From Depreciation to Exhaustible Resources: On Harold Hotelling's First Steps in Economics

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Abstract

Harold Hotelling's 1931 article on the economics of exhaustible resources is considered groundbreaking in the history of nonrenewable resource analysis. Hotelling's innovation has been characterized by comparing his work with other contributions dealing with conservation issues. It has also been connected to his earlier work on depreciation, published in 1925, for using the same kind of mathematical formalism. This article further explores this second research direction on the basis of new archival materials, showing that Hotelling conceived his contributions on resources and depreciation as closely and substantially intertwined. It also suggests that Hotelling's interest in exhaustible resources came from his earlier readings in accounting. These results shed new light on Hotelling's early economic research, on our common understanding of his 1931 contribution, and on the origins of the connection between nature and capital in the history of environmental economics.

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Introduction

Harold Hotelling's 1931 contribution to the economics of exhaustible resources is considered groundbreaking in the history of economic thought, establishing "the Hotelling rule, the fundamental principle of natural-resource economics" (Solow 1974: 12). Prior investigations by historians of economic thought most often connect Hotelling's 1931 article to other works in the field of natural resource analysis, to draw comparisons and filiations with other authors (e.g., Robinson 1989; Kula 1998; Pottier 2014; Missemer 2017). In particular, the role of the conservation movement in Hotelling's motives is frequently scrutinized (Gaudet 2007; Livernois 2009). According to this literature, Hotelling would have determined the optimal extraction path of finite resources on the basis of advanced mathematical techniques, positioning his analysis as an answer to the conservationists, from a rational-choice point of view. A strong support for this claim is Hotelling's own mention of the conservation movement in the opening of his 1931 article (137). Yet, intriguingly, there is no reference in Hotelling (1931) to past economists involved in conservation debates, such as Lewis C. Gray (1913, 1914), Richard T. Ely (1918), and John Ise (1925), while they did propose some theoretical treatment of nonrenewable resources (G. Smith 1982; Crabbé 1983; Ramos Gorostiza 2003; Missemer 2017).

Another research direction explored in the literature advocates a link between Hotelling's previous research on depreciation, published in 1925, and his 1931 work on exhaustible resources. The formal similarities between the two papers, in particular the innovative use of the calculus of variations, are particularly highlighted (Samuelson 1960; Darnell 1988, 1990). Crabbé (1986b: 3) even suggests that, starting with Hotelling's 1925 depreciation theory, "if th[e] function is a negative exponential with a constant parameter, the rate of interest, it becomes Hotelling's rule for nonrenewable resources proposed by him in 1931." Franco, Gaspard, and Mueller (2019) use that filiation to understand Hotelling's specific approach to time discounting from 1931 onward.

Our article investigates the hypothesis that this second research direction offers better insights for understanding the structure and argument of the 1931 contribution and for identifying Hotelling's motives for working on exhaustible resources, relegating conservation issues to the background. Indeed, Hotelling did not continue to work on depreciation after his 1925 publication. Yet the fact that he depicts exhaustible resources as finite "assets" in his 1931 paper suggests that a common thread between his two articles was an overarching ambition on asset valuation, defined as the undertaking to determine the total value of a productive property (machines, plants, public infrastructure, patents, stocks of ore, etc.) from different perspectives (sale, depreciation, optimal exploitation). In other words, the connection between depreciation and exhaustible resources in Hotelling's research is probably substantive, beyond mere formal similarities.[1]

We test this assumption by a novel investigation of Hotelling's archival materials stored at Columbia University, seeking to establish the articulation between his works on depreciation and exhaustible resources. We are led to think that Hotelling's interest in exhaustible resources came from his preparatory work on depreciation, in particular from readings in accounting that put him on the trail of exhaustible assets, to address taxation and fair pricing issues, and not for conservation motives.

Our inquiry is also a contribution to the history of environmental and natural resource economics. In the first decades of the twentieth century, connections between the natural world (sources of power, materials, spaces, etc.) and the theory of capital were drawn more and more frequently (Barbier 2010, 2019)—the appearance of the concept of natural capital at the time is an illustrative example (Missemer 2018).[2] We intend here to explain the extent to which Hotelling contributed to that conceptual link, still in

[1] We do not intend, nevertheless, to minimize the mathematical connection between the two projects, which is essential to understand Hotelling's undertaking. We simply claim that this connection is supplemented by another, more substantial one. Our purpose is therefore not to contribute specifically to the history of mathematical economics, but to address other dimensions of Hotelling's work.

[2] On the representations of nature conveyed by the idea of natural capital, see also Akerman 2003; Fenichel and Abbott 2014; DesRoches 2015, 2018; Nadal 2016; Costanza et al. , 2017; Sullivan 2017; Daly 2020; Victor 2020.

force today for a variety of environmental attributes, including biodiversity, natural resources, and climate balances (Daily 1997; Helm 2015; Karp 2017). On this point, Hotelling is often associated with economists close to the conservation movement, particularly Gray (Robinson 1980; Crabbé 1986a; G. Smith 1986; Sweeney 1993; Brazee and Cloutier 2006). Our results show, to the contrary, that Hotelling touched on this connection through a different, singular channel.

Although Darnell (1990) has already explored Hotelling's archives, in particular for biographical matters,[3] and even if a few other scholars used them for specific research questions (Crabbé 1986b; Hands and Mirowski 1998), our study is the first to be based on a systematic examination of all unpublished materials from the early 1920s.[4] This includes drafts and notes, pieces of correspondence, memos, and monthly reports for the directors of the Food Research Institute at Stanford University, where Hotelling started his professional career (1924–27). We have also mobilized archival materials from Princeton University (PUA herein), where Hotelling prepared his PhD dissertation (1921–24), and from the University of Washington, where he was an undergraduate (1913–19), and then a graduate student (1920–21).

