Bioeconomic factors of natural resource transitions: The US sperm whale fishery of the 19th century

Brooks A. Kaiser

University of Southern Denmark, Gettysburg College, and Univ. of Hawaii

Abstract

This paper uses bio-economic modeling to investigate the transition from whale oil (a renewable, exhaustible natural resource) to petroleum that occurred in the mid-19th century. The discovery of petroleum is often presented as a stochastic event that 'saved the whales'; we combine newer biological evidence (Whitehead 2002) with economic theory of natural resources and uncertainty to address this long-standing controversy over whether sperm whale fishery dynamics would have been sufficient to preserve the sperm whale population without the discovery of petroleum (e.g. Davis et al, 1988; Maran 1974; Shuster 1973). We find that under most economic conditions the dynamics, even without a substitute, would have prevented extinction but not depletion; this result is different than that usually determined for the better studied baleen whales, due in part to biological differences and in part to differences in their economic productivity as harvested resources. The paper is part of a larger project investigating the timing of resource transitions and how the increasing costs and demand for illuminants drove the search for substitutes and how successful drilling for petroleum presented the best substitute from an array of interdependently developing resources and technologies, cementing the decline of the US sperm whaling industry.

JEL Classifications: Q20; N50

Keywords: Sperm whale fishery; bioeconomic modeling; exhaustible biological resources; economic history of natural resources.

I. Introduction

In 1861, Vanity Fair published a cartoon where sperm whales hosted a ball in honor of the new petroleum discoveries thanking them for saving the species (Vanity fair, 1861). Conventional wisdom clearly credits the PA discoveries with a seismic shift in the illumination industry that brought the end of whaling and saved a species from extinction.

Over the decades, this wisdom has been questioned by economic historians and others, and the literature to date on the intertwined fates of the American whaling and petroleum industry has focused mainly on the extent to which the discovery of readily accessible petroleum supplies caused the decline of the whaling industry in the latter half of the 19th century (Daum, 1957; Hutchins, 1988; Maran, 1974; Shuster, 1971). In these works, the questions investigate the demand and supply of whale oils in an industrial setting where the discovery of petroleum is virtually exogenous, though once discovered, it has a tremendous impact on whale oil markets. In this project, we seek to unify our understanding of the transition between the two industries by examining theoretically the extent to which the troubles in the whaling industry influenced the discovery of drillable petroleum in 1859 and the formation of the industry that sealed whaling's fate. We discuss the two industries in terms of a transition from one exhaustible resource to another, we exploit natural resource economics theory to evaluate the historical evolution of the industries. Along the way, we are able to address other interesting questions about resource use, including how the whale population would have fared with different (uncertain) timing in the discovery of illumination substitutes. This latter question is the focus of the immediate paper.

Here we consider whale oil a renewable but exhaustible resource, where the search for a backstop technology results in uncertainty about the availability (marginal cost) and timing of substitutes. These characteristics provide the basis for determining the theoretically optimal time profiles of the primary (sperm whale oil) and backstop (e.g. petroleum) resource supply rates. These optimal time profiles will, in turn, be examined in light of the actual data in order to inform about the overall exploitation of the primary resource in terms of its exhaustibility, i.e. will provide theoretical corroboration or rejection of the empirical findings of Davis, Gallman and Hutchins (1988) that the stock of sperm whales was not, in fact, in jeopardy in the 19th century.

We begin with a brief overview of the illumination business. We use data from several different sources to inform our research. We have data on individual whaling voyages and biologists from which to build our cost (supply) function, and from industry accounts of prices and quantities of whale oil and petroleum traded to build our demand function.

With respect to the whaling industry, we show, using standard theory of renewable but exhaustible resources, how sperm whale oil extraction should have optimally progressed if no alternative technologies were available (so that the present value of marginal user costs were equal across time), and how they would have likely progressed given the estimated stocks of whales and the growing demand for illumination (and lubricants). Using Monte Carlo methods, we investigate uncertainties about the biological capacity of the fishery (both growth and carrying capacity) and our counterfactual assumption about the timing of a substitute illuminant like petroleum or electricity. While our model relies on optimal extraction decisions in all industries, we note that the open access nature of the fishery would exacerbate the resource pressures, but not change the underlying structure of costs and bio-dynamic processes, and leave the details of this problem for future work.

II. History and Background

A. Short History of Illumination, 1800-1859

Illumination up until 1830 was generally restricted to tallow for the common man (Williamson and Daum, 1959). Sperm whales had been actively hunted since 1712, but the oil was expensive enough to be mainly for wealthy, and naval disruptions through the war of 1812 hampered the industry tremendously. The demand for luminants was growing rapidly with industrialization, however. Whale oil dominated the illumination market in the 1850 census (65.5% of the market in oil and gas illuminants (Daum, 1957)), but its competitors had decreased this share to 19% by 1860. Town gas (from coal), was introduced as a potential solution to the illumination problem for urban areas, arriving in Baltimore first, in 1816, and then to New York and Boston by 1830, and had a 16% share of the market by 1850, which grew to 38% in 1860. (Daum,1957).

Several more cities turned to town gas 1830-1837; the financial panic of 1837 slowed this, then town gas expansion picked up again in the mid 1840s. A tariff reduction for coal into the US in 1846 from $1.75 to $0.40 per ton increased coal use, and there were 56 or so plants in operation in 1850 (Williamson and Daum, 1959).

But town gas was expensive to network into homes, and so slow-going. Households were still looking for alternatives. Meanwhile, lamps evolved to burn better and give more light. Lamps also started to be able to take different types of oil (sometimes with a bit of conversion), reducing joint-product problems, in response to a number of potential new fuel entrants. Camphene (from turpentine) was developed, but was highly flammable -- still it had 9% of the market in 1860. Lard oil markets expanded, with 13.5% of the market in

1850 (falling to 8% in 1860). Europeans were working to produce coal oils from the mid 1830s, but not much was going on in the US with converting minerals to oil until 1850. With no measurable share of the illumination market in 1850, by 1860 coal oil (kerosene) had 20% of the market (Daum, 1957).

