common measure of systematic risk is the covariance of an asset's payoff with the payoffs of other risky assets, such as the return to the market portfolio of assets.

Although the payoffs to a natural resource can be risky, this risk is not necessarily systematic. If the values of the streams of services provided by the resource do not exhibit significant covariance with other assets' payoffs, then the risk in the resource is idiosyncratic risk, which does not earn a risk premium. The flows of carbon-capture services from living adult elephants will remain roughly constant on a per-elephant basis, no matter how the payoffs from other assets fluctuate. Fluctuations in the quantities of these service streams come mainly from two sources. The first is expected population growth, which is likely to be uncorrelated with fluctuations in the payoffs from other assets. Unexpected fluctuations in services would primarily come from higher than average mortality among elephants. The events that cause unexpected mortality in elephants include poaching and disease. The occurrence of such events is likely to be uncorrelated with fluctuations in the payoffs from other assets.

The value of carbon-capture services produced by elephants can also vary because of fluctuations in the price of carbon. The most actively traded carbon market in the world currently is the EU's ETS market for carbon-dioxide emissions. We obtained data on monthly closing prices of carbon emissions credits from this market and estimated a standard CAPM regression of the form

$$R_{CO2,t} - R_{f,t} = \alpha + \beta(R_{M,t} - R_{f,t}) + \varepsilon_t$$

where R_{CO2} is the monthly return on carbon emissions credits, R_f is the risk-free rate proxied by three-month U.S. Treasury bill yields, and R_M is the market return proxied by the monthly return on the S&P 500 equity index. Our estimate for the 2014-2019 period produced a positive but statistically insignificant coefficient. This implies that the price of carbon is not significantly correlated with other asset returns, suggesting that the appropriate discount rate for carbon-sequestration services is the long-term, risk-free rate.

Given that a long-term, risk-free discount rate is appropriate for valuing the benefits of elephants, the next question is how to estimate it in the context of environmental valuation. TEEB (2016) argues that the "impatience" component of the risk-free rate should be exactly zero, implying a near-zero risk-free rate when the effect of intertemporal substitution is taken into account. Philips (2017) uses the HM Green Book Social Discount rates, which decline from a top rate of 3.5 percent for periods up to 30 years, to a rate of 2.5 percent for periods up to 100 years, but cautions that these rates tend to "overdiscount" the future, or are in other words too high. Professional investors commonly use the 10-year government bond yield as their estimate of the risk-free rate. Using the U.S. 10-year government bond rate and adjusting for inflation estimated via the GDP deflator, we obtain an average 10-year yield of approximately 2.65 percent over the 1954-2018 period. We choose two percent for the risk-free rate, since this reflects market evidence and the practices in the existing literature, but also lessens the likelihood that we are overdiscounting.

Step 4: Using the values projected in Step 2, calculate the value of the resource using equation (2).

Present values were calculated using a 1000-year horizon. Using a starting population of 100,000 mature elephants, the future population path generated by the population growth model, and the other valuation parameters described above, we calculate a present value of carbon sequestration on elephant bodies of $166 per individual.

The present value of carbon sequestration through an increase in carbon stored in AGB, however, is quite large. The total present value of this service is the sum of the contribution of the current elephants and the contribution from future generations of elephants.

PV of Increased Forest Biomass=$23.5656 Billion + $152.7173 Billion = $176.2829 Billion.

Dividing this total value by the current population of elephants implies a value of $1,762,829 per elephant for this service. If we add the $166 for carbon sequestration on elephants' bodies, we obtain a total value of $1,762,995 per elephant.

Discussion

The result of this valuation demonstrates the potential of our approach to stimulate excitement, concern, and ultimately action. At over $1.75 million, the value of a single forest elephant is a striking number that is likely to gather significant attention, since people will want to know what exactly makes this creature so valuable. These inquiries will lead to further opportunities to educate the public about elephants' contributions to carbon capture, and convince individuals to spend their resources on preservation of this species and its habitat. For example, a public relations campaign could be built around comparing the value of a live forest elephant capturing carbon—$1.75 million—to one that has been killed for its ivory, about $20,000 per tusk. Showing that the loss of a forest elephant implies the loss of valuable and important carbon sequestration services—which benefit humans—converts an intangible and remote psychic harm (the brutal and unnecessary death of a forest elephant) to a more direct and concrete harm to personal wellbeing (worsening consequences of climate change). We argue that this will significantly increase people's willingness to commit resources to elephant preservation and restoration.

This number should also generate interest among investors. Our valuation creates a "fundamentals" based estimate of the worth of a specific, tangible asset. This in turn creates a potential investment opportunity that is similar to the standard investment opportunities that financial professionals are familiar with. The challenge for investors is to devise instruments that would enable them to realize this potential value in terms of cash. Although this will be difficult, the size of the prize—over $176 billion total for the existing population of forest elephants—would undoubtedly attract many entrepreneurs and investment professionals who could profit either from taking an ownership stake in this investment, or earning commissions from marketing this instrument to other investors.

4. Applying the Framework to the Valuation of Great Whales Frequenting the Brazilian and Chilean Coasts

This application considers great whales found off the coasts of Brazil and Chile. The great whales we include in our valuation are the nine large baleen whales (blue, bowhead, fin, minke, sei, right, humpback, gray and Bryde's), plus the sperm whale. Most but not all of these different species spend significant parts of the year off the coast of Brazil, and some are resident year round. In the case of Chile, we consider only the blue whale due to data limitations. Whales make an interesting valuation case study because they produce several distinct services to which market values can be assigned, including services that recent research has helped to quantify.

As in the case of elephants, we project future populations by assuming that the populations of whales will eventually grow to reach their historical (pre-industrial-whaling) numbers. We construct a model of population growth for each whale species that utilizes data on birth rates, survival rates of calves and adults, ages at first reproduction, and intervals between births for each species of great whale. A logistic function is used to model the birth rate, which converges to the death rate as the population reaches its steady-state value. Free parameters of the growth model are calibrated so that the initial numbers of births imply a constant ratio of births to population. Details of the construction of the population growth models are given in Appendix 1.

Step 1: Identify the services produced by the resource

Whales produce at least three services that society values and which have been measured by scientists and economists: ecotourism (whale watching), carbon capture, and fisheries enhancement. The carbon capture services can be further separated into the carbon captured in whale biomass, and the carbon captured by phytoplankton production that can be attributed to whale activities.

Step 2: Project the market value of services provided into the future

Ecotourism (Whale Watching)

A benchmark estimate of the market value of whale-watching services can be obtained from the direct and indirect expenditures on whale watching worldwide. The International Fund for Animal Welfare estimated that whale watching tours generated $2.1 billion of expenditures in 2008, including both direct ticket sales and indirect expenditures generated by whale watching.

At the time this estimate was made, many countries with the potential for whale watching had not developed this industry. Cisneros-Montemayor et al (2010) estimate that the global whale-watching industry could generate up to $2.5 billion per year if fully developed. We assume that the current income flow from whale-watching is $2 billion.

We also argue that ecotourism revenues vary positively with whale biomass, so that as whale populations increase, ecotourism revenues will also increase. In particular, we assume that a return of whales to their pre-whaling populations will result in a doubling of global ecotourism revenues, to $4 billion annually. This projection is conservative in the sense that it allows for diminishing returns of services from whales. As shown in Table 1, if whales return to their pre-industrial whaling numbers, this is an average increase of over 173 percent in great whale populations for each species. Thus, an increase in services on the order of 100 percent would allow for significant diminishing marginal returns. In the case of ecotourism, the diminishing returns could be caused by lower novelty of watching whales, should whales become much more abundant.

Table 1: Global Whale Populations

Species	Current Population	Steady-State Population	Carbon on Body (tonnes)
Blue	5,400	303,500	12.2692
Bowhead	26,000	110,000	4.4719
Bryde's	132,000	146,000	2.4359
Fin	110,000	763,000	6.7067
Gray	16,000	25,000	2.9262
Humpback	66,000	307,000	5.4842
Minke	704,000	928,000	0.4190
Right	14,500	124,000	6.0215
Sei	49,100	246,000	2.0493
Sperm	360,000	1,101,000	6.7125
Total	1,483,000	4,053,500	

Carbon Capture and Sequestration Through Whale Biomass

Because whales are some of the largest animals on earth, their bodies contain nontrivial amounts of carbon. The total amount of carbon captured by whale biomass over time can be decomposed into the carbon stored in the current population of whales, the carbon captured by future net additions to the whale population, and the carbon effectively sequestered by future whale falls.

The carbon captured in whale biomass has been calculated by Pershing et al (2010) for various species of great whales. A stable population of whales will effectively sequester a quantity of carbon proportional to the number of individuals. Estimates of current whale populations are given by Smith et al (2019), and are presented in Table 1, along with estimates of the pre-industrial whaling populations of each species, which are from Pershing et al (2010), and Whitehead (2002). Table 1 also shows the amount of carbon sequestered on the body of the average whale by species. We estimate the value of the carbon currently sequestered on whale bodies by converting the carbon per body to its CO_2 equivalent, and then multiplying by the current population as well as the price of $24.72 per tonne of CO_2. In addition, as the equilibrium population of whales increases, the net increase in the population will also create additional flux proportional to this increase. Our population growth model implies a time-varying increase in whale populations until they reach their long-run, steady-state equilibrium number.

Because whale falls (deaths in which the whale carcass falls to the ocean floor) effectively sequester carbon on the ocean floor, there is an additional annual flux in carbon sequestration equal to the annual number of whale falls multiplied by the carbon sequestered on the body of the particular species. The rate of whale falls lowers the rate of population growth used in our model, but the amount of carbon sequestered by these falls must be accounted separately from the carbon captured by the increases in population.

Carbon capture and sequestration through enhancement of primary production (phytoplankton fertilization)

Whales play an additional role in carbon capture and sequestration by promoting phytoplankton growth. Through their normal feeding behavior, which involves diving in search of food followed by resting and defecating at the ocean surface, whales transport nutrients upward through the water column in a process dubbed the "whale pump" (see for example Roman and McCarthy 2010). In the Southern Ocean, whales transport needed iron to the ocean surface, where it leads to increased phytoplankton blooms. In addition to the whale pump, the migration behavior of whales also transports nutrients to areas where they are in limited supply. This process, dubbed the "whale conveyor" (Roman et al 2014), transports nitrogen from high-latitude feeding areas to low-latitude calving areas, where availability of nitrogen limits phytoplankton growth.