This article is organized as follows: Section 1 demonstrates that Hotelling's works on depreciation and natural resources are to be considered as twin projects, pertaining to the same set of theoretical questions. Section 2, focusing on the early 1920s, investigates why and how Hotelling decided to work on depreciation issues after completing his PhD at Princeton. Section 3 scrutinizes Hotelling's preparatory work on depreciation, particularly his readings in accounting, in search of the possible sources of his interest in exhaustible resources. Section 4 further explores how Hotelling translated these readings into full economic research questions for his 1925 and 1931 papers. Section 5 traces the influence of this preparatory work not only on the connection between depreciation and exhaustible resources, but also on the precise content of "The Economics of Exhaustible Resources," especially regarding taxation. The final section is for concluding remarks.

1. Depreciation and Exhaustible Resources as Twin Projects

In his 1931 paper on the economics of exhaustible resources, Harold Hotelling situates his demonstration on two parallel grounds. On the rst ground, the basic principle for the optimal extraction of resources ($p = p_0 e^{\gamma t}$), today known as the Hotelling rule, is stated for resources whose sole characteristic is finite and known availability, in a theoretical framework of free competition. This is an abstract, stylized object, which leads Hotelling to talk about "exhaustible assets" (137) rather than concrete natural resources (minerals, oil, and gas). On the second ground, as soon as these concrete resources are concerned (in particular from section 8 onward in the 1931 article), other characteristics than finite and known availability are to be taken into account, such as geological constraints (uneven location, increasing costs). Hotelling is clear: these concrete resources require other theoretical principles beyond the basic equation to be accurately circumscribed (see Ferreira da Cunha and Missemer 2020).

In other words, in "The Economics of Exhaustible Resources," Hotelling defines his subject of investigation as pertaining to two research directions: one is the valuation and exploitation of generic stylized assets, the other, the extraction and management of concrete real-world natural resources. The first of these questions is related to the general issue of asset valuation, for which the theory of depreciation, as explored by Hotelling in 1925, is a particular case. This suggests that a part of the 1931 article, focusing on generic assets, can be considered as belonging to

[3] Unfortunately, Darnell's archival referencing is not always clear, so it is difficult to know which materials he consulted.

[4] This article is part of a research project (#BNREproject), the participants of which produced other articles and working papers providing complementary insights on the basis of the same bundle of materials (e.g., Franco, Gaspard, and Mueller 2019; Gaspard and Missemer 2019; Ferreira da Cunha and Missemer 2020; Missemer and Nadaud 2020; Gaspard and Muel- ler 2021). The overall set of deliverables from this project, including the present article, aims to give a renewed view of natural resource economics in the 1920s–1930s, in particular regarding Hotelling's contribution.

the same set of broad concerns as the 1925 paper, when the assets to value (and then, possibly, depreciate) have a specific feature, that is, they are irreplaceable.

Hotelling's archival materials from the 1920s allow a clearer view of Hotelling's work on asset valuation. They include a two-page document, with a few related drafts, for a talk at the American Mathematical Society in Chicago on December 26, 1924.[5] The main document is divided into four parts. Part 1 is about the "depreciation" of a machine (i.e., a replaceable productive asset), with a few bullet points reproducing the main conclusions to be published in the following year (Hotelling 1925). Parts 2 and 3 are about the "competition of exhaustible assets" and the "monopoly of exhaustible assets," and part 4 sketches some reflections on the generic dimension of the results, in relation to "the problem . . . of maximizing functionals."

At that date, Hotelling had just submitted his article on depreciation to the *Journal of the American Statistical Association*,[6] and he aimed to explore more sophisticated theoretical cases related to his theory of depreciation. The first case makes abstraction of the assumption of productive assets running "to full capacity"—common in the literature on valuation and depreciation, an assumption "not even approximately true" (Hotelling 1925: 351) when dealing with the case of mines. In such cases, theory has to consider the fact that the owner of the property may voluntary control its rate of working, and limit the produced quantity at any given point in time.

Part 1, on the one side, and parts 2 and 3, on the other, are not presented as independent exercises of mathematical economics. They constitute separate research questions, but they share common formalisms (i.e., integrals) and common theoretical assumptions, in particular regarding "full capacity" or "rate of working." The Chicago talk confirms that Hotelling conceived that there was a junction between his projects on depreciation and exhaustible assets from the very beginning of his economic research.

[5] Harold Hotelling Papers, box 10, "AMS Reports and Correspondence (3)."

[6] The submission letter dates from December 19, 1924, Harold Hotelling Papers, box 10, "AMS Reports and Correspondence (3)."

Archival documents help to reconstruct, month by month, Hotelling's early work on both depreciation and exhaustible resources, in the autumn of 1924. After completing his PhD in topology at Princeton in June, Hotelling got a junior associate position at the Food Research Institute of Stanford University. He obtained the position a few weeks before his defense, after being recommended by his advisor Oswald Veblen.[7] His official contract started on October 1, 1924. During the previous summer, Joseph S. Davis, the executive secretary of the Food Research Institute, asked his staff to produce monthly reports for "keeping all the directors periodically informed of the progress . . . made, the major difficulties . . . encountered, the plans for further work . . . and the suggestions . . . in conjunction with his own work or the work of the Institute in general."[8]

Hotelling's first report dates from November 3, 1924, and shows in a few paragraphs his activity during his first weeks at the Food Research Institute.[9] Among various occupations, Hotelling explains he dedicated most of his time to "the completion of a major piece of research on the mathematics of Depreciation." There is no mention of any research on exhaustible resources.

In the following report, dated from December 1, 1924, Hotelling depicts a progression from depreciation to the subject of "exhaustible assets":

> The month [November 1924] was chiefly devoted to study in what seems to be a virgin field—the economics of exhaustible assets. . . . Some of the simpler problems in this field are covered in my recent paper on "A General Mathematical Theory of Depreciation," in which are discussed the cases in which the Calculus of Variations is not required for solution. This rather abstruse branch of mathematics is necessary, however, for dealing with such problems as the determination of the most profitable rate of working a mine when demand is elastic. ("Agriculture 3," box 41, HHP)

[7] Letter from Alsberg to Hotelling, March 13, 1924, Harold Hotelling Papers, box 6, "Wallis-Fry"; and letter from Wilbur to Hotelling, March 29, 1924, Harold Hotelling Papers, box 1, "Wilbur, Ray Lyman."