Coal-oil kerosene and lamps really dominated the growth in the mid- late 1850s, replacing the dangerous but cheap (and therefore popular) camphene. This transformation put distilling and networks in place. Those working with distilled oils were aware of the theoretical potential of petroleum, but didn't know how to get enough of it. The innovation of drilling, borrowed from salt wells that had actually been producing petroleum as a by-product in the Mid-Atlantic region, was needed to settle the question of which mineral or oil resource would capture the market at the lowest cost. In 1859, oil was struck at Pithole, PA, and quickly outcompeted other forms of illuminants.

B. Demand for Illumination

To model the demand for whales, we need to model the demand for illumination. We do so using an instrumental variables model estimating a growing inverse demand function for illumination from oils, $D^{-1}(q_t)$, where $q_t = q_{wt} + \phi q_{bt}$, so that q_t is the total quantity of luminants demanded at time t, q_{wt} is the quantity of in thousand gallons of sperm oil, q_{bt} is the quantity of the alternative (backstop) resource, here petroleum, in thousand gallons. ϕ is a coefficient translating illuminating power, which we set here equal to approximately 0.64 based on reports of chemists suggesting that 1.57 gallons of petroleum oil (transformed to kerosene) were needed to produce the same illumination quality and hours as one gallon of sperm oil (Silliman, 1871). We assume that demand for all illuminating oils starts to fade rapidly in the 1880s with the advent of electricity.

We determine empirically (Table 1) that the main components of demand for illumination (captured in one dimension by adjusting petroleum extraction quantities first to kerosene and then for light producing capabilities so that the units are in sperm oil equivalence) over the 19^{th} century are captured by industrial progress, time, and price, and the price of the lesser substitute whale oil (as opposed to sperm oil), which is included in Table 1, Col III. The index of industrial production (Table 1, Col I) is a more targeted measure of growth than per capita GDP (Table 1, Col II) and seems to capture more clearly the demand for illuminants.

The regressions in Table 1 are estimated as 2SLS estimators to account for endogeneity with supply, with error corrections for heteroskedasticity and autocorrelation stemming from the time-series nature of the data[1].

[1] Both heteroskedasticity and autocorrelation are found in preliminary testing. Results not included. Heteroskedasticty corrected with standard robust estimators. Autocorrelation corrected with Newey and West's (1994) automatic non-

Note that the advent of electricity in the late 19th Century provides a secondary backstop to illumination needs from either sperm oil or kerosene, and helps explain why the coefficient on year is positive while that on the index of industrial production is negative – the total effect of this is to show growth for demand in illumination oils until the 1880s and then this begins to fall. We feel that it is more than reasonable to assume that technological progress would continue in some form even if petroleum had not been discovered (indeed, census data shows sperm oil illumination was already decreasing in importance by 1860, due to town gas, coal oil kerosene, and camphene alternatives), so that our counterfactual is not simply that a failure to discover petroleum would mean that whale oils must supply all illumination needs.

Thus we choose $D^{-1}(\mathrm{q}_t) = \alpha e^{\gamma \cdot t + \gamma' \tau + \lambda \mathrm{I}} p_t^{-\eta}$ as our functional form, so that quantity is a function of price, p_t and an industrial production index (Davis, 2004), *I*, growing over time as the North American economy expands, with a structural break possible at 1879, signaling the advent of electricity as a substitute form of illumination (e.g. $\tau = 1$ from 1879 forward). While the coefficient on the price of (inferior substitute) whale oil is statistically significant in our estimation, its main effect on the model for demand is to lower the own price elasticity, so we do not allow the coefficient to vary for parsimony in further simulations, instead holding it constant at its mean and folding it into the constant, α. Instruments are the shipping tonnage in the whaling industry and the whale population, both of which should affect supply of oils but not demand.

Using the results from Table 1, col III, the elasticity of demand, η, is estimated to be 3.06%. It may seem surprising that we would find such elastic demand, but anecdotal evidence for a high elasticity of demand for sperm oil comes from as early as the mid 1760s, when spermaceti candle manufacturers in New England tried (rather unsuccessfully) to restrict entry and keep down oil prices through a monopsonistic cartel because oil input prices were rising faster than the market would allow candle output prices to grow. Between 1761and 1774, the premium on the highest quality oil had increased almost 7-fold while the price of candles had only increased about 20% in Boston (Dolin, 2007). Elasticity of demand for petroleum was also fairly high in the early days of petroleum, with many substitutes, uncertain customers, and evolving methods for storage and distribution.

The coefficient on the industrial production index is small and somewhat surprisingly negative, at -0.004. In combination with the strong coefficient on time (0.2) and the post-1879 dummy (-1.7), this only begins to shift the demand curve back after about 1880, when electricity begins to come on the scene as an alternative for illumination. We exploit this tradeoff between overall growth, that should increase demand for illumination, and growth in industrial production that might bring substitutes, in our demand, using these parameters as a second backstop to the importance of kerosene illumination.

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parametric bandwidth-selection procedure in Stata (asymptotically efficient for a given rule for weighting covariances [kernel])

Table 1: Instrumental Variables (2SLS) estimation for demand for illumination (dep. Var = log quantity illuminating oil, gallons. Ln Qt= Ln (Q[whale oil]+0.64[petroleum]) P-values in parentheses.