Whales' contributions to phytoplankton growth in turn lead to increased capture and sequestration of carbon. Because phytoplankton currently capture the equivalent of 37 billion tonnes of carbon dioxide annually, a small percentage increase in the quantity of phytoplankton due to whale activity could result in large absolute contribution to carbon capture.

Several studies estimate the impact of the whale pump and whale conveyor on primary production. Lavery et al (2010) estimates that the 12,000 sperm whales in the Southern Ocean export 400,000 tonnes of carbon annually through their impact on phytoplankton. Roman et al (2014) estimate that the nitrogen transported by whales may increase primary production in whale calving areas by 15 percent. This large increase is a localized effect and is difficult to extrapolate to an impact on total primary production, however. On the other hand, Lavery et al (2014) estimates that a return of the blue whale population to its pre-whaling level in the Southern Ocean would increase primary production by 0.23% in that body of water. Ratnarajah et al (2016) estimate the impact of three whale species on primary production in the Southern Ocean. Mean estimates of the contributions of these species to primary production, assuming they return to their pre-whaling populations, sum up to nearly one percent of current primary production.

Given the limited number of studies and the variation in their estimates of whale impact on primary production, caution is warranted when using their results. Nonetheless, attributing one percent of current phytoplankton production to the current whale population appears, given the current state of the research, to be a reasonable initial estimate of the impact of whales on primary production.

We further argue that the amount of carbon capture services produced increases with whale populations. In particular, we assume that the quantities of services produced increase as whale biomass increases. We reason that whales' contributions to primary production should vary according to the quantity of feces produced, which we assume is positively related to biomass. The increase in primary production will in turn increase carbon capture by phytoplankton as well as further enrich fisheries, as we discuss below. Specifically, we project an increase on the order of one percent of global primary production due to whale activity, if whales were to return to their pre-whaling numbers. Because existing phytoplankton is estimated to capture ten billion tonnes of carbon annually (equivalent to 37 billion tonnes CO_2), this implies that whales currently stimulate the capture of 100 million tonnes of carbon (equivalent to 370 million tonnes CO_2) and will increase phytoplankton carbon capture by a further 100 million tonnes as their populations returns to pre-whaling levels. Again, we note that this projection allows for significant diminishing marginal returns of whale contribution to primary production.

Fisheries Enhancement

In addition to carbon capture, the increase in phytoplankton due to whale activity has also been shown to increase production throughout the marine food chain. We therefore attribute a portion of commercial fisheries income, one percent per year, to whale activities. This portion is equivalent to our estimate of whales' contribution to phytoplankton production. The UN's Food and Agriculture Organization (FAO) estimates that annual global fish production in 2018 was worth $401 billion (FAO, 2020), which was divided between $250 billion in aquaculture and $150 billion in traditional commercial fishing. Although much aquaculture takes place in ocean environments and therefore would potentially benefit from whale activity, we base our estimate on the value of traditional commercial fishing, which implies a value of $1.5 billion per year for the current annual service flow from fisheries enhancement. In addition, we project that whales' contributions to fisheries revenues increase from $1.5 billion to $3.0 billion per year as whale populations return to pre-whaling levels.

Using the population projections and the upper bounds on the increases in the three services described above, we then project the annual increases in the three services. We assume that the annual rate of increase $v_{i,t}$ in ecotourism, carbon capture through primary production, and fisheries enhancement services for each whale species i is equal to the ratio of the annual increase in the population, $N_{i,t} - N_{i,t-1}$ to the difference between the steady-state and current populations $N_{i,T} - N_{i,0}$: $v_{i,t} = \frac{N_{i,t} - N_{i,t-1}}{N_{i,T} - N_{i,0}}$.

The annual service flows of each service j = 1, 2, 3 from each species i = 1, 2, …, 10 during each future year t are therefore equal to the initial flows multiplied by one plus the cumulative sum of the increases up to that year: $s_{i,j,t} = s_{i,j,0}\left(1 + \sum_{u=1}^{t} v_{i,u}\right)$.

Step 3: Assign a discount rate appropriate to the natural resource and the service(s) produced.

As in the case of service flows from elephants, we argue that the flows of carbon-capture and fisheries enhancement services from living adult whales will remain roughly constant on a per-whale basis, no matter how the payoffs from other assets fluctuate. Fluctuations in the quantities of these service streams come mainly from two sources. The first is expected population growth, which is likely to be uncorrelated with fluctuations in the payoffs from other assets. Unexpected fluctuations in services would primarily come from higher than average mortality among whales. The events that cause unexpected mortality in whales include ship strikes, entanglement in fishing lines, disease, and ingestion of plastics. The occurrence of such events is likely to be uncorrelated with fluctuations in the payoffs from other assets.

We have already argued that carbon prices do not exhibit systematic risk, so that the carbon sequestration services from whales should also be discounted at the risk-free rate. Ecotourism revenues, on the other hand, are probably at least somewhat correlated with the business cycle and hence with other asset returns. Likewise, the values of fisheries are probably also correlated somewhat with the business cycle. Thus, there is probably some systematic risk in the values of the service flows that whales produce. Sufficient data does not exist to enable estimation of the correlations of the returns on these service flows with the overall market return, however. We argue that the systematic risk component of the overall value of the services provided by whales is small, because the cyclicality of ecotourism and fisheries revenues are not expected to be very high, and because (as we show below) the majority of the value of the services provided by whales is associated with carbon capture, which should be discounted at the risk-free rate. Therefore, we conclude that the risk-free rate is a good first approximation of the appropriate discount rate.

Step 4: Using the values projected in Step 2, calculate the value of the resource using equation (2).

The projected values constructed in Step 2 include the services produced by the entire world population of great whales. Therefore, the next step in valuing the whales off the coasts of Brazil and Chile is to assign the appropriate shares of global values to the local populations**. In principle, valuation of the whales in a particular area can begin by prorating the total value of each service produced by the fraction of total whale biomass present in local species. In the case of carbon sequestration on whale bodies, however, the value of this service can be constructed by applying the population growth models described in Step 2 to each local species.

In order to apply the population growth model to the whales off the coast of Brazil, we obtained or constructed estimates of both current and steady-state (pre-whaling) populations in this location. The Brazilian research organization Baleia Jubarte provided per-species estimates of current populations for minke, humpback, right, and sperm whales in Brazil††. Bowhead and gray whales are not present in Brazilian waters. Baleia Jubarte also estimated that the total number of blue, Bryde's, fin and sei whales present off the coast of Brazil is currently 3,500 but did not provide estimates for each species. We allocated this total among the four species by assuming that the population of each of these four species in Brazilian waters is proportional to their current relative abundance in the world.

Estimates of pre-industrial whaling populations for each species present off the coast of Brazil were constructed by assuming that the steady-state levels reached by local populations will be proportional to their relative abundance in the global pre-industrial whaling population. The initial and steady-state population estimates are presented in Table 2.

Table 2: Whale Populations in Brazil and Chile

Species	Current Population	Steady-State Population	Share of Total Whale Biomass
Blue (Brazil)	64	3,583	0.00015547
Blue (Chile)	760	57,000	0.00185364
Bowhead	0	0	0
Bryde's	1,558	1,723	0.00186513
Fin	1,298	9,007	0.00173128
Gray	0	0	0
Humpback	25,000	28,198	0.02725305
Minke	25,000	32,955	0.00208124
Right	800	6,841	0.00103650
Sei	580	2,904	0.00023615

** It is possible that the flows of services produced by whales vary by their location. But sufficient data does not yet exist to measure local variations in services produced, let alone test the hypothesis that migrating whales produce identical flows of services at each location they visit. Our estimates assume this hypothesis is true.

†† See Appendix 2 for details on the sources of the estimates provided by Baleia Jubarte.

Sperm	10,000	30,583	0.01334434

The current local population estimates and data on the average biomass of each species were used to construct biomass weights w_i equal to the current biomass of each whale species found off the coast of Brazil, divided by total current great whale biomass: $w_i = \frac{b_i N_{i,0}^{Brazil}}{\sum_{i=1}^{10} b_i N_{i,0}}$ where N^{Brazil} denotes the local whale population in Brazilian waters. These weights were used to estimate each species' initial contribution to the flows of services from ecotourism and primary production. The weights are reported in Table 2.

The calculations for the population of blue whales off the coast of Chile were done in a similar way. Galletti Vernazzani et al (2017) estimates that the current population of blue whales is between 570 and 760, and we assume that this represents one percent of the country's pre-industrial whaling population of blue whales. In order to keep the valuation as conservative as possible, we assume that the pre-whaling population is based on the lower current population estimate, or 57,000 blue whales, while the higher estimate of 760 is used for the current population. Doing so will lower the valuation of whales by reducing the present value of total services (the numerator of the per-whale value) and increasing the number of whales producing these services (the denominator of the per-whale value). The parameters of the population growth model used to estimate future blue whale populations in Chile are the same as those used for the Brazilian blue whales, with the exceptions of the starting and ending populations. A biomass weight used to estimate the Chilean blue whales' initial contribution to the flows of services from ecotourism and primary production was also constructed analogously to the biomass weights for the Brazilian whales.

As described above, the service flows from ecotourism, phytoplankton carbon capture, and fisheries enhancement are assumed to be proportional to each species' share of global whale biomass, reported in Table 2. The implied initial values for these services are reported in Table 3. The annual rates of increase in the production of ecotourism and phytoplankton-related services were then constructed for each species as described in Step 2. Similarly, estimates of carbon sequestered on the bodies of whales were constructed directly from local population forecasts, as described in Step 2. The value of the initial stock of carbon presently sequestered on the bodies of the Brazilian and Chilean whale populations is also reported in Table 3.