[8] Letter from Davis to the Institute Circle, July 30, 1924, Harold Hotelling Papers, box 39, "Misc. (5)."

[9] Harold Hotelling Papers, box 41, "Agriculture III."

This passage demonstrates how Hotelling connected his depreciation theory and his research on "exhaustible assets": the latter is a new case of asset valuation, in which more complex problems than those treated in his "theory of depreciation" occur. This quotation also provides historical information about Hotelling's self-positioning in the literature. By characterizing his investigation as exploring "a virgin field," he does not seek to participate in the economic debates on conservation, as had Gray, Ely, and Ise. He prefers instead to characterize his undertaking as a new field, namely, the economics of exhaustible assets. This is a further indication that the conservation movement did not play an essential role in Hotelling's original motivations.[10]

In the draft entitled "Monopoly of an Exhaustible Asset," from November 1924 and used for the Chicago talk, the objective function is the same as in the depreciation work, now with the constraint $\int_0^T q_t \bullet dt = a$, where a is the "total amount contained in the mine."[11] We clearly see Hotelling establishing a mathematically treatable constraint on the overall valuation function, describing a particular feature present in the case of mines. Hotelling probably considered this a "virgin field" not because no one discussed mines before but because no one had abstracted from mines a subclass of "exhaustible assets" in the economy.

The issues at stake are mentioned briefly at the end of Hotelling's article on depreciation: considering cases where the owner of the property voluntarily controls the rate of working of the productive asset, the production path becomes a strategic or political choice leading to "a great deal of economic and even ethical theory" (1925: 353).

In summary, archival documents from the autumn of 1924 demonstrate the close, substantial (not only formal) relation in Hotelling's research between his twin projects on depreciation and on exhaustible resources, as particular instances of the broader asset valuation problem. We know he published his depreciation theory in 1925. However, he shelved his drafts and notes on exhaustible assets for a few years, only relaunching them in 1928, under new influences and with partly new ambitions (Gaspard and Missemer 2019). The architecture of the 1931 article, with the exploration of two parallel research directions, suggests that he kept in mind the view of depreciation and exhaustible resources as twin projects.

2. Why and How Did Hotelling Come to Work on Depreciation?

Depreciation theory is rightly considered as Hotelling's first achievement in mathematical economics (Samuelson 1960; Darnell 1990), but the conditions that led him to the subject have not been examined so far. The monthly report from November 3, 1924, shows that Hotelling devoted October to completing his paper on depreciation. There is no previous trace of any work on the subject in his early notes from 1923–24, which suggests that he worked fast on his theory of depreciation.[12] We sought explanations for his motivation to work on this topic and found several leads worth mentioning.

First, in the 1910s and early 1920s, depreciation issues were widely discussed in academia, in relation to the fair pricing of public utilities. Controversies followed the decision of the US Supreme Court to recognize the practice of charging in advance selling prices of public utilities with depreciation allowances (City of Knoxville v. Knoxville Water Co., 212 U.S. S.1, 1909). This decision, inherited from the "Smyth doctrine" (Smyth v. Ames, 169 U.S. 466, 1898),

[10] Supporting this statement even more, we found that conservation (mentioned in the opening of the 1931 article) came into Hotelling's drafts at the very end of his research; in preliminary versions of the introduction, sketched as late as December 1929, the mention of the conservation movement is missing (Harold Hotelling Papers, box 42, "Exploitation of Irreplaceable Assets"). These drafts are discussed in Ferreira da Cunha and Missemer 2020. Likewise, this suggests as well that Hotelling was not well aware of areas of literature making connections between capital and natural resources (e.g., early works on "natural capital"; see Barbier 2010; Missemer 2018).

[11] Harold Hotelling Papers, box 10, "AMS Reports and Correspondence (3)."

[12] The drafts from 1923 are about "oscillations of supply with time" and "maximum utility by individual + by joint action" (Harold Hotelling Papers, box 45, "Misc. Problems, Dated 1923–1929"). There is no trace of other early notes in either the Princeton archives or the archives of the University of Washington.

which had recommended the reproduction cost method to value railroad and public utility plants (Giocoli 2018), stimulated research on depreciation methods and raised questions about the impact of the calculations on the fair pricing of utilities (Allison 1914). The American Society of Civil Engineers asked for the creation of a special committee to establish principles for the valuation (and depreciation) of public utilities. Its final report (Stearns et al. 1917) changed the way depreciation methods were used, giving birth to seminal contributions (Taylor 1923; Skinner 1924; Canning 1929).

Hotelling's autobiographical notes (1948) reveal that he paid attention to the issues of public utilities at an early age and that he became familiar with technical aspects of the debate while completing his undergraduate curriculum in journalism at the University of Washington.[13] His courses comprised not only political science and political economy but also accounting and business administration, including the "theory of assets, liability and propriety, depreciation and appreciation."[14] The department was mostly influenced at the time by J. Allen Smith, who played an important role in the controversies over public utilities commissions (McClintock 1962).[15] Hotelling never explicitly stated that this environment directly motivated his theory of depreciation, but as he later wrote, his undergraduate courses helped him to detect economic questions requiring further mathematical investigation:

> The formal study of several branches of economics while I was nominally a student of journalism laid an invaluable foundation for later work. . . . The combination of science and political economy led to the thought of applying the methods proven so fruitful in the exact sciences to discover new truth in economics and political science. Proficiency in these methods required in the first place mathematics. (Hotelling 1948: 17)

After a disappointing experience as a journalist for the *Washington Standard*, Hotelling returned to the University of Washington for a master's program in science, with applied mathematics as the main subject (1920–21). His application to the PhD program at Princeton University, dated February 1921, helps us identify which courses Hotelling attended and with whom he had connections while in the master's program. Hotelling indeed specifies that he had been taught "differential equations, analytical geometry, projective geometry, analytical mechanics, limits and series, determinants and symmetric functions, theory of life insurance, mathematical physics," mentioning Eric Temple Bell, Robert E. Moritz, Lewis J. Neikirk, and Lloyd Leroy Smail as professors.[16]