Variable	I	II	III	Variable provenance
Price (log, $2007)	-4.296*** (0.002)	-2.777* (0.067)	-3.059*** (0.014)	Whales: Tower (1907); Petroleum: US Bureau of mines, Mineral resources of the US (annual) [Series Db56 in Historical Statistics of the US] (Deflator, CPI, Sahr, 2010)
Year (1800=1)	0.203*** (0.000)	0.210*** (0.000)	0.197*** (0.000)	
Post 1879 dummy	-1.987* (0.090)	-0.494 (0.639)	-1.714* (0.093)	
Index of industrial production	-0.004*** (0.003)		-0.004*** (0.002)	Series Ca19 in Historical Statistics of the US
Real GDP per capita		-0.002** (0.028)		Series Ca11 in Historical Statistics of the US
Price sub. whale oil (log, $2007)			-1.33* (0.078)	
Constant	19.99*** (0.000)	19.17*** (0.000)	19.42*** (0.000)	
Instruments	Tonnage Whale population	Tonnage Whale Population	Tonnage Whale Population	Tonnage from Tower (1907) Whale Population estimated from Whitehead (2002)
Regression F stat	146.93***	131.23***	170.87***	
Centered R2	0.919	0.920	0.934	
Uncentered R2	*0.996*	*0.996*	*0.997*	
N. Obs.	101	101	101	
Underidentification test	4.733* (0.094)	4.581 (0.101)	4.581	Kleibergen-Paap rk LM stat Rejection of null -> identified
Weak ID test ()	58.84***	115.24***	33.89***	Kleibergen-Paap rk Wald F stat Significance -> relevant instruments
Over ID test ()	0.325 (0.568)	0.214 (0.643)	0.068 (0.794)	Hansen J stat Rejection of null -> overidentification

To simplify the demand function for use in our simulations, we divide demand into two time periods: before and after an innovation (shown here as occurring in 1879) that reduces demand pressure on illuminating oils and estimate the resulting demand equations holding the industrial production index constant at its value of the time period in question. Thus before such an innovation, we have

$$q = 6*10^7 e^{0.2t} p^{-3}, \tag{1.1}$$

and after the innovation we have

$$q = 2.5*10^6 e^{0.2t} p^{-3}. \tag{1.2}$$

We also consider the unlikely alternative that no innovation is discovered, but that demand for illumination grows along with industrialization. In this case we consider demand for illuminating oils will grow quite large, and seek to determine the dynamics of an optimally managed fishery if whales alone were used to meet this demand. In this case we estimate the demand function as

$$q = 1.4 * 10^{10} e^{0.2t} p^{-3}, \tag{1.3}$$

Where the shift in the constant parameter reflects the growth in the economy that occurs post-1879 (and is in reality accommodated by the rapid expansion of electricity) but does not account for the electricity innovation itself. Thus it will allow us to investigate the role that increased pressures on the resource would play if sperm oil were to try to satisfy the market as it evolved. Thus, using equation 1.1, we forecast sperm oil use and pressures on whaling that accommodates some growth but does not expect a dynamic innovation, equation 1.2 allows us to envision a reduction in pressure on the whales occurring at some future date, and using equation 1.3 we forecast heavier demand from greater industrialization without other resources for production. This allows us some potential insights into the exchange between illumination sources and overall growth: if whale populations cannot even sustain growth along the lines demanded in eqn. 1.1, then the population would have been doomed without the coming of other sources of illumination. If, however, they could support such demand, then we suggest that the advent of the new technologies was not required to save the whales, though it was likely required to expand growth along the scale indicated by eqn. 1.3. In the unexpected event that the whale population could even support demand along the lines of eqn. 1.2, then certainly the advent of petroleum cannot be credited with saving the whales. If the lowest level of demand (represented in eqn. 1.2 with new alternatives but not growth in their demand) does accommodate preservation of the whales but the original demand (eqn 1.1) does not, then there is more evidence that the discovery and use of kerosene can be credited with preserving the whales.

C. Whaling for oil: extraction of a renewable but exhaustible resource

1. Marginal cost for sperm oil production

We assume that the marginal cost of supplying sperm oil is non-declining in the quantity of sperm oil, q_{wt}, and decreasing in the stock of sperm whales, n_t. We then estimate, again using instrumental variables, a cost function for supply of sperm oil, particularly as a function of the whale population. Table 2 shows results for the cost function (we control for the ship's logged destination, not reported here.) The voyage data come from the American Offshore Whaling Database (2011), which records over 10,000 whaling voyages, mainly over the 19th Century. The whale population data is calculated from Whitehead (2002), where the biologist estimates population levels for global sperm whale populations from 1712 to 2000 using a density dependent logistic growth model (see Appendix I).

Table 2: Instrumental Variables (2SLS) estimation for Marginal Cost function for sperm whale oil (dep. Var = log price sperm oil, gallons, $2007. P-values in parentheses.

Variable	I	II	III	IV
Gallons sperm oil delivered to port (ln)	0.247*** (0.000)	0.239*** (0.000)	0.201*** (0.000)	0.177*** (0.000)
Whale population, (ln)	-8.55*** (0.000)	-8.742*** (0.000)	-3.183*** (0.000)	-3.206*** (0.000)
Year (1800=1)	-0.13*** (0.000)	-0.135*** (0.000)	-0.009*** (0.000)	-0.010*** (0.000)
Year^2	0.0006*** (0.000)	0.0006*** (0.000)		
Price subs. whale oil (ln, $2007)	0.304*** (0.000)	0.305*** (0.000)	0.406*** (0.000)	0.415*** (0.000)
Months of voyage	-0.00008 (0.484)		-0.00003 (0.802)	
Ship tonnage (max)	0.0009** (0.031)		-0.001*** (0.002)	
Constant	122.3*** (0.000)	125.33*** (0.000)	43.53*** (0.000)	44.23*** (0.000)
Other controls	Destinations (n=23)	Destinations (n=23)	Destinations (n=23)	Destinations
Instruments	Price of petroleum (gal, $2007)	Price of petroleum (gal, $2007)	Price of petroleum (gal, $2007)	Price of petroleum (gal, $2007)
Regression F stat	1527.6***	1608.1***	2000.6***	2086.5***
Centered R2	0.763	0.756	0.746	0.747
Uncentered R2	*0.997*	*0.997*	*0.997*	*0.997*
N. Obs.	9794	9950	9794	9950
Underidentification test	1255.73*** (0.000)	1209.71*** (0.000)	473.67***	542.86***
Weak ID test ()	1712.8***	1613.9***	570.13***	651.53***
Clusters (by Vessel)	1299	1344	1299	1344

Whitehead (2002) does not establish a minimum viable population for the sperm whales, so our mathematical model does not incorporate such a threshold directly. There is evidence that the minimum viable population may be very small indeed, as biologists now consider the Mediterranean population as distinct from the global population and consisting of only a few thousand, possibly only several hundred, whales (in a smaller space). (Notarbartolo di Sciara et al, 2012). We hypothesize that a very high (conservative) estimate of a global threshold for population could exist at 300,000 whales.