Table 3: Values of Current Service Flows/Stock of Carbon				
	Current Values of Annual Service Flows:			Value of Stock:
Species	Ecotourism	Phytoplankton Carbon Capture	Fisheries Enhancement	Carbon on Body
Blue	$310,941	$1,421,994	$233,206	$74,754
Bowhead				

Bryde's	$3,730,269	$17,059,268	$2,797,702	$357,927
Fin	$3,462,555	$15,834,959	$2,596,917	$816,453
Gray				
Humpback	$54,506,095	$249,267,274	$40,879,571	$12,496,213
Minke	$4,162,488	$19,035,891	$3,121,866	$969,621
Right	$2,072,994	$9,480,217	$1,554,746	$456,281
Sei	$472,296	$2,159,906	$354,222	$111,226
Sperm	$26,688,674	$122,052,644	$20,016,506	$6,207,708
Totals (Brazil):	$95,406,313	$436,312,152	$71,554,736	$21,490,183
Blue (Chile)	$3,707,269	$16,954,085	$2,780,452	$845,183

Annual service flows for each species were discounted and summed in order to estimate the total value of each species as well as the average values of individual whales. These are reported in Table 4.

Table 4: Present Value of Whales in Brazil and Chile		
Species	Total Value	Average per Whale
Blue	$230,079,877	$3,609,454
Bowhead		
Bryde's	$3,573,801,371	$2,293,839
Minke	$4,129,486,080	$165,179
Fin	$2,862,258,915	$2,205,130
Gray		
Humpback	$52,191,344,148	$2,087,654
Right	$1,766,748,598	$2,208,436
Sei	$400,868,032	$691,634
Sperm	$22,282,689,815	$2,228,269
Total:	$87,437,276,836	
Blue (Chile)	$3,107,530,267	$4,088,856

The difference between the values of the Brazilian and Chilean blue whales is due to the difference in the ratios of starting to ending populations in the two countries. In the case of the Chilean blue whales, we are assuming that the starting population is a greater fraction of the steady-state population than for the Brazilian whales, which in turn implies an earlier acceleration of population growth in Chile, producing larger service flows that occur sooner, leading to a higher overall value of the services.

Discussion

Although this exercise produces a wide range of values for the great whales from $165,000 for a Minke whale to $4 million for a blue whale, most of the whales have a value of about $2 million.

We argue that, like the example of forest elephants, our estimated values of whales will generate excitement and concern among individuals and investors, for the same reasons as discussed above.

The whale valuations, however, incorporate services beyond carbon sequestration, namely ecotourism and fisheries enhancement. This is important because the flows from these services provide additional ways to use these valuations to promote action. As we show in Table 3, the values of the annual flows of services such as ecotourism and fisheries enhancement are significant. These amounts translate into economic activity and opportunity for local residents, which are both tangible and immediate benefits. Thus, quantifying these annual flows can be quite important in convincing important ecosystem stakeholders who interact directly and frequently with the resource to take actions to preserve or restore it. (Note: this is not a new argument, so we should get a cite or two about programs that have successfully used these flows to convince locals to support preservation.)

5. Conclusion

In the introduction to this paper, we argue that our valuation strategy will be more effective at prompting action because it takes better advantage of humans' psychological tendencies. In this section, we also argue that our method will be more effective because it opens up new possibilities for action.

First, we argue that our valuation method will stimulate further research into the services produced by all natural resources and the value of these services to society. By demonstrating that individual resources such as elephants and whales can have significant value, our method will prompt efforts to identify and price the services produced by other individual resources—much as a profitable investment in one company leads investors to investigate the fundamentals of related companies in order to uncover hidden or overlooked value. Similarly, we believe that the demonstration effect arising from valuations of individual resources will stimulate additional interest in valuing the services flowing from entire ecosystems, using our framework.

Our valuation approach also facilitates a transformation in how people view natural resources, which in turn enables new approaches to conservation and restoration policies. The assignment of credible money values to individual natural resources, even if lower bounds, prompts society to view each natural resource as an agent that produces services with a marketable monetary value. This can lead to the legal recognition of the natural resource, not necessarily as a person, but nonetheless as an agent with rights (and obligations)[‡‡]. Chief among these can be the rights to legal protection against harm and to reasonable compensation for services rendered. This change is a foundation upon which to build a new generation of conservation and restoration policies. Because natural resources do not have the capacity to speak for themselves or defend themselves, guardians or advocates can be appointed to protect them and their interests, including the standing to initiate lawsuits on behalf of the resource.

[‡‡] New Zealand, for example, has recently recognized all animals as sentient beings.

One legal tool that our valuation method makes possible is the levying of economically appropriate and meaningful fines on agents who damage or destroy protected natural resources. These fines should be based on the values assigned to the resource. For example, a ship that strikes and kills a blue whale off the coast of Brazil should be fined the full value of the whale, or $3.6 million. The value could also be used to incentivize private monitoring of the (mis-)use of natural resources. Rewards linked to the values of whales could be paid to those who provide evidence leading to the successful prosecution of agents who harm or kill whales.

Similarly, our valuation of forest elephants can be used to establish penalties for poaching and incentives for monitoring that more nearly represent the true social costs and benefits of doing so. Tukalo et. al. (2017) estimated that poaching of elephants increases the mortality rate of elephants by 1.71 percentage points. The current population growth rate of 1.9% is conditional on the existence of poaching, so that removing poaching would increase the growth rate of elephants in African tropical forests to 3.62%. Under this higher growth rate of elephants, we repeated the same analysis of the three cases of elephants' contribution to tropical forest carbon stocks. When the higher population growth rate is used, the value of increased carbon capture in tropical forests increases to $375.2405 billion, or $3,752,405 per elephant. This means that poaching reduces the present value of the current 100,000 elephants by $198.9576 Billion or $1,989,576 per elephant.

The establishment of meaningful fines can stimulate private investment directed at protecting individuals and businesses from these penalties, but which simultaneously promotes the protection of natural resources. In other words, government-imposed penalties on the destruction of natural resources that are linked to the values of these resources can create markets for protecting them. For example, maritime insurers can develop whale-strike products that will compensate shippers for large fines incurred by ships that inadvertently harm whales. And insurers will doubtlessly wish to limit moral hazard-related losses by requiring the purchasers of insurance to take actions to avoid whale strikes, such as using goods or services that alert ship captains of whale proximity. This in turn provides incentives for private companies to improve existing methods of monitoring whales, or to invent better ones.

Credible valuations also justify the levying of user fees and license fees on those who enjoy or profit from natural resources. Such fees accomplish two complementary purposes. First, they give agents an incentive to stop overusing a resource, because doing so is no longer costless. In addition, the revenues from such fees can be earmarked for the financing of protection and restoration programs. As in the case of fines, the amounts of the user and license fees can be calibrated to the value of the services, so that they are effective in both curbing overuse and generating revenues. For example, significant user fees could be built into the prices of whale watching or elephant watching tours, or licensing fees on the companies that offer them (or both).

Moreover, imposing fees on the use of natural resources can also serve as a catalyst for private investment in conservation and restoration projects. A portion of fee revenues can provide impact investors, who seek both social and financial returns on their investments, the money component of return that up to now has largely been missing or nearly impossible to secure, due to lack of property rights. Such impact investing initiatives would be structured as public-private partnerships (PPPs) in which private-sector entities contribute management skills and technology to restoration projects, as well as the ability to recruit other private investors. PPPs could raise the initial capital required to start conservation and restoration projects from the private sector, based on the dual promises of improved protection for natural resources and future income flows from fee revenues. This would help establish natural resources as a new asset class for private investment, and also relieve governments of the burden of funding conservation projects from general tax revenues. This approach has great potential for protecting all resources, but particularly for resources like elephants that are illegally misused or destroyed, since PPPs would have a direct and strong incentive to protect their investments.

The potential gains discussed above also create incentives for international cooperation on conservation and restoration. Many natural resources are shared by countries, either because an immobile resource spans multiple countries' territories, or because a migratory resource visits multiple countries. The total value of a shared resource often depends on how well it is managed or protected by each of the countries sharing it. The value of a river in one country, for example, depends on how upstream countries managed their section of the river. The value that a resource provides to a particular country can be impaired or destroyed if the resource is misused in one of the other countries sharing it. Thus, if a particular country would like to assign value to a shared resource in order to stimulate private sector investment in its conservation and restoration, it will need other countries to commit to at least doing no harm to the resource.

On the other hand, the benefits of acting jointly to conserve and protect resources could be a strong incentive for more active cooperation. Countries could agree to coordinate the fines they levy on agents who misuse shared resources, and to share the proceeds from these fines. Governments could harmonize rules to create larger, single markets for protection of resources that would attract more private investment. Similarly, they could create international PPPs that would attract greater numbers of investors, who would be attracted by the more reliable promises of income flows due to larger user bases and uniform user and license fees across countries.

The policies described above will not necessarily result from the adoption of credible monetary valuations of individual natural resources, but it is difficult to imagine how such policies could develop without this foundation. Expert valuation of natural resources can—and indeed, we argue must—play the role that price discovery performs in markets for private goods and services.

References

Berzaghi, F., Longo, M., Ciais, P., Blake, S., Bretagnolle, F., Vieira, S., Scaranello, M., Scarascia-Mugnozza, G., Doughty, C.E., 2019. Carbon stocks in central African forests enhanced by elephant disturbance. Nat. Geosci. 1. https://doi.org/10.1038/s41561-019-0395-6

CIEEM England Policy Group, 2019. Natural Capital and Biodiversity: A Briefing Note for Policy-Makers. Winchester, Hampshire, U.K.: Chartered Institute of Ecology and Environmental Management. July.

Cisneros-Montemayor, A.M., U.R. Sumaila, K.Kaschner, and D.Pauly, 2010. The Global Potential for Whale Watching. Marine Policy 34, 1273 – 1278.

Costello, Christopher, Leah R. Gerber, and Steven Gaines, 2012. A Market Approach to Saving the Whales, Nature 481 (12 January), 139-140.

da Rocha, Jesuina Maria, 1983. Revision of Brazilian Whaling Data. Report of the International Whaling Commission 33: 419 – 427.

de la Mare, William K., 2014. Estimating relative abundance of whales from historical Antarctic whaling records. Canadian Journal of Fisheries and Aquatic Science. 71: 106–119. dx.doi.org/10.1139/cjfas-2013-0016

Doughty, Christopher E., Joe Roman, Soren Faurby, Adam Wolf, Alifa Haque, Elisabeth Bakker, Yadvinder Malhi, John B. Dunning Jr., and Jens-Christian Svenning, 2016. Global Nutrient Transport in a World of Giants, Proceedings of the National Academy of Sciences of the United States of America 113(4), 868–873

FAO (Food and Agriculture Organization), 2020. *The State of World Fisheries and Aquaculture 2020. Sustainability in action.* Rome.