During the year 1920–21, Bell taught analytical mechanics (D'Alembert's, Hamilton's, and Lagrange's principles), and encouraged Hotelling to do research in applied mathematics (Darnell 1990). Neikirk taught differential equations and supervised Hotelling's master's thesis on the dynamics of population. Moritz, who was the head of the mathematics and astronomy department, promoted a "more scientific" training for students in economics and commerce, through the introduction of mathematics and statistics (Moritz 1919). Moritz was in charge of all finance and actuarial science classes. As we traced in the catalogues of the University of Washington, "theory of life insurance" was in

[13] It is his "acute interest in problems of economic and political reform, stimulated by the democratic debates and problems of the new city" (1948: 17) that led him to pursue a BA in journalism during 1913–19. Although Hotelling does not make a list of the debates and problems evoked here, he refers in the same document to events and difficulties experienced in Seattle in the 1900s and 1910s, including tensions between local businesses and railroad companies over rates "that all the local people thought were too high" (1948: 12).

[14] The University of Washington makes available the catalogues describing departments and curricula. See, for instance, the catalogue for 1917–19 at: www.washington.edu/students/gencat/archive/GenCat1917-19v1.pdf.

[15] Smith's major book, *The Spirit of American Government* (1907), had become a reference for liberal leaders during the Progressive Era. Smith aimed at demonstrating the antidemocratic intentions of the Founding Fathers as well as the way the Supreme Court had preserved the privileges of the capital-owning class and corporations against the demands of democratic movements. A third part of the book exhibited the relation between the doctrine of laissez-faire and the rising of trusts and monopolies. In the 1910s, Smith was engaged in a criticism of the social and political composition of the public utilities commissions that were emerging in the territory to regulate private and public utilities (J. A. Smith 1914).

[16] Application form for admission to Princeton's graduate program, February 21, 1921, Princeton University Archives, box 36, "Hotelling Harold."

fact called "Insurance-Premiums and Reserves," and had as prerequisites two others courses by Moritz: one devoted to mortality tables, the other to "mathematical theories of finance." The latter precisely dealt with "a comprehensive study of the theory of interest and discount symmetrically developed; valuation of annuities; determination of rates of income; valuation of redeemable and irredeemable securities; capitalization and depreciation; sinking funds and amortization of debentures and of options; construction and use of bond tables; Makeham's formula."[17] Hotelling therefore learned at the beginning of the 1920s, with Moritz, basic formalizations of depreciation—a subject to which Moritz would contribute in later publications.[18] He acquired at that moment the technical bases necessary to address the issue.

In addition to this first set of leads, we know Hotelling's will to contribute to the literature on depreciation found inspiration in a 1923 article by James S. Taylor.[19] Taylor departed from the 1917 report of the American Society of Civil Engineers to complete a "unit cost plus" method of depreciation using statistical data on the useful life of capital assets. Hotelling explicitly refers to Taylor's article in the opening of his 1925 paper, stating, "Dr. Taylor puts forward a method which, it is fair to say, is the only one that has been proposed which ever gives correct results" (340). By admitting that his own paper "owes much" to Taylor's analysis, Hotelling confirms that he found a decisive inventiveness in the paper published in 1923 to elaborate his own theory (340). Taylor's central contribution was to provide a way to estimate and distribute depreciation charges throughout the life of a machine or an asset producing an output. He determined the endogenous useful life of a machine, depending on the moment when the unit cost of production becomes higher than the cost a new machine would allow.

In his 1925 paper, Hotelling disconnects the estimation of depreciation from the sole operating cost of production, in favor of the global value of the machine. By defining depreciation as the decreasing rate of the economic value of this machine, he argues that the objective of the owner is to maximize this value (not to minimize costs). Depreciation therefore depends on selling prices, costs, the initial value of the machine (or asset), and its (endogenous) lifetime. Building on Taylor, Hotelling clearly discusses asset valuation when examining depreciation issues.

Archival materials give a third set of leads for illuminating Hotelling's interest in depreciation. When he was recruited by the Food Research Institute at Stanford University, he was told by Carl L. Alsberg that he was expected to work "in collaboration with other members of the staff."[20] Internal correspondence between administrators further reveals that the nomination of Hotelling was motivated by "the need [of] the assistance of a man thoroughly trained in pure mathematics [for] the crop estimating project of the Institute."[21] This information shows that Hotelling was invited to work with other colleagues from the Food Research Institute right after his arrival in October 1924. The institute was a place where teamwork and cooperation were particularly encouraged.[22] On December 19, 1924, in the submission letter of his paper to the *Journal of the American Statistical Association*, Hotelling wrote: "The mathematical part of the work has been checked by Professor H. F. Blichfeldt, the numerical computation by Miss E. Gail Benjamin, and the nonmathematical portions by Pro-

[17] Catalogue for 1920–21: www.washington.edu/students/gencat/archive/GenCat1920-22v1.pdf. See page 254 for a more complete description of Moritz's three courses. Moritz's letter of recommendation praises Hotelling's predispositions to conduct "successful research work . . . along applied lines of mathematics" (Letter from Moritz to Veblen, February 19, 1921, Princeton University Archives, box 36, "Hotelling, Harold").

[18] Moritz mainly published papers in algebra and topology. Yet he also worked on applied mathematics, in particular on a mathematical theory of depreciation of physical assets (Moritz 1932). The earliest published elements we can find related to this work are dated from 1927, under the title "A Modification of the Reducing Balance Method on Estimating Depreciation" (Special Collections Library, University of Washington).

[19] Taylor presented his paper at the thirtieth annual meeting of the American Mathematical Society in New York, December 1923. We know Hotelling attended the meeting, as mentioned in the bulletin of the Society (Richardson 1924).

[20] Letter from Alsberg to Hotelling, March 13, 1924, Harold Hotelling Papers, box 6, "Wallis-Fry."

[21] Letter from Alsberg to Wilbur, March 27, 1924, Harold Hotelling Papers, box 6, "Wallis-Fry."