In Table 2 we present results from estimation of the marginal cost curve under four slightly different specifications. Supply (Price = marginal extraction cost in a competitive industry) is estimated as a function of quantity of sperm oil delivered from the vessel (instrumented with petroleum prices), estimated quantity of whales available, time (and time squared), the price of the substitute whale oil, the length of voyage and tonnage in the vessel (Table 2, Col. 1). We do not find that the length of the voyage itself has a significant impact on the marginal cost (supply price). This is possibly a function of the fact that prices are average annual prices and not individual prices received by the ships. Neither omission of length of voyage nor ship tonnage greatly affects the results (Col. II). Time captures much that is difficult to observe about the industry as a whole and we include it in a non-linear fashion as well in specifications I and II of Table 2. We omit the non-linear time factor in specifications 3 and 4 (Col III, IV). Results do not change dramatically though the influence of tonnage switches from having an expected positive impact on price to having a negative one in specification 3(Col III) results. Thus for use in further (simplified) simulations, Col IV presents the preferred results.

Using Table 2, Col IV, we focus on the relationship between the whale population and the marginal cost, so we hold the price of the substitute whale oil constant at its mean[2] to obtain the marginal extraction cost function for the primary resource, whales, of:

$$C(n,q,t) = e^{-0.01t}\left(\frac{3.49*10^{19}}{n^{0.321}}\right)q^{0.177}$$

Thus marginal costs are slightly increasing in quantity harvested and decreasing in the stock level of the resource, where the stock, n_t, evolves over time according to the growth function for the sperm whale population and the harvest rate, discussed in Appendix 1. Furthermore there is an unspecified technological or similar component to the passage of time that lowers marginal costs.[3]

As discussed below, we simplify this cost function further for our simulation, so that we linearize costs with respect to harvest quantity and leave the time trend to the constant term. This results in a cost function of

[2] We also include in the constant term the significant destination effects evaluated at their means.
[3] Starting from t=1, at t=100 MC fall non-linearly to 37% of original costs, all else constant.

$$c(n_t)\,q_t = \frac{5.85*10^{16}}{n_t^{2.8}} q_t \quad . \tag{1.4}$$

This more tractable cost function for the simulation still captures accurately what evidence we have about the whaling costs experienced in the 19th C.

These parameters for demand and marginal cost inform a dynamic model of the whale fishery. We simulate the fishery's evolution over time under changing assumptions about the arrival of a cheap substitute (kerosene) in order to determine how the industry would have fared under differing levels of technological progress.

III. Methodology and simulation

A. The whale fishery

We now have virtually all the elements needed to model how the sperm oil industry would have fared without the discovery of abundantly cheap mineral fuel oils, if the whale fishery were optimally managed (as opposed to the more realistic open access, discussed briefly but left for further analysis elsewhere). This will illustrate, in a sense, the time frame that existed for new discoveries, and show the pressures to discover new sources of illuminants.

To determine the optimal use of the sperm whale resource over time, we write the (deterministic) maximization problem as

$$V(N_0) \equiv Max \int_t SW_t = \max_{q_{wt}} \int_{t=0}^{\infty} e^{-rt} \left(\int_0^{q_{wt}} D^{-1}(z)\,dz - c(n_t, q_{wt}) \right)$$

Subject to

$$\dot{n} = g(n_t) - q_{wt} = \rho n_t \left(1 - \frac{n_t}{K_0}\right)^{1+b} - q_{wt},$$

$q_{\mathrm{wt}} \geq 0; n_t \geq 0,$ and N_0 given.

where social welfare, SW_t, is the net surplus from consumption of the whales, q_{wt}, given the inverse demand , $D^{-1}(z)$ and the harvest costs $c(n,q,t)$ as a positive, decreasing function of the population of whales ($c_n < 0$) and the passage of time $(c_t < 0)$, and non-decreasing function of the level of harvest, $(c_{q_w} \geq 0)$. For the current iteration of this work, we ignore the time sensitive effects and simplify marginal costs to a function of whale population and harvest levels, *c(n,q)*. We further simplify by assuming costs are linear in harvest so that $c(n_t, q_t) = c(n_t)q_t$ The system is subject to the equation of motion determined by the growth rate of the whales, $\dot{n}$, which is in turn a function of the intrinsic growth rate, ρ, the current population, n_t, the carrying capacity of the oceans, K_0, and a density dependent exponent, *b*, and illustrated in Appendix 1. [4]

The current value Hamiltonian for this problem is

$$H = \int_0^{q_{wt}} D_t^{-1}(\mathrm{z})\,\mathrm{dz} - \mathrm{c(n)}\,\mathrm{q}_{wt} + \left[g(n_t) - \mathrm{q}_{wt}\right]\lambda_t \quad \text{where } \lambda_t \geq 0$$

and the necessary conditions for an optimal solution are

$$\dot{n}_t = \frac{\partial H}{\partial \lambda_t} = g\left(n_t\right) - q_{wt}$$

$$\dot{\lambda}_t = r\lambda_t - \frac{\partial H}{\partial n_t} = r\lambda_t + c_n\left(n_t\right)q_t - g'\left(n_t\right)\lambda_t$$

$$\frac{\partial H}{\partial q_t} = D_t^{-1}\left(q_{wt}\right) - c\left(n_t\right) - \lambda_t \leq 0, \quad if < then\, q_t = 0.$$