Ferrell, C.L., Jenkins, T.G., 1998. Body composition and energy utilization by steers of diverse genotypes fed a high-concentrate diet during the finishing period: II. Angus, Boran, Brahman, Hereford, and Tuli sires. J. Anim. Sci. 76, 647–657. https://doi.org/10.2527/1998.762647x

Freeman, A. Myrick III, 2004, *The Measurement of Environmental and Resource Values*, 2nd ed., Washington, D.C.: Resources for the Future.

Galletti Vernazzani, Barbara, Jennifer A. Jackson, Elsa Cabrera , Carole A. Carlson, Robert L. Brownell, Jr., 2017. Estimates of Abundance and Trend of Chilean Blue Whales off Isla de Chiloé, Chile. PLoS ONE 12(1): e0168646. doi:10.1371/journal.pone.0168646

Groch, Karina R., Jose T. Palazzo, Jr., Paulo A.C. Flores, Fred R. Adler, and Marta E. Fabian, 2005. Recent rapid increase in the right whale (Eubalaena australis) population off southern Brazil. Latin American Journal of Aquatic Mammals 4(1): 41-47, January/June.

Grubb, P., Groves, C., Dudley, J., Shoshani, J., 2000. Living African elephants belong to two species: Loxodonta africana (Blumenbach, 1797) and Loxodonta cyclotis (Matschie, 1900). Elephant 2. https://doi.org/10.22237/elephant/1521732169

Karlin, Samuel, and Howard M. Taylor, 1975, *A Second Course in Stochastic Processes*. New York: Academic Press.

Lavery, Trish J., Ben Roundnew, Peter Gill, Justin Seymour, Laurent Seuront, Genevieve Johnson, James G. Mitchell, and Victor Smetacek, 2010. Iron Defecation by Sperm Whales Stimulates Carbon Export in the Southern Ocean, Proceedings of the Royal Society B 277, 3527–3531.

Lavery, Trish J., Ben Roundnew, Justin Seymour, James G. Mitchell, Victor Smetacek, and Steve Nicol, 2014. Whales sustain fisheries: Blue whales stimulate primary production in the Southern Ocean, Marine Mammal Science 30(3), 888 – 904.

Lew, Daniel K., 2015. Willingness to Pay for Threatened and Endangered Marine Species: A Review of the Literature and Prospects for Policy Use, Frontiers in Marine Science 2 (November), Article 96.

Maisels, F., Strindberg, S., Blake, S., Wittemyer, G., Hart, J., Williamson, E.A., Aba'a, R., Abitsi, G., Ambahe, R.D., Amsini, F., Bakabana, P.C., Hicks, T.C., Bayogo, R.E., Bechem, M., Beyers, R.L., Bezangoye, A.N., Boundja, P., Bout, N., Akou, M.E., Bene, L.B., Fosso, B., Greengrass, E., Grossmann, F., Ikamba-Nkulu, C., Ilambu, O., Inogwabini, B.-I., Iyenguet, F., Kiminou, F., Kokangoye, M., Kujirakwinja, D., Latour, S., Liengola, I., Mackaya, Q., Madidi, J., Madzoke, B., Makoumbou, C., Malanda, G.-A., Malonga, R., Mbani, O., Mbendzo, V.A., Ambassa, E., Ekinde, A., Mihindou, Y., Morgan, B.J., Motsaba, P., Moukala, G., Mounguengui, A., Mowawa, B.S., Ndzai, C., Nixon, S., Nkumu, P., Nzolani, F., Pintea, L., Plumptre, A., Rainey, H., de Semboli, B.B., Serckx, A., Stokes, E., Turkalo, A., Vanleeuwe, H., Vosper, A., Warren, Y., 2013. Devastating decline of forest elephants in Central Africa. PLoS ONE 8, e59469. https://doi.org/10.1371/journal.pone.0059469

National Research Council, 2005. Valuing Ecosystem Services: Toward Better Environmental Decision-Making. Washington, DC: The National Academies Press. https://doi.org/10.17226/11139.

Office for National statistics, 2016. Scoping UK coastal margin ecosystem accounts. https://www.ons.gov.uk/economy/environmentalaccounts/methodologies/scopingukcoastalmarginecosystemaccounts

Parker, K.L., Barboza, P.S., Gillingham, M.P., 2009. Nutrition integrates environmental responses of ungulates. Funct. Ecol. 23, 57–69. https://doi.org/10.1111/j.1365-2435.2009.01528.x

Pershing, Andrew J., Line B. Christensen, Nicholas R. Record, Graham D. Sherwood, Peter B. Stetson 2010. The Impact of Whaling on the Ocean Carbon Cycle: Why Bigger Was Better. PLoS ONE 5(8): e12444. doi:10.1371/journal.pone.0012444

Philips, Jack, 2017. Principles of Natural Capital Accounting, U.K. Office for National Statistics.

Ratnarajah, Lavenia, Jessica Melbourne-Thomas, Martin P. Marzloff, Delphine Lannuzel, Klaus M. Miners, Fanny Chever, Stephen Nicol, and Andrew R. Bowie, 2016. A Preliminary Model of

Iron Fertilisation by Baleen Whales and Antarctic Krill in the Southern Ocean: Sensitivity of Primary Productivity Estimates to Parameter Uncertainty, Ecological Modeling 320, 203 – 212.

Renault-Braga, Eduardo Pires, Karina Rejane Groch, Paulo A. de Carvalho Flores, Eduardo R. Secchi and Luciano Dalla-Rosa, Area usage estimation and spatiotemporal variability in distribution patterns of southern right whales, Eubalaena australis, of southern Brazil, 2018. Marine Ecology e12506. DOI: 10.1111/maec.12506

Robbins, C.T., Moen, A.N., Reid, J.T., 1974. Body Composition of White-Tailed Deer. J. Anim. Sci. 38, 871–876. https://doi.org/10.2527/jas1974.384871x

Roman Joe, and James J. McCarthy, 2010. The Whale Pump: Marine Mammals Enhance Primary Productivity in a Coastal Basin. PLoS ONE 5(10): e13255. doi:10.1371/journal.pone.0013255

Roman, Joe, James A. Estes, Lyne Morrisette, Craig Smith, Daniel Costa, James McCarthy, J.B. Nation, Stephen Nicol, Andrew Pershing, and Victor Smetacek. 2014. Whales as marine ecosystem engineers. Frontiers in Ecology and the Environment 12, 377–385.

Smith, Craig R., Joe Roman, and J. B. Nation, 2019. A metapopulation model for whale-fall specialists: the largest whales are essential to prevent species extinctions

Smith, Laura V., Andrew McMinn, Andrew Martin, Steve Nicol, Andrew R. Bowie, Delphine Lannuzel, and Pier van der Merwe, 2013. Preliminary Investigation into the Stimulation of Phytoplankton Photophysiology and Growth by Whale Feces, Journal of Experimental Marine Biology and Ecology 446, 1 – 9.

Taylor, Barbara L., Susan J. Chivers, Jason Larese and William F. Perrin, 2007. Generation length and percent mature estimates for IUCN assessments of cetaceans, Administrative Report LJ-07-01 National Marine Fisheries Service, Southwest Fisheries Science Center

TEEB, 2010. The Economics of Ecosystems and Biodiversity Ecological and Economic Foundations. Edited by Pushpam Kumar. Earthscan, London and Washington

Torres-Florez, Juan Pablo, 2020. IWC Western South Atlantic Southern Right Whale Conservation Management Plan –Progress Report April 2020. International Whaling Commission.

Turkalo, A.K., Wrege, P.H., Wittemyer, G., 2017. Slow intrinsic growth rate in forest elephants indicates recovery from poaching will require decades. J Appl Ecol 54, 153–159. https://doi.org/10.1111/1365-2664.12764

Turkalo, A.K., Wrege, P.H., Wittemyer, G., 2018. Demography of a forest elephant population. PLoS One 13. https://doi.org/10.1371/journal.pone.0192777

Wedekin, L.L., M. H. Engel, A. Andriolo, P. I. Prado, A. N. Zerbini, M. M. C. Marcondes, P. G. Kinas, P. C. Simões-Lopes, 2017. Running fast in the slow lane: rapid population growth of humpback whales after exploitation, Marine Ecology Progress Series 575: 195–206. https://doi.org/10.3354/meps12211

Whitehead, Hal, 2002. Estimates of the Current Global Population Size and Historical Trajectory for Sperm Whales. Marine Ecology Progress Series 242: 295 – 304.

Williamson, Gordon A., 1975. Minke Whales in Brazil. Sci. Rep. Whales Res. Inst. 27: 37 – 59.

Zerbini, Alexandre N., Grant Adams, John Best, Phillip J. Clapham, Jennifer A. Jackson, Andre E. Punt, 2019. Assessing the recovery of an Antarctic predator from historical exploitation. Royal Society Open Science 6: 190368. http://dx.doi.org/10.1098/rsos.190368

Appendix 1: Population Model

The populations of elephants and whales are based on a logistic model of births and an exponential model of the survival of living individuals. We assume each population follows the differential equation $\frac{dN(t)}{N(t)} = \nu(t)dt$ subject to an initial population $N(0)$, where *ν(t)* is the population growth rate. Following Karlin and Taylor (1975 p.420), the population under exponential growth rate ν leads to

$$N(t) = N(0)exp\left[\int_0^t \nu(\tau)d\tau\right] \quad (1)$$

where N(0), the initial population of each species, is taken to be the number of elephants after poaching, and the number of whales after industrial whaling, respectively. N(T) is the steady-state population, for which we use the number of elephants before poaching and whales before industrial whaling.

Because we do not expect the populations of elephants or whales to grow indefinitely, we assume that $\nu(t) \to 0$ as $t \to \infty$. We also want to account for birth and deaths. As a result, we define $\hat{\nu}(t) = \nu(t) + c$, so that $\hat{\nu}(t)$ is the birth rate of whales or elephants, c is their constant instantaneous death rate, and $\nu(t)$ is the (net) growth rate of the population. Thus, $\hat{\nu}(t) \to c$ as $t \to \infty$.