[22] In one article devoted to the history of the institute, Johnston (1998) describes the early Institute as "a body of cooperating scholars."

fessor J. B. Canning, all of Stanford University. The manuscript has been read carefully by all three of the directors of the [Food Research Institute], whose names appear above."[23]

This quote demonstrates that Hotelling discussed his project on depreciation with his colleagues at the institute. H. F. Blichfeldt was a full professor of mathematics at Stanford University, informally involved in the "crop estimating project" mentioned by Alsberg for the recruitment of Hotelling—obviously, the two researchers had occasion to work together. E. Gail Benjamin was a statistical assistant at the Food Research Institute throughout the 1920s. J. B. Canning, who arrived at Stanford in 1919, had been trained at Chicago. During his doctoral program, he had followed and taught many courses, in particular in insurance, accounting, statistics, and corporate nance. At Stanford, he built an entire curriculum in accounting for undergraduate students. According to those who followed this curriculum, what they learned was that accounting was not just a matter of bookkeeping (Zeff 2000: 13). Interestingly, in 1922–23, Canning opened a new course at Stanford in advanced accounting about the "valuation of fixed assets or private enterprises, and the distribution among accounting periods of costs and losses incurred in connection with investment in fixed assets."[24] More generally, in the mid-1920s, he pushed for the transformation of accounting studies, promoting the introduction of economics, mathematics, statistics, and law into the curriculum (Canning 1929). This ambition appears in line with Hotelling's 1924–25 analysis of depreciation. Although we do not have full evidence of Canning's role in driving Hotelling to the subject of depreciation, the archives give credence to the hypothesis that Hotelling was encouraged by Canning to fully explore depreciation issues when they met at Stanford in the beginning of the autumn of 1924.[25]

[23] Letter from Hotelling to Ogburn, December 19, 1924, Harold Hotelling Papers, box 10, "AMS Reports and Correspondence (3)."

[24] Register for 1922–23, Stanford University, quoted in Zeff 2000: 17.

[25] Canning (1929) discusses Hotelling's paper, albeit without mentioning that he read a draft of it in the autumn of 1924. Canning remembers having worked on depreciation issues from March 1922 onward and having used his own manuscript for instruction in the 1920s.

In summary, we cannot ascribe a definitive reason why Hotelling came to work on depreciation in 1924, but we explored the different avenues that seemed to us consistent with the archives. We know that he had a long lasting awareness of issues linked to the valuation and depreciation of productive assets (in particular, in the case of public utilities); that he was equipped to provide his own understanding of the issue thanks to his curriculum at the University of Washington; and that he shared with Canning, at the moment of his arrival at the Food Research Institute, the ambition to give sounder mathematical and theoretical foundations to the theory of depreciation. The question remains as to why, in the autumn of 1924, Hotelling conceived exhaustible resources as intertwined with depreciation issues.

3. Exhaustible Assets in Hotelling's Preparatory Work on Depreciation

Taylor's 1923 contribution to the theory of depreciation does not mention any reference to exhaustible assets. There are no such elements among the archival materials either, leading us to think that Canning could have directly influenced Hotelling on this matter. At first sight, it is thus difficult to explain why Hotelling worked on exhaustible assets right after working on depreciation, and why he articulated the two projects in his reports to the directors of the Food Research Institute.

Among the references cited by Hotelling in his article "A General Mathematical Theory of Depreciation" (1925), some can be related to archival materials pertaining to his preparatory work on the matter. One is Earl A. Saliers's book, *Depreciation: Principles and Applications*, published in 1922.[26] The archives contain a small bibliographical memo, probably destined for a librarian—the memo consists of four reference cards plus a cover titled "bibliography on depreciation," with headings (title, author, volume, etc.) filled in by Hotelling.[27] There is no date on this memo, but it was stored in the same envelope as the drafts from the autumn of 1924,

[26] Taylor (1923, 1010) also cites Saliers 1922.

[27] Harold Hotelling Papers, box 10, "AMS Reports and Correspondence (3)."

and the classification numbers of the books correspond to Stanford University's references.[28] We can infer that it dates from the first weeks Hotelling spent in Stanford.

Each card corresponds to a separate volume. Hotelling requested *Depreciation of Public Utility Properties and its Relation to Fair Value and Changes in the Level of Prices* by Henry E. Riggs (1922), *Theoretical Depreciation* by George N. Webster (1920), and two editions of Saliers's *Depreciation: Principles and Applications* (1915, 1922).[29] This latter volume is particularly interesting for our inquiry. It consists of an extensive survey of legal and accounting debates pertaining to depreciation theory and applications. Saliers reports cases and decisions by the American and British courts about depreciation rules, and he makes the synthesis of several controversies on the definition and implications of depreciation in various business activities. Interestingly, his book not only addresses general problems associated with depreciation, but also sheds light on the particular situation of mineral assets.[30]

As reported by Saliers, in the theory and application of depreciation principles, the specificity of mines intervenes on several occasions. First, the lifetime of a piece of equipment is usually determined by "ordinary wear and tear and deterioration" and by "obsolescence and inadequacy" (Saliers 1922: 60). But "in the case of mines the plant and equipment should be written down on the basis of useful life when their natural life is longer than the life of the mine" (60). In other words, the usual rules do not apply to the depreciation of mining equipment, because the finiteness of the deposits implies the duration of activity that does not depend on wear and tear but on the size of the deposits. Second, mining companies invest in equipment and in deposits when they start their business. Their entire productive property is thus composed of (1) various machines and physical assets, as well as (2) exploitable mining reserves. Saliers (1922: 37) states that discounting procedures are required in both cases, through "depreciation" for "the nancial effects produced by deterioration, wear and tear, obsolescence, and inadequacy," and through "depletion" for the "exhaustion of mines." This means that the ore owned by a mining company needs to be valued as an asset among others for the conduction of the business activity. It needs special procedures (470), but it is part of the same issue of the valuation of the productive property.