We define $p_t = D_t^{-1}\left(q_{wt}\right)$. Rearranging the necessary conditions and combining them with the time derivative on price gives us that the optimal harvest requires:

$$\dot{p}_t = (g'(n_t) - \mathrm{r}) * (\mathrm{p}_t - c(n_t)) - g(n_t) * c_{n_t}(\mathrm{n}_t)$$

$$\dot{n}_t = g(n_t) - q_{wt}, \text{ and}$$

$$\lambda_t = (p_t - c(n_t)).$$

We use Mathematica 8 (see appendix II) to solve these equations simultaneously and to illustrate the patterns of whale populations, extraction rates, optimal price and cost over time. These results illustrate how the

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[4] Some functions, in particular the marginal cost of harvest with respect to the resource population, need translation from whales to gallons. This is accomplished by assuming that there are 35 gallons per barrel on average for sperm whale oil (Ellis, 1980) and about 25 barrels of oil per sperm whale, for a multiplicative factor of 875.

fishery could have evolved under limited access (first best conservation) management. The actual open access nature of the fisheries increased the pressure on the resource but from the optimal solution we can discern whether the fishery was inherently doomed or whether good management, rather than discovery of a new resource source, would be sufficient to meet demand. We consider the three demand scenarios estimated from the data above in a deterministic setting. We then use Monte Carlo methods to investigate changes in parameters for additional sensitivity analysis.

Scarcity rent, λ_t, is the difference between price and marginal harvest cost, and captures the dynamics of the model. If there is no shortage of whales, $\lambda_t=0 \ \forall t$ and the dynamic problem collapses to a static problem. If, on the other hand, a resource grows scarcer over time, we expect the scarcity rent to rise, dramatically so in the case of a resource dwindling to zero, for example, as is the case if the whales are pushed to extinction. Note that this can only happen if the growth function for the population of whales is critically depensated, which is not the biologists' assumption in the case of sperm whales, or if the cost of hunting the last whales does not rise toward infinity, contrary to what is generally assumed for most fish species, especially given the whaling technology of the day. If costs increase toward infinity, additional harvesting becomes infinitely unprofitable at low enough populations (Clark, 2005). In a case where it is profitable to 'overharvest' - that is, to harvest to a point below maximum sustainable yield (MSY), then increased pressure from growing demand will result in either a series of oscillations in the harvest (and therefore in price and cost) over time or a somewhat tenuous equilibrium at an unstable steady state. Because the evidence regarding the behavior of the sperm whale populations at low levels has significant uncertainty, we expect that reaching a period of chaotic behavior may well lead to unrecoverable stocks of the whales.

We analyze the question from the standpoint of 1800, at which point we assume that the sperm whale population has already been drawn down to about 71% of its estimated carrying capacity (Whitehead, 2002), but is still above MSY. We do this to determine whether the previous rates of harvest were too high or too low to maximize dynamic efficiency, given demand. If harvests were too high, we should find a period of lower harvests where the fishery can recover before it is more rapidly exploited to meet higher future demand. If harvests were too low, we should find a rapid drawdown of the population with no period of conservation.

An important question is how fast would the demand for illumination grow without the advent of cheap petroleum illuminant? We investigate several possibilities that are based around the growth rate of the 19th century. The growth rate in industrial production (Davis, 2004) is on average 5.6% for the century while overall GDP growth is on average 4%. Rather than assume there is no technological change (e.g. the utilization of other illuminants as we see occurring from 1850-1860 before petroleum) we build the demand for illumination above as if fuels were available, incorporating the advances those brought in efficiency to the production of light, but then assume the fuel itself would need to be provided by the whales. This defines the scope of the counterfactual more reasonably than assuming no advances in technology or production of such an important good.

IV. Results

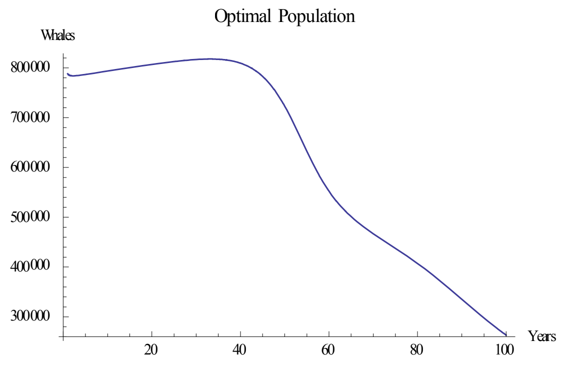
A. Low demand case

A1. Interest rate = 0.03

Using parameterization determined by the lowest demand curve for illuminating oils (eqn 1.2), which still exhibits very rapid growth in demand of 20% ($\gamma = 0.2$), we find that at an interest rate of three percent the whale population would eventually be exhausted, but the time frame for this exhaustion is over 400 years if there is no critical population threshold for whale reproduction. If a population of approximately 300,000 whales is required, then the time span is approximately 90-95 years.

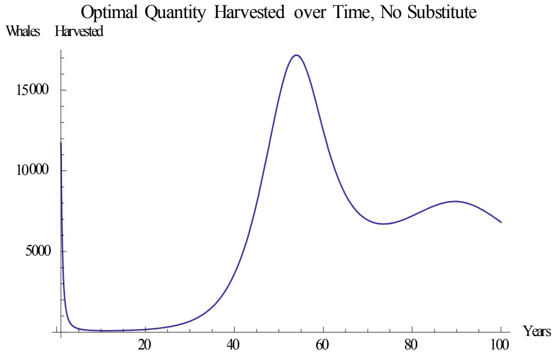
Figure 1 illustrates the optimal population level over the first 100 years, which pushes the population just below 300,000 whales ($n_{100} = 292,417$). If this is higher than the threshold for reproduction (as we expect it in fact is), the optimal population is allowed to recover slightly and then a few years of heavier harvest may occur followed by a few quickly dampening 'pulses.' If not, then even this lowest demand level for illuminating oils pushes the species to extinction.

Figure 1: Optimal whale population over time.



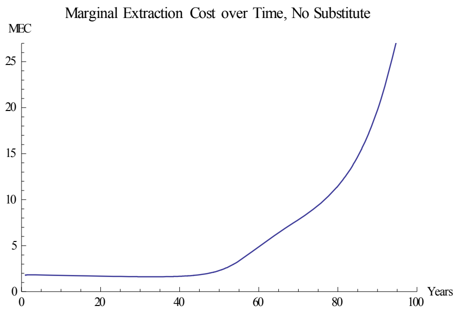
The optimal extraction path is shown in Figure 2. We see that there is a first year harvest to capture immediate rents, followed by a period of some resource conservation for about 40 years, allowing the population to grow higher because the growth in demand will make it worth even more in future time periods.