These properties are captured by a logistic model for the birth rate such that

$$\hat{\nu}(t) = \begin{cases} \beta\left[1 - \frac{N(t)}{\alpha}\right] for\ N(t) \le \frac{\alpha(\beta-c)}{\beta} \\ c \qquad\qquad\quad for\ N(t) > \frac{\alpha(\beta-c)}{\beta} \end{cases} \quad (2)$$

where $\frac{\alpha(\beta-c)}{\beta}$ is the level of population when the birth rate is equal to rate of death and the population growth rate is zero. As a result, $\frac{\alpha(\beta-c)}{\beta}$ is the steady state value of the population. For simplicity we set $\beta = \nu(0) + c$

We know the survival rate S_a for mature elephants and whales over one year, so that the mortality rate c is given by the solution of

$$\int_0^1 e^{-ca}\, da = \frac{1}{c}(1 - e^{-c}) = S_a. \quad (3)$$

Substituting $\nu(t) = \hat{\nu}(t) - c$ and (2) into the differential equation $\frac{dN(t)}{N(t)} = \nu(t)dt$ for the growth rate of the population gives

$$\frac{dN(t)}{dt} = N(t)(\beta - c) - \beta\,\frac{N(t)^2}{\alpha}\ for\ N(t) \le \frac{\alpha(\beta-c)}{\beta} \text{ and 0 otherwise.}$$

The solution to this ordinary differential equation is

$$N(t) = \frac{\alpha(\beta-c)\,N(0)}{\beta\,N(0)\left[1-e^{-(\beta-c)t}\right] + \alpha(\beta-c)e^{-(\beta-c)t}}\ for\ N(t) \le \frac{\alpha(\beta-c)}{\beta} \text{ and 0 otherwise.} \quad (4)$$

As stated above, we use the post poaching or whaling population for N(0). The population converges to $N^* = \frac{\alpha(\beta-c)}{\beta}$, which we associate with the population before poaching or whaling. This means

$$\alpha = N(T)\frac{\beta}{(\beta - c)}.$$

Now we add a model of births that will be consistent with the above population model. We do so in order to be able to construct alternative scenarios in which we can show the impact of different birth and survival rates on future populations. We assume that births are always the same proportion b of population (which implies that births also follow the logistic model of population). This means $\nu(0)$ is the same for both population and births. If B(t) is the number of births, then

$$B(t) = bN(t) \Longrightarrow \frac{B(0)}{B(T)} = \frac{N(0)}{N(T)} \Longrightarrow B(T) = \frac{N(T)}{N(0)} B(0) \qquad (5)$$

This implies from (1) that

$$bN(t) = bN(0)exp\left[\int_0^t \nu(\tau)d\tau\right] \Longrightarrow B(t) = B(0)exp\left[\int_0^t \nu(\tau)d\tau\right]. \qquad (6)$$

To complete the differential equation model we need to set B(0). We know the average number of births in the first year is $m = \frac{1}{IBI}$ for an average female, where IBI is the interval between births. Let AFR be age of first reproduction. Therefore, there are AFR years before a female born at time 0 can give birth at time AFR, so that the females born at time 0 mature in AFR years with survival chance of $S_{0AFR} = (So)^{AFR}$.

Let **O** be the oldest age of reproducing females. We assume the distribution of the ages of individuals is uniform across ages 0 to **O**. The number of female births (half the population) at time 0 is given by

$$B(AFR) = \frac{O - AFR}{O}\frac{mN(AFR)}{2} = \frac{O - AFR}{O}\frac{mN(0)\left[\sum_{i=0}^{AFR-1} 0xS_o^{AFR-i}B(i) + \sum_{i=AFR}^{O}\frac{1}{O}S_a^i\right]}{2}$$

$$= \frac{O - AFR}{2\,O^2} mN(0) \sum_{i=AFR}^{O} S_a^i$$

$$= \frac{O - AFR}{2\,O^2} mN(0) S_a^{AFR} \sum_{i=A}^{O-AFR} S_a^i = \frac{O - AFR}{2\,O^2} mN(0) S_a^{AFR} \frac{1 - S_a^{O-AFR}}{1 - S_a}$$

where Sa is the survival rate of adults. The female calves from ages 0 to AFR do not give birth, so that the first summation in the second equality is equal to zero and drops out.

We let B(AFR) be the number of births by mature females at the end of the initial period, so that

$$B(AFR) = B(0)exp\left[\int_0^1 v(\tau)d\tau\right] = \frac{O - AFR}{2\,O^2} mN(0)S_a^{AFR}\frac{1 - S_a^{O-AFR}}{1 - S_a}.$$

As a result, the initial number births by mature females is given by

$$B(0) = \frac{1}{exp\left[\int_0^1 v(\tau)d\tau\right]}\frac{O-AFR}{2\,O^2} mN(0)S_a^{AFR}\frac{1-S_a^{O-AFR}}{1-S_a} =$$

$$\frac{1}{\frac{1}{v}[e^{v}-1]}\frac{O-AFR}{2\,O^2} mN(0)S_a^{AFR}\frac{1-S_a^{O-A}}{1-S_a} \quad . \qquad (7)$$

Now that we have the initial births, we can solve the differential equation for births at any time. Because births are a constant fraction of population, the differential equation for births can be written as (see equation (6))

$$\frac{dB(t)}{dt} = v(t)B(t).$$

Also, since births are a constant share of population, we can rewrite (2) in terms of births:

$$\hat{v}(t) = \begin{cases} \beta\left[1 - \frac{B(t)}{\alpha_B}\right] for\ B(t) \le \frac{\alpha_B(\beta-c)}{\beta} \\ c \qquad\qquad for\ B(t) > \frac{\alpha_B(\beta-c)}{\beta} \end{cases} . \qquad (8)$$

where $\alpha_B = b\alpha$.

Substituting $\hat{v}(t) - c$ for *v(t)*, as well as the logistic model for $\hat{v}(t)$ in terms of births (8) into the differential equation for births above gives

$$\frac{dB(t)}{dt} = \begin{cases} B(t)(\beta - c) - \frac{\beta}{\alpha_B}B(t)^2\ for\ B(t) \le \frac{\alpha_B(\beta-c)}{\beta} \\ 0 \qquad\qquad\qquad for\ B(t) > \frac{\alpha_B(\beta-c)}{\beta} \end{cases}$$

(9)

This differential equation has the solution

$$B(t) = \frac{\alpha_B(\beta-c)B(0)}{\beta\,B(0)\left[1-e^{-(\beta-c)t}\right] + \alpha_B(\beta-c)e^{-(\beta-c)t}}\ for\ B(t) \le \frac{\alpha_B(\beta-c)}{\beta}, \text{ and c otherwise.} \qquad (10)$$

Births net of deaths converge to 0 when $B(T) = \frac{\alpha_B(\beta-c)}{\beta}$.

$$\frac{\alpha_B(\beta-c)}{\beta} = B(T) \Longrightarrow \alpha_B = \frac{\beta}{\beta-c}B(T).$$

We also know that the population and births grow at the same rate with initial ratio of $bN(t) = B(t)$, so that

$$N(t) = \frac{1}{b}\frac{\alpha_B\,(\beta-c)B(0)}{\beta\;B(0)\left[1-e^{-(\beta-c)t}\right]+\alpha_B(\beta-c)e^{-(\beta-c)t}}\;for\;N(t) \leq \frac{\alpha_B(\beta-c)}{b\beta}. \quad (11)$$

Appendix 2: Valuation of Elephants in Central Africa Forest

This Appendix values forest elephants in Central Africa based on two services: 1) carbon capture on elephant bodies, and 2) increased carbon capture in trees. The quantities of each service produced per period depend on the elephant population. We use the same logistic model discussed in Appendix 1 to estimate the evolution of the elephant population. The parameter values for elephants are given in Table A1. We take these parameters from Turkalo et. al. (2017, 2018). The population is currently 100,000, and we assume that the elephant population will stabilize at the pre poaching level of 1,100,000. The Central Africa forest covers an area of 2,200,000 km^2, which is about 44% of the size of the Amazon forest. Most of the Central African forests do not have elephants, so that the elephants can be spread over the current forest without changing the density of elephants per hectare.

Table A1: Parameters for Population Model for Elephants

AFR	O	IBI	Sa	So	$\nu(0)$	Pop Pre Poaching	Current Elephants
10	65	5.6	0.9691	0.97	0.019	1,100,000	100,000

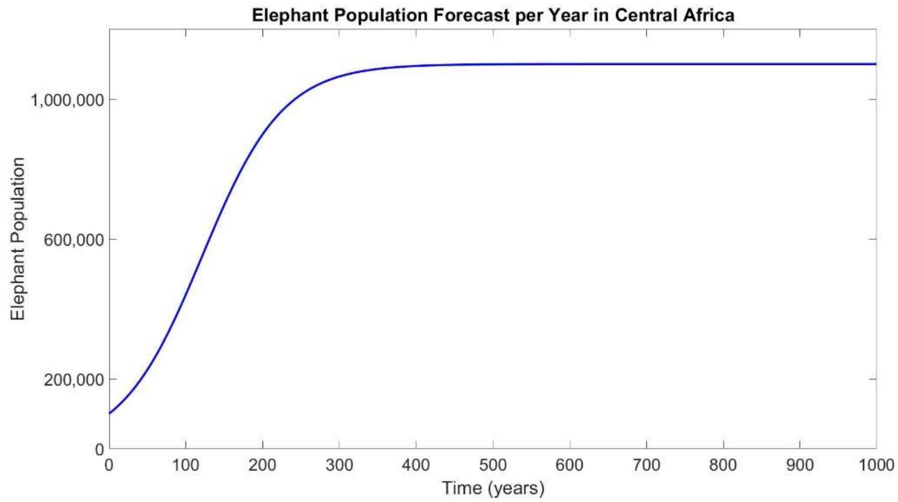
AFR is age of first reproduction, O is oldest age of reproducing females, IBI is the interbirth interval, Sa is the survival rate of adult elephants, So is the survival rate of elephant calves, and $\nu(0)$ is the population growth rate.