Throughout his essay, Saliers constantly shows that the case of mining companies deviates from general depreciation methods. This is reflected in the way he builds his chapters, starting with the general theory, and referring to mines in the end as a special case with separate proposals (for instance, in chap. 8 with the last section "Application to Mining Companies"). The term "exhaustible asset" is not used by Saliers. The closest occurrence is the term "exhaustible capital" (282), which appears in the principles recognized by the Treasury Department for specific methods of asset valuation. This confirms, in a sense, Hotelling's opinion that investigating "exhaustible assets" was a "virgin field."

Obviously, Saliers does not elaborate a theory of exhaustible resources such as the one in Hotelling's 1931 article—his book is primarily a handbook for accountants, observers, and practitioners. Yet Saliers's presentation of both subjects within a single book is, at the very least, parallel to Hotelling's double interest in these subjects. As far as we know, and in absence of evidence of other readings connected to the issue of exhaustible assets during this period, it seems likely that Hotelling started investigating the subject of "exhaustible assets" right after exploring depreciation issues because of his reading of Saliers in the autumn of 1924. This sheds light on Hotelling's entry point in exhaustible resources: accounting and asset valuation, not conservation.

With respect to the history of environmental

[28] Today, one of the books still has the same call number in the online catalogue of Stanford Libraries (searchworks.stanford.edu/).

[29] Hotelling mentions a 1923 edition for Saliers's book, but such an edition does not exist. It is certainly the 1922 edition that he requested.

[30] Neither Riggs nor Webster mentions this subject. We investigated why Saliers put emphasis on mineral assets in his work on depreciation. One track is Saliers's early interest in the mining sector, from his PhD dissertation on labor in coal mines (Saliers 1912). This work does not show clear reference to depreciation issues but demonstrates deep monographic knowledge of the history of mining industry, its structure and organization, with connected impact on the evolution of costs and wages.

and natural resource economics, this provides a new thread to understand in retrospect how natural items were progressively conceived as capital in the early twentieth century: in addition to the commonly highlighted relation between the theory of capital and the conservation movement (e.g., G. A. Smith 1982; Barbier 2010; Turnbull 2017; Missemer 2018), we trace here a second, parallel line, between accounting and exhaustible assets. In other words, Hotelling did not conceptually connect capital with natural resources in the same manner, nor for the same reasons, as the other economists of his time. He followed a singular path, starting from accounting, not from the theory of production or from the theory of interest, to reach the economics of natural resources.[31]

4. From Accounting to Economics

Hotelling's 1925 "General Mathematical Theory of Depreciation" and 1931 "Economics of Exhaustible Resources" are considered seminal contributions because they mark turning points in the history of both fields (Arrow 1987; Darnell 1990). Hotelling claimed to be innovative. In the opening of his 1925 article, he stated, in contrast to "the older treatments of depreciation . . . it will be shown . . . that depreciation and theoretical selling price must be computed simultaneously from a pair of equations which are frequently a bit complicated" (340). And in his 1931 paper, he declared his differences with "the conservationist belief," and unveiled the "intriguing problems" of "the economics of exhaustible assets" (138). In other words, he was aware that his approach to depreciation and natural resources was different from prior treatments.[32]

The literature that Hotelling consulted in the early 1920s was the work of experts who were not, for the most part, economists. Notably, the four books mentioned in his bibliographical memo were not written by economists: Riggs was a professor of civil engineering at the University of Michigan and one of the authors of the aforementioned 1917 report; Webster was an essayist who apparently did not publish a lot; and Saliers was a professor of accounting at Yale University. All of them focused on technical and practical problems for the valuation of business assets, without clearly addressing economic theory. Taylor was not an economist either.

By appropriating the questions of depreciation and exhaustible assets, Hotelling transformed accounting and engineering issues in full economic questions.[33] He introduced the principle of rational action as a postulate allowing a determination of the value of the considered assets. He realized early (December 1924) that such a value, depending on future selling prices, also depends on the elasticity of demand and therefore on the competitive structure in which the asset is used. Finally, he explored not only generic rules applicable to generic assets but also tools applicable to specific cases.

The existence of two research lines in the 1931 article on exhaustible resources—one on generic stylized assets, the other on concrete natural resources—also suggests that Hotelling was undertaking a departure from the accounting literature. He first examined generic stylized assets whose sole characteristic is finiteness because this was the way the legal literature (and Saliers) defined the specificities of minerals for the theory of depreciation. He then progressively became more concerned with additional characteristics, other than finiteness (e.g., geological constraints), when he realized that concrete natu-

[31] A third thread could partially link Hotelling's work to that of Frank P. Ramsey (1928) on optimal saving. As noted by Erreygers (2009) and Duarte (2009), Hotelling (1931) was one of the first to cite Ramsey (1928). However, Hotelling's first notes on asset valuation (renewable or not) largely predate Ramsey's early work on saving. Gaspard and Missemer (2019) report that after the publication of Ramsey's article, Hotelling sought to meet Ramsey when he visited England in 1929, but no document confirms that the meeting took place. Hotelling may have added sections to his manuscript after reading Ramsey (e.g., sections devoted to estimating the social value of the mine). Yet Franco, Gaspard, and Mueller (2019) note that Hotelling never adopted the subjectivist representation of welfare dear to Ramsey.

[32] As already pointed out, his opinion was not fully accurate for natural resource analysis, in particular when we read Gray's contributions from the 1910s (Crabbé 1983; Hartwick 1999; Brazee and Cloutier 2006; Missemer 2017), but it can be explained by his different entry point to the subject.

[33] In the *New Palgrave*, Arrow (1987) confirms this observation, by characterizing Hotelling's 1925 article as "the reorientation of accounting towards more economically meaningful magnitudes."

ral resources actually were not generic stylized assets for economic theory, insofar as sector dynamics, competitive effects, and market mechanisms also depend on these additional characteristics (Ferreira da Cunha and Missemer 2020). An economic treatment of exhaustible resources required going beyond the definition of exhaustible assets provided by the accounting literature.