Figure 2: Optimal harvest over time, sperm whales



Then there is a rapid drawdown for about 15 years that then slows as marginal costs rise. Figure 3 shows the marginal costs over time.

Figure 3: MC sperm whale oil production, $2007/gallon.

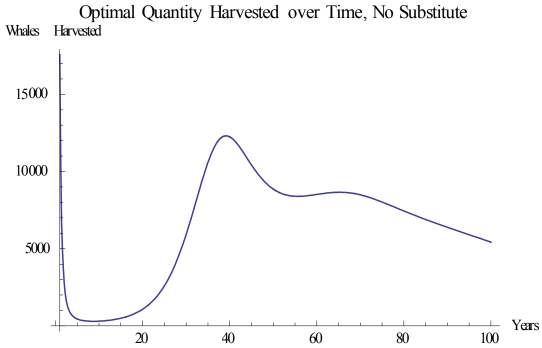


We note that the Marginal costs begin to steadily climb after about 50 years, which, from our start date of 1800, means that at mid-century, much as was witnessed, costs of production were rising. We estimate that in 1859, had this lower demand existed, the population of whales would be at 633,061 and the marginal cost of harvest at $3.30 per gallon ($2007 dollars).

A2. Interest rate= 10%

The results as interest rates change are similar to the above. Figure 4 shows the optimal extraction path for the case of an interest rate of 10% as an example. In all cases there is an initial drawdown in the first year, followed by conservation (for a shorter time than with the lower discount rate, as expected) and increased harvest. The cycles of harvest and conservation dampen as rates increase. There is slightly less conservation in the beginning but the resource is drawn down to about 300,000 whales in approximately 80-90 years regardless of discount rate from 0.01 to 0.10. If there is no population threshold, the population continues at least 200 years for all rates.

Figure 4: Optimal harvest path, r=0.10



Though the higher interest rates increase current resource pressures, these increased early harvests drive up costs more steeply, curtailing later harvests.

A3. Moderate demand

Increasing the demand parameters to represent the case where there is no innovation that reduces pressures on illuminating oils, but neither is there an increase in demand for illumination as witnessed after 1879 (eqn 1.1) does not significantly change the pattern of the results above, though the time frame for preservation of the species is shorter and the initial drawdown in population is larger. In that case, the predicted population of whales at 100 years is 201,605, with marginal extraction costs of \$82/gal. The 1859 population is expected to be 455,424 whales with MC of \$8.4/gal.

B. High demand scenario

B1. Interest rate 3%

If the much higher demand (eqn 1.3) is assumed to exist, without alternative sources, the optimal harvesting suggests an immediate drawdown to a population of about 200,000 whales and then a long period of conservation followed by faster harvesting from 80-95 years as price rises quickly, then another, shorter conservation period and smaller spike as populations dwindle (Figure 5 graphs population over time). Thus if the population does not crash at around n=300,000, the resource lasts for about 130 years before being driven to extinction. We interpret this to suggest that if demand for illumination had grown to the levels witnessed at the end of the 19th century and needed to be satisfied with only sperm oil rather than kerosene/petroleum and electricity, the pressures on the fishery would certainly have been severe. If the species did have a population threshold above approximately 200,000 whales then an early extinction would indeed have been likely. However without this threshold the resource could have been exploited even in the face of extremely high and rapidly growing demand for over 100 years. The prices would have become extraordinarily high (figure 6) as well, which, while increasing pressure on extraction, should also have spurred innovation and exploration for new sources, as we in fact saw throughout the 19th Century.

Figure 5: Optimal whale population, high demand r=0.03

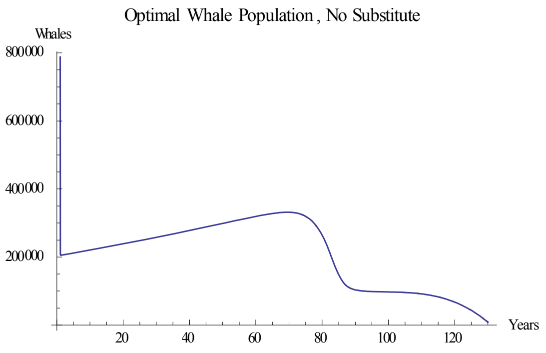
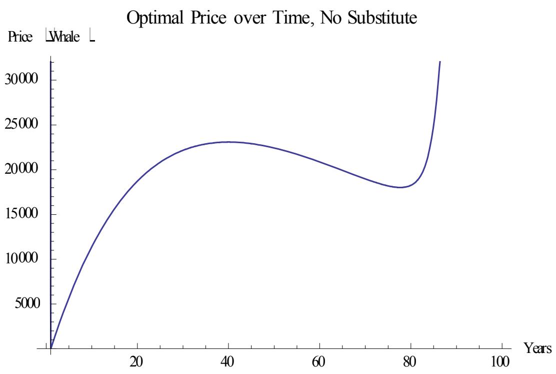


Figure 6: Optimal price path at high demand



V. Sensitivity analysis

A. Uncertainty in biological parameterization

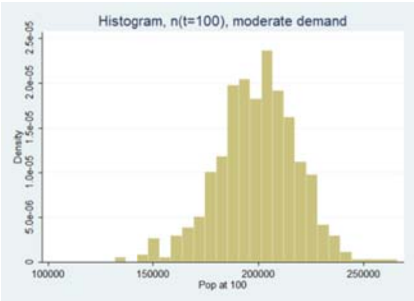
We investigate parameter uncertainty using Monte Carlo simulation methods. We draw from the distributions provided in Whitehead (2002) for both the initial carrying capacity, K, and the intrinsic growth rate, g, to test sensitivity of the results to assumptions about the whale fishery's size and growth rates. The carrying capacity is assumed to be a normally distributed random variable with mean 1,110,000 and standard deviation of 223,000 whales. The intrinsic growth rate is assumed to be a normally distributed random variable with mean 0.011 and standard deviation 0.0025.