We know the survival rate over 1 year $S_a = 0.9691$ for mature elephants, so that (3a) yields a continuously compounded death rate of

$$c = 0.0631.$$

This means $\beta = \nu(0) + c$ = 0.019 + 0.0631= 0.0821.

Given these parameter values, the population of elephants following (3) with $\alpha = 4{,}753{,}552$ is given in the next graph.



The birth of elephants following equation (8) starts at

$$B(10) = \frac{O - AFR}{2\, O^2} mN(0)S_a^{11} \frac{1 - S_a^{O-10}}{1 - S_a} = 2{,}259.$$

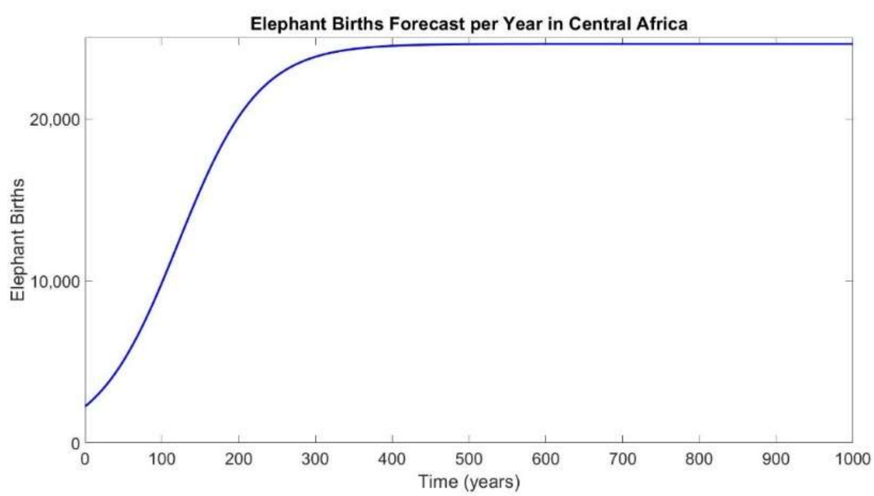
Consequently, the initial value of births, following equation (9), is given by

$$B(0) = 2{,}238.$$

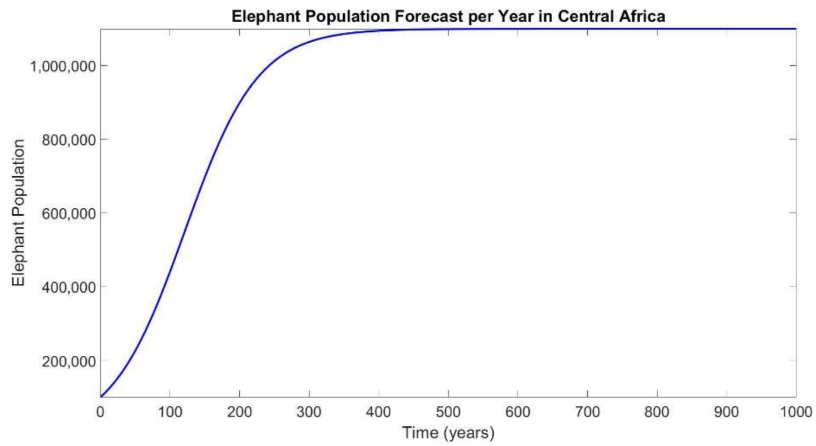
Since the population of elephants grows to 11 times its initial size, the terminal births also increase by 11 times. Consequently, B(t) = 0.0348 N(t) for each time period, following equation (5). We use the solution to the logistic model for births (11) with parameter

$$\alpha_B = 106.3739.$$

This leads to the graph of elephant births over time in the next Figure.



The population of elephants follows (12)



Carbon Capture in Elephant Bodies

Assuming an average body mass of 3000 kg (Grubb et al., 2000), of which 24% is carbon, we can calculate the CO_2 equivalent of the carbon captured in elephant bodies:

$$C = 0.24x3{,}000 = 720\ kg; \quad CO_2 = \frac{11x720}{3} = 2{,}640\ kg\ or\ 2.64\ metric\ tons$$

The cash flow per year from increased carbon capture on bodies, CF(i) is equal to the increase in population multiplied by the CO_2 captured per body, multiplied by the price of carbon, $P_C =$ \$24.72, so that for each species we have the market value for this service during period $t + i$

$$p_{1,t+i}\, s_{1,t+i} = P_C CO_2[N(i) - N(i-1)] \text{ for i} > 0.$$

This corresponds to the increase in the value of carbon dioxide sequestration because of the increase in elephants.

Assuming a discount rate of r = 0.02, the present value of carbon content of 100,000 elephants is

$$V_{1,t} = PV(Body\ Carbon) = P_C\ CO_2 N(0) + \sum_{i=1}^{\infty} \frac{P_C CO_2[N(i)-N(i-1)]}{(1+r)^i} = \$6{,}526{,}080 + \$10{,}059{,}942 = \$16{,}586{,}022.$$

This corresponds to a present value of carbon on an elephant's body of \$166.

Carbon Capture Enhancement through Interaction with Tropical Forest

The historical elephant population was 1.1 million individuals spread over 2,200,000 km² of the central Africa tropical rain forest, implying an average density of 0.5 elephants/km² (Turkalo et al., 2017). At a density of 0.5 elephants per km^2, the carbon boosting effect of 0.5 elephants has been estimated at 13 metric tons (tonnes) per hectare. Since 1 km^2 = 100 hectares, the increase in carbon capture at a density of 1 elephant per km^2 is 13 * 2 * 100 = 2600 tonnes of carbon per km^2. The CO_2 equivalent is given by 2600 * 11/3=9533.33 tonnes. This calculation allows us to compute the increase in carbon capture based on the number of elephants.

We assume that as the elephant population increases, it will distribute itself among the African tropical forest in a way that maintains a density of 0.5 elephants/km^2. Therefore, as the population grows, elephants will expand their range maintaining an average density of 0.5 elephants/km^2. Thus, our calculations are based on maintaining the average effect of elephants per hectare while extending the elephant-occupied range.

The effect of elephants on CO_2 depends on how long the elephants are in a particular area of the forest. We begin with an initial plot of forest containing the currently existing 100,000 elephants (200,000 km^2) and assume that these elephants have been around long enough to increase carbon capture in this plot to its higher steady state. Consequently, $CO_2(0) = 9533$ tonnes per elephant on the initial plot.

The initial population of elephants N(0) = 100,000 occupies a plot of forest of 200,000 km^2 with a biomass of 953 million metric tons of CO_2. Thus, the initial 100,000 elephants produces carbon capture services worth $23.5656 billion at the price of $24.72 per metric ton of CO_2.

Now we consider how elephants affect carbon capture when they move to a currently unoccupied plot of land that is nonetheless within their historical range. Given that elephants had occupied these areas before, it is possible that the previous occupants had already enhanced the carbon capture in them and that some of this enhancement continues despite the lack of elephant activity.

Let C(0) be the initial CO_2 in a forest plot. We assume that it takes 200 years to reach the steady state of 9533 tonnes per elephant when C(0) starts at zero. In this case, the change is 9533/200 = 47.67 tonnes per year. We also assume that carbon is captured at this constant rate irrespective of the initial CO_2, i.e. C(0). Therefore, given an initial C(0), we can solve for the number of years to reach a CO_2 of 9533 metric tons per elephant using

$$Change = \frac{9533 - C(0)}{years} = 47.67.$$

Given the uncertainty about the initial carbon level on each re-occupied plot, we consider three cases:

1.) Initial Carbon per hectare is one quarter of its maximum (3.25 tonnes) or C(0) = 9533/4 = 2383 tonnes per elephant. Elephant activity increases capture by 47.67 tonnes per year for 150 years.

2.) Initial Carbon per hectare is one half of its maximum (6.5 tonnes) or C(0) = 9533/2 = 4767 tonnes per elephant. Elephant activity increases capture by 47.67 tonnes per year for 100 years.

3.) Initial Carbon per hectare is 0 or C(0) = 0. Elephant activity increases capture by 47.67 tonnes per year for 200 years.

At time 1 there is an increase in population of N(1) - N(0), following the logistic population growth model for elephants. This new generation enters a plot of forest with biomass of C(0) tonnes per elephant and increases it to 9533 metric tons of CO_2 over 150, 100, and 200 years for cases 1, 2, and 3 respectively. The size of the plot is adjusted so that the density of elephants in the forest is maintained at 0.5 elephants/km^2.

At time 2, a new generation of elephants is born with size N(2) – N(1), which occupies a new plot and contributes to the growth of the biomass of the tropical forest as described above. We repeat this process for 1000 generations to ensure convergence of the elephant population to its steady state, at which point the total increase in carbon capture converges to zero.

Given the growth rate of carbon sequestration in the tropical forest for each generation, we can determine the value of the contribution of each generation of elephants. Assuming a price of carbon $P_c = \$24.72$ and an interest rate of 2%, the present value of each generation k's contribution to carbon capture in aboveground biomass, $V_{k,2,t}$, is given by

$$\frac{24.72 * 47.67 * [N(k) - N(k-1)]}{.02}\left[1-\left(\frac{1}{1.02}\right)^{Y}\right]\left(\frac{1}{1.02}\right)^{k}$$, where Y is the number of years corresponding to each case. Then the present value of each generation's contribution is summed to obtain the total present value of carbon capture by all future generations. The total present value of the biomass added to the tropical forest, $V_{2,t}$, is the sum of the contribution of the current elephants and the present value of the contributions from the future generations of elephants.

Results of these calculations are as follows:

Case 1: C(0) = 9533/4 = 2383 per elephant, Y = 150 years.

These calculations imply a present value of biomass added to the tropical forest to by future generations of elephants of $152.7173 billion. The total $V_{2,t}$ of forest biomass added by elephant activity = $23.5656 billion + $152.7173 billion = $176.2829 billion.

This corresponds to a contribution to the biomass of the tropical forest worth $1,762,829 per elephant. If we add the $166 for the carbon on the body of the elephant, we obtain a total value of $1,762,995 per elephant.

Case 2: C(0) = 9533/2 =4767, Y = 100 years.

Total $V_{2,t}$ of forest biomass added by elephant activity = $23.5656 billion + $113.1792 billion = $136.7448 billion.