As mentioned above, even as a student Hotelling had been aware of the economic and political issues lying behind the fair pricing of public utilities. Riggs, Webster, and Saliers, although they were not economists, probably also played a role in Hotelling's transfer of depreciation and exhaustible assets from accounting to economics. They may have indirectly helped him to settle the economic dimension of depreciation issues, when presenting technical questions related to hidden economic concerns. In particular, by depicting different conceptions of what depreciation can be, they showed that the distribution of charges among economic agents could vary. If depreciation is seen as a cost of production—a classic understanding in accounting—then the consumer will be charged for it, as is the case for all production costs. However, if it is conceived as capital erosion, it will be deducted from the profits of the investor or owner.

Saliers's 1922 essay contains several statements about the definition of depreciation as a cost.[34] In contrast, Riggs (1922: 17) argues that depreciation "in the sense of loss of value" will not happen if "proper provision [from] the owner" is done. Depreciation here, therefore, is not a matter of cost but of securing future investment. For public utilities, the owner of the plant is indirectly the taxpayer (18), who is also a consumer. Yet, we should add, as commonly advocated in public economics, this does not mean that charges are distributed in the same way to economic agents in both cases because not all taxpayers are necessarily consumers of the service provided by a particular public utility. Thus, the two conceptions mentioned above are not equivalent, even in the case of public ownership. Different ways of sharing the burden of depreciation leads to different income and charge distributions among economic agents (consumers, producers, investors, taxpayers, etc.). This can have economic consequences in terms of taxation, purchasing power, and profitability. Hotelling would have been motivated, therefore, to investigate depreciation because the subject covered important economic issues, not only accounting ones.

Webster (1920: 1) also shows some indirect economic concerns in relation to depreciation, denouncing the "unsound and destructive theories of valuation," which would deprive investors of a portion of their income. This is in line with the questions raised by Saliers (1922: 18) about a "fair income" and by Riggs (1922: 24) about a "fair return" for investors. Many debates on depreciation at the turn of the 1920s were about the determination of a compromise in accounting and taxation to balance profitability with the risk of abusive depreciation practices. Negotiations and political arbitrages were decisive in the control of business activities (Saliers 1922: 7, 206, 210, 213, 315).

Hotelling had an opportunity to give free rein to his "strong bias toward the social and economic applications of advanced mathematical method."[35] We know he had a conception of mathematical tools as enabling the clarification of reasoning and the identification of ideological biases or erroneous preconceptions influenced by beliefs or political positions; with mathematics, Hotelling sought to design sound public policies following explicit and transparent objectives (Gaspard and Missemer 2019; Gaspard and Mueller 2021). In an article on the heuristic role of mathematics in all disciplines, published in 1936, he made explicit his conception of the interrelation between advanced mathematics, economic theory, and policy applications: "In economic theory we can prove a great many things of vital importance to public policy by means of higher mathematics" (Hotelling 1936: 163), mentioning as examples problems related to exhaustible resources, taxation, competition, and laissez-faire.

If we connect this conception with his early

[34] For instance: "depreciation . . . is a cost of production as truly as are fuel and labor" (6); "depreciation is cost as much as are labor, fuel, and raw materials" (8); "depreciation . . . is one of the costs of production" (71); "the cost of maintaining the investment may . . . be regarded as one of the elements entering into the cost of the output" (129).

[35] Letter from Bell to West, February 21, 1921, Princeton University Archives, box 36, "Hotelling, Harold."

research, we can argue that in 1924, confronted with contested, partly arbitrary depreciation principles for the determination of fairness, he would have seen a need to provide a more transparent and robust theory of asset valuation, "by means of higher mathematics." His words in his 1925 article support this conjecture: he points out the "serious errors of reasoning" (340) and the usually "arbitrary" principles (340), and explains that "the depreciation methods hitherto used . . . are found in general to give false results" (353). By providing a full economic treatment of depreciation issues on the basis of advanced mathematics, Hotelling tried to avoid any "arbitrary" or biased discourse on the fairness of depreciation and asset valuation.

In summary, our investigation leads us to argue that Hotelling detected in his readings in accounting opportunities for building economic theories requiring advanced skills in mathematics. He started with depreciation, having noticed along the way the specificity of exhaustible assets. Interestingly, reading "The Economics of Exhaustible Resources" in light of the intertwining of these two subjects, and in light of Hotelling's preparatory work in accounting, provides a fresh look at his 1931 contribution and helps us understand the underlying architecture of his argument, especially in the end toward taxation.

5. Taxation, a Surviving Entry Point in Hotelling's Economics of Exhaustible Resources

It took Hotelling several years to write "The Economics of Exhaustible Resources," from November 1924 to the summer of 1930. The final version of the article results from the arrangement of paragraphs elaborated at different moments throughout the 1920s.[36] The published version consists of fifteen sections exploring various competitive settings and several regulation environments. These "variants" of the analytical framework (Slade and Thille 2009: 241) make Hotelling's analysis particularly rich for investigating the impact of different factors on resource extraction.

Intriguingly, sections 13 and 14, which are about taxation and are respectively titled "Capital Value Taxes and Severance Taxes" and "Mine Income and Depletion," appear at first to be fairly isolated in the paper, not really connected to the overall main argument. From the outset, there are no traces of preliminary drafts for these sections in the archives, so we cannot exactly know when and how Hotelling elaborated them. Nonetheless, our inquiry into Hotelling's early career reveals a pattern that helps shed light on this issue.

In his 1922 essay, Saliers dedicates a large part of his analysis to the presentation of the evolution of the fiscal treatment of depreciation in the American and British traditions. In particular, he shows that contentious issues about depreciation in the case of mining companies started in the late nineteenth century (206) and developed until the end of the 1910s. The key question surrounded the debate over whether exhaustible assets had to be valued on the basis of the intrinsic value of the reserves, or the actual capital investments deployed on the equipment required for extraction. If considering the intrinsic value, as production takes place, the deposit depletes, and therefore its value depreciates by the exact same amount attained as gross revenues from the sale of resources. As income taxes are due on the net income of mines, if it is given by gross revenues minus depreciation, this fiscal treatment of depreciation would result in a net income of zero. That is, in this limit case, mine owners would be completely exempt from income taxes, as one unit of income would exactly correspond to one unit of depreciation in the mine's value.