A1. Moderate demand

Using the estimated demand parameters from eqn 1.1, we find that over 632 trials with random draws of K and g, the average population after 100 years is 199,318 (std. deviation =19,149), with a minimum population of 131,656 (K=863,338; g=0.0039) and a maximum of 265,751 (K=1.64*106; g=0.0182). In fact

51% of trials have predicted populations at t=100 of over 200,000 whales. Figure 7 shows the histogram for the population at t=100.

Figure 7: Histogram of estimated whale populations, 1900, with moderate demand (eqn 1.1)



A2. Potential threshold effects

We calculate that under these uncertainty parameters for carrying capacity and growth, if the low level of demand were only so much higher as $q = 9*10^6 e^{0.2t} p^{-3}$, then maintaining a population of approximately 300,000 whales after 100 years would be quite unlikely. Only 1.15% of trials have an expected population of at least 300,000 whales after 100 years of optimal use, though 97% have a population over 200,000. Running 520 simulations with that demand curve with random draws of both K and g, we find a minimum population estimate of n=176,032 whales at t=100 (where K is 1.15*10^6 but g is only 0.004254) and a maximum of n=322,900 whales at t=100 (where K is 1.44*10^6 and g=0.18673). The mean estimate is 248,365 whales with a standard deviation of 22,929. Assuming, therefore, a minimum viable population of 300,000, the whale fishery would indeed have been exhausted within 100 years. If, however, the minimum viable population is no more than 175,000 whales, then we can be fairly certain the fishery could have withstood the low demand scenario.

The highest deterministic demand function that allows for a population of at least 300,000 whales after 100 years is $q = 2*10^6 e^{0.2t} p^{-3}$, slightly lower than our estimated demand without kerosene but with electricity by 1879.

A3. High demand without alternatives

Repeating the exercise for the high demand case, we find in that case that after 100 years, the average estimated population would be only 97,454 whales with a minimum of 53,672 (K=1.34*10^6 and g=0.0035) and a maximum of 151,395 (K=1.08*10^6 and g=0.0189) whales. Thus if there is a minimum viable population for sperm whales above 150,000, high demand would certainly have exhausted the whales under the best of management scenarios.

It is clear that uncertainty over the intrinsic growth rate is more detrimental to modeling than uncertainty over the carrying capacity. The correlation between the population after 100 years and the growth rate is 0.93, 0.95 and 0.97 respectively for the low, moderate and high demand scenarios, while the correlation between the 100 year population and the carrying capacity is only 0.28 for the low demand, 0.26 for the moderate demand and 0.09 for the high demand case.

B. Uncertainty in demand parameterization

We create a simulation where the original demand function is as in equation 1.1 for 1800, and the intensity of demand is allowed a shock at some time during the next 100 years. This shock occurs with 2/3 probability, as we draw the timing of the shock from a uniformly distributed random variable[5] across 150 years.

We consider here a shock that reduces demand from eqn 1.1 to eqn 1.2[6]. In this case, we find that when the demand shock occurs within the first 100 years (67% of trials), the population of the whales is on average 292,978 whales (std dev. 43,091) across 615 trials, and 40% of trials result in populations greater than 300,000. We compare this to the population at 100 years when the shock occurs any time over 150 years, where the expected population at t=100 is only 262,343 (std devn=57,363), with only 27% of total runs having the population above 300,000 at t=100. The timing of any transition away from sperm whale oil use could indeed have made a difference in the longevity of the whales if there is a population threshold around 300,000 whales.

VI. Discussion and Conclusions

We estimate, using instrumental variables techniques to account for endogeneity, the demand for illumination oils in the 19th century and the marginal cost of producing one of those illuminating oils: sperm whale oil. We then use these estimates to calibrate a bio-economic model of the dynamics of the whale fishery over a hypothetical 19th century, in which the stock of whales would have been optimally managed. Under these conditions, we simulate the population trajectory of whales as costs and prices evolve over time in response to the resource pressures. We explore the implications of simple shifts in demand. These reflect the conflicting possibilities of increasing demand that is not satisfied by other discoveries (petroleum) or innovations (electricity) on the one hand, or of decreasing demand due to such discoveries and innovations.

Our goal is to determine the risk to the sperm whale populations, in order to support or contradict the contemporary claims that the discoveries of petroleum in fact saved the whales from extinction, as well as those from earlier economic historians using different models for population and growth as well as supply

[5] A future iteration of this paper will tie the draw on the timing of the shock to the price and costs of the oil, and will allow the shock to be either positive or negative.

and demand. Our results suggest that the answer hinges in large part on the question of whether there is a minimum viable population for the whales to survive, and if so, what that population is. This question is still unanswered in science, although the current population estimate for sperm whales globally is approximately 360,000 (Whitehead, 2002; Notarbartolo di Sciara, 2012). In particular, we find that with high demand, pressure on the resource drives the population quickly down to less than 1/5 of its natural carrying capacity (to around 200,000 whales from 1,110,000), even under optimal management[7], so that the fishery would not survive and would not have been able to unilaterally fulfill the growth needs of the latter portion of the 19th century. The whales would, however, have been likely to be able to sustain moderate growth in demand over the century and the claims that the 1859 discovery of petroleum decidedly saved the sperm whale population seem overreaching. In this, we agree with the findings of Davis et al., 1988, though we believe their estimates of the population of whales is much too high and that the results depend more heavily on increasing costs of resource extraction than on abundance.

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[7] If there is a known minimum viable population, the management incentives are likely to shift, creating a ceiling for the harvest that trades off additional whales today for future profits over extinction. This is not necessarily the case, however, as it depends on the ability of the species to recover quickly enough to warrant waiting for some recovery over harvesting all that is possible in the present. We do not model this here.