The contribution to the biomass of the tropical forest is worth $1,367,448 per elephant.

Case 3: C(0)=0. Y = 200 years.

Total $V_{2,t}$ of forest biomass added by elephant activity = $23.5656 billion + $173.4365 billion = $197.0021 billion.

The contribution to the biomass of the tropical forest is worth $1,970,021per elephant.

Our preferred case is case 1, since we believe that the impact of elephant activity has persisted, though elephants have been removed from much of their habitat for several decades, dramatically reducing their impact on these areas. Table A2 presents a sensitivity analysis showing how the total present value of carbon enhancement in each case depends on the number of years considered in the calculations. The present value of the elephants starts at $43.8705 Billion in 50 years and increases to $176.2222 Billion in 300 years. The last value is within $0.0607 Billion or $607 per elephant relative to the present value over 1000 years.

Table A2: Impact of Years on Present Value of Elephants (Billion $)

Years/Cases	Case 1	Case 2	Case 3
50	$43.8705	$43.8705	$43.8684
100	$98.7666	$98.7666	$98.7587
150	$149.5936	$129.4208	$149.5804
200	$171.3928	$135.7389	$182.0976
300	$176.2222	$136.7378	$196.6588

In Table A2 the first 100 years is the same since the same amount of carbon dioxide is being added each year. Starting at 150 years the amount is smaller, since the first generation is no longer adding to carbon dioxide under case 2.

The first 150 years are similar for Case 1 and Case 3, but the present values deviate over the next 50 years because the contribution of 47.67 of carbon dioxide lasts for 200 years for Case 3.

The Cost of Poaching

By Turkalo et. al. (2017), poaching of elephants increases the mortality rate of elephants by 1.71 percent per year. The current growth rate of 1.9 percent is with poaching, so that removing poaching would increase the growth rate of elephants in African tropical forest to 3.62 percent. Using the higher growth rate of elephants, we carry out the same analysis of the elephants' contributions to carbon capture under each Case. Under Case 1, the V_t of elephant activity increases to $375.2405 billion or $3,752,405 per elephant. This implies that poaching reduces the present value of the current 100,000 elephants by $198.9516 billion, or $1,989,516 per elephant.

Appendix 3

Estimation of Whale Populations off Brazil's Coast

Humpback whales: The Humpback Whale Institute (2015, unpublished data), estimated 17,000 humpbacks off the coast of Brazil in 2015. Wedekin et al (2017) recorded a population increase of 12 percent per year between 2002 and 2011. Therefore, the most recent estimate, from Zerbini et al (2019) of 25,000 humpbacks is consistent with previous findings.

Right whales: Groch at al (2005) and Renault-Braga et al (2018) present partial estimates of right whales off the coast of Brazil, but the numbers in these papers relate only to the South/Southeast of Brazil, although the species distribution is confirmed all the way to 12 degrees S. The estimate used in this paper is from a personal communication from Groch, K.R., head scientist of the Brazilian Right Whale Project. A report (Flores-Torrez, 2020) presented to the IWC Scientific Committee includes the following comment:

Population analyses and trends in abundance of Southern Brazil right whales are being carried out under a PhD thesis to be concluded in the end of May, 2020. The information will be available upon final approval of the thesis. IWC estimated 3,300 Southern Right whales in Western South Atlantic in 2009. In Brazil the population probably will be something between 500-900 animals.

Minke whales: Unfortunately for the two species of **minkes** (*B. acutorostrata* and *B. bonaerensis*), recent population estimates for Brazil do not exist. The IWC's most recent estimate was 515,000 minkes for the southern hemisphere in 2003/2004. Based on whaling data in Williamson (1975), da Rocha (1973), and de La Mare (2014), and given that these species were always considered the most abundant, the same number estimated for humpbacks was used for Minke whales, assuming they would at least be as abundant as humpbacks.

Fin, Sei, Bryde's and Blue whales: Aerial surveys conducted in the Santos Basin (off Santa Catarina, Paraná, São Paulo and part of Rio de Janeiro States) recorded an estimated 2,990 masticates (interval: 2,038-4,385); this area included the main range of these species for which records have been kept. Given that the aerial survey covered only a small part of the historic range, however, author (Palazzo) estimated a total population of 3,500 individuals spread over the four species.

Sperm whales: Author's (Palazzo) calculations, based on frequent records (mostly unpublished) of sightings at the continental shelf edge.

Appendix 4: Valuation of Whales

We value whales based on four services: 1) carbon capture in whale bodies, 2) carbon capture through phytoplankton enhancement, 3) fisheries enhancement, and 4) ecotourism. As in the case of elephants, the quantities of each service produced per period by whales depend on whale populations. We use the same logistic model developed in Appendix 1 to estimate the evolution of whale populations. The growth model parameters are given in Table A3.[§§] The populations before and after whaling are provided in Table 2 of the paper. In the discussion below, we use Brazilian Blue whales as our example.

First, we use the basic logistic model (1) and (2). From Table A3 we have $S_a = 0.9750$ for the Blue whale, which implies a continuous time mortality rate of c = 0.0509. As a result, $\beta = \nu(0) + c = 0.05 + 0.0509 = 0.1009$. The population of Brazilian Blue whales is given in the following Figure.

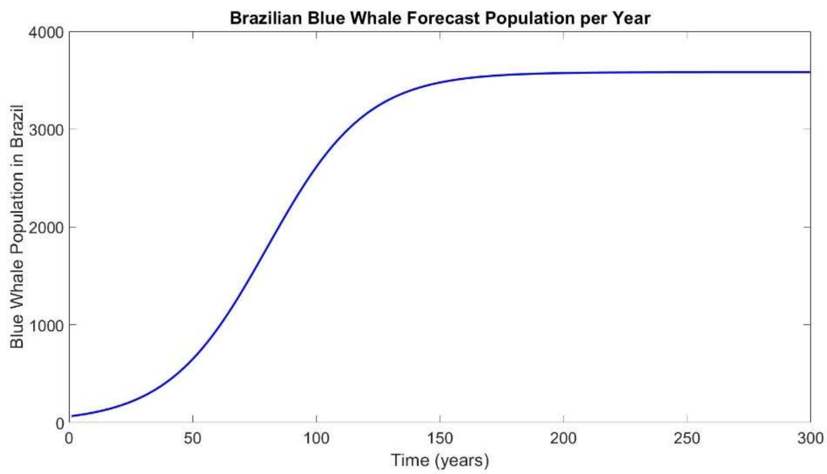


Table A3: Population Parameters for Each Species of Whales						
Species	AFR	O	IBI	Sa	So	$\nu(0)$
Blue (Brazil)	11	65	2.5	0.9750	0.8190	0.05
Blue (Chile)	11	65	2.5	0.9750	0.8190	0.05
Bowhead	20	118	3.1	0.9800	0.8230	0.03
Bryde's	10	69	4	0.9900	0.8800	0.05
Fin	10	62	2.24	0.9600	0.8060	0.04
Gray	10	55	2	0.9500	0.7000	0.03
Humpback	6	55	2.36	0.9600	0.7600	0.05
Minke	8	51	1	0.9600	0.8060	0.09
Right	10	69	4	0.9900	0.8800	0.05
Sei	20	53	2.5	0.9600	0.8060	0.04
Sperm	12	59	5	0.9860	0.8280	0.03

[§§] The same parameters are used for Brazilian and Chilean blue whales except for the beginning and ending populations. See Table 2.

AFR is age of first reproduction, **O** is oldest age of reproducing females, IBI is the interbirth interval, Sa is the survival rate of adult Blue whales, So is the survival rate of Blue whale calves, and $\nu(0)$ is the population growth rate for Blue whales. The parameters come from Taylor, Chivers, Larese and Perrin (TCLP, 2007).

Next we examine the population of Brazilian Blue whales using the model of births and deaths, equations 4 to 12. Suppose the survival rate is $s(a) = e^{-ca}$ where c is the continuously compounded mortality rate. Following TCLP (Table 1, first row), reproduced in Table A3 for the 11 species of whales, the interval between births for Blue whales IBI = 2.50. The average births over one year (see page 3, last paragraph TCLP) are m=$\frac{1}{IBI} = \frac{1}{2.50} = 0.4$. We know the number of births in the first year is m = 0.4 for an average female Blue whale. However, there are 11 years before a whale born at time 0 can give birth at time 11, so that the births at time 0 mature in 11 years with survival chance given by $S_{011} = (So)^{11} = 0.1112$. We assume the distribution of the age of whales is uniform across ages 0 to **O**. The number of female births (half the population) at time 0 is given by (8), so that

$$B(11) = \frac{O-AFR}{2\,O^2} mN(0)S_a^{11}\frac{1-S_a^{O-10}}{1-S_a} = 3.6910.$$

We let B(11) be the number of female Blue whales at the end of the initial period, so that

$$B(11) = B(0)exp\left[\int_0^1 \nu(\tau)d\tau\right] = 3.6910.$$

This implies that $\nu = 0.05$, which we assume is constant for the first year. As a result, we have from (9) that the initial number of mature females satisfies

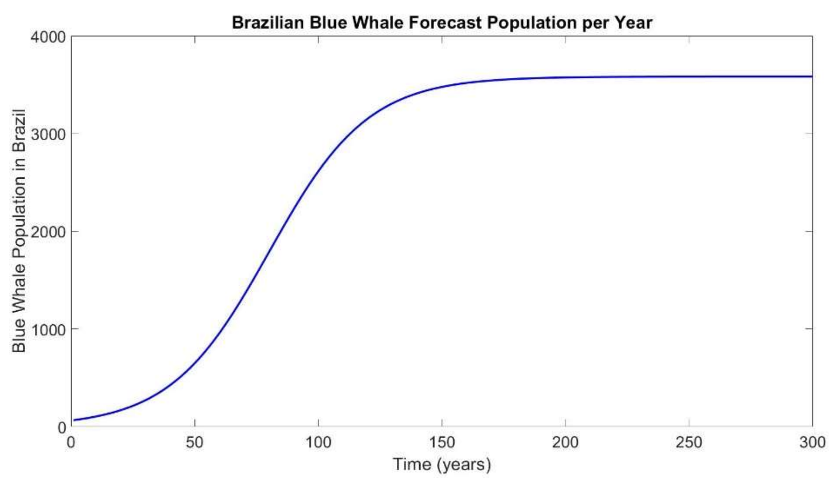
$$B(0) = \frac{2{,}259}{\frac{1}{\nu}[e^{\nu}-1]} = 3.5995.$$

By (11), the births converge to $\frac{\alpha_B(\beta-c_1)}{\beta}$ and $B(T) = \frac{3{,}583}{64}\,3.5995 = 201.5$ with N(T) = 3,583.