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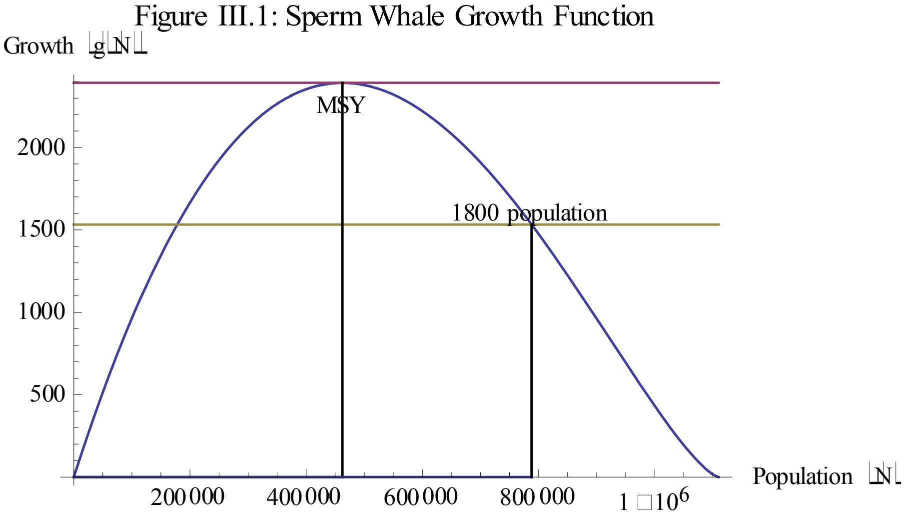
Appendix 1.

Figure A.1 shows the estimated growth function for sperm whales generated from Whitehead (2002). He estimates that carrying capacity, or the population of whales before harvesting (N_0) began in 1712, was 1,110,000 whales. Using population estimates and harvest records from 1800 to 1999, he estimates the annual biological growth function to be $\dot{n} = 0.011 n_t \left(1 - \frac{n_t}{K_0}\right)^{1.4}$. Thus the maximum sustainable yield, or the highest number of whales that can be taken in a year without causing harvest to exceed growth, is estimated to be 2,392 whales per year (shown on Figure).

Note that this is considerably lower than the MSY estimate of 13,893 whales used by Hutchins (1988), which is based on higher initial expected populations of between 1.8 and 2.4 million and a higher growth rate. In fact, using the upper bounds estimated by Whitehead (2002), the highest his data allows MSY to be is 5,172 whales, still less than half the value used by Hutchins (1998) and Davis et al (1988). This throws their finding that sperm whales were not being overhunted into doubt on a purely biological basis, though costs are still a factor.

Figure III.1: Sperm Whale Growth Function



Appendix II

Mathematica estimation (deterministic case. Monte Carlo set-up available from author)

```
Clear[g,gprime,n0,nmax,c,p0,pf,cprime,t0,tf,r,qw,gamma,eta,alpha,neqn,peqn,nopts, nopt, n,p,t, K,result,x]
g=0.011*n[t]*(1-(n[t]/K))^1.4 (* growth rate of whales *)
```

```
gprime=D[g,n[t]] (*rate of change in growth*)
K=1110000 (*carrying capacity*)
n0=0.71*K (*1800 estimated popn*)
nmax=First[Select[n[t]/. Solve [g == 0, n[t]], #>0 &, 1]]
c=(5.85*10^16)/((n[t])^2.8)  (*Marginal cost function wrt q*)
p0=8 (*estimated initial price per gal*)
pf=42 (*estimated final price per gal*)
cprime=D[c,n[t]]/(1/875)  (*Rate of change in marginal costs as function of whale population, converted back to gallons*)

t0=1
tf=100 (*time frame for simulation *)

r=0.03 (*interest rate*)
gamma=0.2 (*growth rate of demand*)
eta=3 (*elasticity of demand*)
alpha=9000000
qw=alpha *(E^(gamma*(t)))*((p[t])^(-eta))       (* demand function,  g/yr *)

neqn=n'[t]==g-qw (*equation of motion, whale population*)
peqn=p'[t]==(-r+gprime)*(p[t]-c)-cprime *g (*first order condition*)

nopts=n[t] /. Solve[neqn,n[t]]
nopt=Select[nopts, Im[#] == 0 && Re [#] >0 && Re[#]<nmax &, 1]

result=NDSolve [{neqn, peqn, n[t0] == n0, p[t0] == p0},{n,p},{t,t0, tf}]

Show[Plot[p[t]/.result, {t, t0, tf}, PlotStyle->{Blue}],  Plot[c/.result, {t, t0, tf},PlotStyle□{Red}],
 Graphics[Text["Price",{tf,pf},{-1,0}]], (* Graphics[Text["Cost",{tf,cf},{-1,0}]],*)
 PlotLabel□"Optimal Price"(* and Cost "*), AxesLabel->{"Years", "Dollars"}, AxesOrigin->{t0,0}]
(* Graph time-paths of price and cost *)
Show[Plot[n[t]/.result,{t,t0,tf}],PlotLabel->"Optimal Population",
 AxesLabel->{"Years", "Whales"}, AxesOrigin->{t0,0}  (* Graph time-path of popn *)

fnn[t_]=(n/. First [result])[t]          (*population as function of time to ease plotting costs and quantities*)
fnp[x_]=(p/. First[result])[x]  (* price as function of time to ease plotting*)
fnc[t_]=(5.85*10^16)/(fnn[t]^2.8)  (*marginal costs as function of population at t*)
fnq[t_]=alpha E^(gamma(t-t0))(fnp[t])^(-eta) (* extraction as function of price at time t*)

Plot[fnc[t], {t, t0, tf}, AxesLabel—> {"Years", "MEC"}, PlotLabel —>
"Marginal Extraction Cost over Time, No Substitute", PlotRange → {{0, tf}, {0,50}}]

Plot[fnq[t], {t, t0, tf}, AxesOrigin → {t0,0}, AxesLabel → {Years,Whales Harvested}, PlotLabel →
Optimal Quantity Harvested over Time, No Substitute]
```