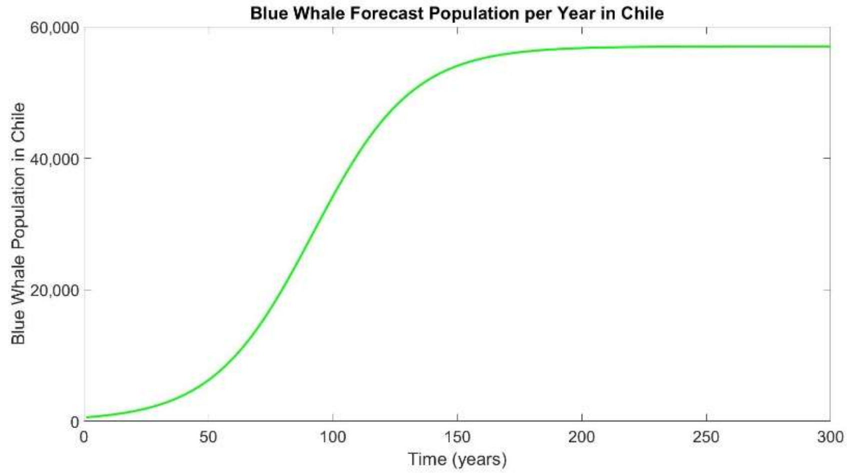
$$\frac{\alpha_B(\beta-c)}{\beta} = 201.5 \Rightarrow \alpha_B = 201.5\frac{0.1009}{0.05} = 406.5.$$

The number of annual births over 300 years for Brazilian Blue whales are given in the following figure.

We also know that the population and births grow at the same rate with initial ratio, $b = 0.0562$, so that the total population implied by (12) is graphed in the next figure over 300 years for the Brazilian Blue whales.



The Chilean population of Blue whales starts between 570 and 760, which is only 1% of the pre-whaling number of whales. As a result, we set the upper limit of Blue whales in Chile at N(T) = 57,000 based on the initial number of 570 whales. The next graph depicts the population of Blue whales in Chile using the same logistic model. The parameters for the Blue whales in Chile are the same as for the Brazilian whales in Table A3.



Carbon Capture in Whale Bodies

The quantity of the carbon captured in the body of a mature whale is dependent on the biomass of the whale. The weight of Blue whales is given by

$$W = aL^b = 0.000061x\ [3.281\ x\ 27]^{3.25} = 130.0809 \text{ metric tons,}$$

where a and b are parameters from the Table A4 below. The weight is the same for the Chilean Blue whales, so that the carbon content (and carbon dioxide equivalent) is the same for Brazilian and Chilean Blue whales.

The first two parameters in Table A4 are for each species of whales. The length comes from Smith et. al. (2019), Table 3, for each species.

Table A4. Parameters for Weight of Each Species of Whales			
Species	A	B	L (Meters)
Blue (Brazil)	0.000061	3.25	27
Blue (Chile)	0.000061	3.25	27
Bowhead	0.00255	2.916	16
Bryde's	0.0005	2.74	7
Fin	0.00025	2.9	23
Gray	0.0054	3.28	15
Humpback	0.00049	2.95	16
Minke	0.003188	2.31	7
Right	0.000348	3.08	16
Sei	0.001436	2.43	16
Sperm	0.000152	3.18	18.5

The values of a and b from Pershing et. al. (2010).

The carbon dioxide content, in metric tons of CO_2 per Blue whale, is

$$CO_2 = 0.1048\ x\ W\ x\ 0.9\ x\ \frac{11}{3} = 0.1048\ x\ 130.0809\ \ x\ 0.9\ x\ \frac{11}{3} = 44.\ 9872 \text{ metric tons.}$$

The cash flow per year from increased carbon capture on bodies, CF(i), is equal to the increase in population multiplied by the CO_2 equivalent captured per body, multiplied by the price of carbon dioxide, $P_C = \$24.72$, so that for each species we have

$$p_{1,t+i}\, s_{1,t+i} = P_C CO_2\, [N(i) - N(i-1)] + P_C\, Fall\, N(i) \text{ for i} > 0.$$

The last term reflects the carbon content of whales that die and fall to the ocean floor, where $Fall = 1 - S_a$ per year and per whale.

Assuming a discount rate of r = 0.02, the present value of carbon captured by the bodies of the 64 Blue whales in Brazil is

$$V_{1,t} = PV(Body\ Carbon) = P_C\ CO_2 N(0) + \sum_{i=1}^{300} \frac{p_{1,t+i}\, s_{1,t+i}}{(1+r)^i}$$

$$= \$74{,}754(845{,}183) + \$2{,}260{,}168(13{,}907{,}802) = \$2{,}334{,}922(14{,}752{,}985).$$

The present values for Chilean Blue whales are in parenthesis. These values are larger because of the larger population of Blue whales in Chile.

Phytoplankton Capture Enhancement

We now value the benefit of whale activity on phytoplankton, assuming that current whale populations are responsible for one percent of existing phytoplankton biomass, which captures the equivalent of 370 million metric tons of CO_2. We assume that as whales return to their pre-whaling populations, they stimulate an additional one percent increase in phytoplankton and therefore an additional one percent increase in carbon capture. We apportion this benefit according to the percentage of the total whale biomass accounted by each species, where these shares are reported in Table 2. For the 64 Brazilian Blue whales the biomass weight is 0.0001555 of the total population of whales in the world. This means that the Blue whales in Brazil currently account for the equivalent of 0.0001555 * 370 million = 57,524 metric tons of CO_2. The 760 Chilean Blue whales account for 0.001853 of the biomass of all whales in the world, which accounts for 685,845 metric tons of CO_2.

In each period the population of each species grows, so that the increase in capture each period by Blue whales in Brazil is given by

$$p_{2,t+i}\, s_{2,t+i} = value\ of\ Phyto\ \ Capture_{Blue}\ per\ period(t) = \left[1 + \frac{\int_0^t dN(a)}{\int_0^T dN(a)}\right] xP_c\ 57{,}524$$

$$= \left[1 + \frac{N(t) - N(0)}{N(T) - N(0)}\right] x\ P_c\ x\ 57{,}524.$$

Since we know the beginning and ending population as well as the population at each time, this can be easily calculated.*** This value at time 0 is $P_c\ x\ 57{,}524$ and converges to $P_c\ x\ 2\ x\ 57{,}524$ at the steady state.

For Chilean Blue whales, we replace the 57,524 with 685,845 because of the larger population. Using an interest rate of r = 2% and a price of carbon dioxide of $24.72, the present value of a one percent increase in phytoplankton from additional Blue whales in Brazilian waters is

$$V_{2,t} = PV(Phyto\ Capture\ _{Blue}) = \int_0^T \left[1 + \frac{N_{Blue}(t) - N_{Blue}(0)}{N_{Blue}(T) - N_{Blue}(0)}\right] xP_C x\ 57{,}524\ x\ e^{-rt}dt$$
$$= \$164{,}714{,}579\ (1{,}916{,}963{,}736).$$

The present value of carbon capture from increased phytoplankton is $\$164{,}714.579$ for Brazilian blue whales under continuous compounding.††† The present value of the 570 Chilean Blue whales is $1,916,963,736.

Fisheries Enhancement

The total contribution to fisheries in the world is $1.5 billion per year for all whales, which we assume increases by another one percent or an additional $1.5 billion per year as whales return to their pre-whaling populations. Again, we apportion each species' contribution to increased fisheries according to its share of total whale biomass. This weight is 0.0001555 for Blue Brazilian whales, which implies a current flow of 0.0001555 * $1.5 billion or $233,206 per year. Each species' contribution to fisheries enhancement increases with its population so that

$$V_{3,t} = PV(Fish_{Blue}) = \int_0^T \left[1 + \frac{N_{Blue}(t) - N_{Blue}(0)}{N_{Blue}(T) - N_{Blue}(0)}\right] x\$233{,}206\ x\ e^{-rt}dt = \$27{,}013{,}018.$$

The present value of Brazilian Blue whales' contribution to fisheries is valued at $\$27{,}013{,}018$ using a 5% growth rate for Brazilian Blue whales. For 760 Chilean Blue whales, the present value of fisheries enhancement is $314,380,041.

Ecotourism Revenues

Tourism from all whales is currently $2.0 Billion per year, which we assume increases to $4 billion per year as whales return to their pre-whaling populations. Once again the contributions are apportioned according to biomass weights, so that for Brazilian Blue whales we estimate the current contribution to ecotourism by 0.0001555 * $2.0 billion, which is $310,941. The contribution increases with its population so that

*** In the second step we use the fundamental theorem from Calculus..

††† We approximate the integral by using summation over the T years and using discrete compounding.

$$V_{4,t} = PV(Tourism_{Blue}) = \int_0^T \left[1 + \frac{N_{Blue}(t) - N_{Blue}(0)}{N_{Blue}(T) - N_{Blue}(0)}\right] x\$310{,}941\ x\ e^{-r}\ dt$$
$$= \$36{,}017{,}358.$$

The 760 Blue whales in Chile has a present value for tourism of $418,818,311.

In the Table below we summarize these results for the Brazilian Blue whale in column 2. The total value is $230,079,877 for 64 whales or $3,609,454 per Blue whale in Brazil. In Chile the total present value of the 760 Blue whales is $3,107,530,267 or $4,088,855.61 per Blue whale.

Present Value	Brazilian Blue Whales	760 Chilean Blue Whales
Carbon Capture	$2,334,922	$14,752,985
Phyto Expansion	$164,714,579	$1,916,963,735
Fisheries	$27,013,018	$314,380,041
Tourism	$36,017,357	$418,818,311
Total	$230,079,877	$3,107,530,267

The values of the other great whales off the coast of Brazil are estimated in a similar way, using the corresponding parameters from Table 2, Table A3 and Table A4.