Saliers devotes a full chapter to this issue (1922: 269–304). As he explains (271), the dispute between mining companies and the US Treasury about how to determine an accurate procedure for the depreciation of mines had reached the Supreme Court on more than one occasion. The value of the in situ resource admitted for depreciation was finally lower than the market value. In 1913, the revenue act arbitrarily defined the in situ value as 5 percent of the market value. From that moment on, the discussion concerned how to establish this rate, say, relative to the different points in time that va-

[36] Hotelling's 1931 article is a complex and puzzling object with different parts written at different dates and numerous intertwined issues. For a detailed examination of these drafts, see Gaspard and Missemer 2019; Ferreira da Cunha and Missemer 2020.

rious discoveries took place, or how future revisions of a mine's resource stock would reflect on depreciation allowances.

Saliers is the only source, among all the citations and consultations mentioned in the archives, that displays a connection between the subjects of depreciation and exhaustible resources, in particular with regard to fiscal matters. The wording used in sections 13 and 14 by Hotelling is clearly parallel to that used by Saliers. In section 14, and only there, Hotelling uses the word "depletion" (1931: 170–71). As discussed before, Saliers's 1922 essay makes a special case of "depletion" in the case of mineral assets (37). In section 14, Hotelling also addresses the historical debate pertaining to "income taxes" (170), in light of his theory of depreciation and of his new theory of exhaustible assets. In line with Saliers's extensive discussion about the "reasonable allowance for depletion" (214), Hotelling (1931: 170) confirms that "the problem of allowance for depletion has been a perplexing one."

Although Saliers 1922 is cited in "A General Mathematical Theory of Depreciation," it is not mentioned in "The Economics of Exhaustible Resources." Nonetheless, these parallels with Saliers were the only lead we could find in Hotelling's archives for the origins of sections 13 and 14. This suggests that Hotelling became aware of the debates involving an intertwined articulation between the subjects of depreciation and exhaustible assets by reading Saliers and that his sections 13 and 14 should not be considered as "variants" among others but as a surviving entry point coming from his early work on the topic.

Conclusion

Our exploration of Hotelling's archival materials from the early 1920s helps to clarify some blind spots in the history of his intellectual trajectory. Among his various contributions to economic theory, his work on depreciation (1925) and his research on exhaustible resources (1931) have a deeper connection than is usually established by the literature, which insists on formal similarities. There is a substantial connection between the two projects, through the common thread of asset valuation. This can be seen in the architecture of the 1931 article, which is the synthesis of two different research directions (generic assets versus concrete natural resources). It can also be seen in Hotelling's early drafts and notes, in which explicit association between depreciation and exhaustible resources is advocated.

We conducted an in-depth inquiry into Hotelling's early career in order to investigate why he had this conception of the twin projects and how he came to work on them. By highlighting his background and following his first weeks at the Food Research Institute of Stanford University, we have been able to discover with whom he worked and from whom he could have drawn inspiration. Our examination of his early reading also provided us with information about the most likely source of his interest in exhaustible assets right after completing a paper on depreciation: Saliers (1922), who extensively discussed mineral assets in the broader context of depreciation issues. Obviously, the mathematical part of Hotelling's research was not influenced by these readings. Griffith C. Evans and Charles F. Roos may have had an impact on this matter—Evans is notably mentioned in Hotelling's notes for the Chicago talk.[37] Yet in substantive terms, it is rather in that preparatory work on depreciation that we find the most decisive insights.

Interestingly, Hotelling's early readings not only shaped his junction between depreciation and exhaustible resources, they also led him to identify economic questions beyond accounting issues. The share of the burden of depreciation between economic agents, the avoiding of arbitrary debates about fair allowances, the difference between the accounting definition of minerals (limited to finiteness), and the necessity for economic theory to address their full characteristics (geological constraints) are various subjects in which Hotelling entered sooner or later after his preparatory readings.

[37] We can notice, however, that Hotelling states in his article on depreciation (1925: 353n) that several of Evans's papers appeared after he drafted his article. Similarly, Roos may have played a role in Hotelling's formalisms at a later time. In any case, a full examination of Hotelling's ambition with mathematics would require a separate article to characterize his originality and filiations in the history of mathematical economics (Weintraub 2002).

These findings shed new light on Hotelling's intellectual trajectory, informing the origins of his projects and clarifying his entry point in the examination of natural resources.[38] The reference to the conservation movement in the opening of the 1931 article is a late addition and did not play such a structuring role in his project. Other sentences, related to the fair sharing between producers and consumers of the added value from mines (138), the attribution of the proceeds of mines as income or as return of capital (139), or to taxation as a way to harmonize private interest and public good (139) are more relevant for those who try to identify Hotelling's ambitions in his article.

With respect to the history of environmental and natural resource economics, our findings also provide new threads to understand how natural items became associated with capital in the first decades of the twentieth century. The usually highlighted connection between the theory of capital and the conservation movement is not relevant for the Hotelling case. What was at stake for him was rather a link between the accounting literature, depreciation issues, and the specificities of exhaustible assets. This shows that the conceptual connection between nature and capital in the history of economic thought occurred through various channels and not a single one. It also gives an answer to the historiographical (so far unsolved) question of why Hotelling did not cite, and does not appear to have been aware of, the previous works by Gray, Ely, and Ise on nonrenewable resources: he arrived at the connection between capital (i.e., assets) and nature (i.e., exhaustible resources) by another, singular path (i.e., accounting, not the theory of production or the theory of interest).

Viewed from another angle, it means that Hotelling's 1931 contribution should not be analyzed only from the point of view of the conservation of natural resources. In a way, it belongs to the history of asset valuation economics almost as much as, if not more than, the history of natural resource analysis. Given the importance of Hotelling's arguments, in particular the Hotelling rule, in the subsequent evolution of the field of resource and environmental economics to date, this observation possibly opens the way for new interpretations and assessments of these arguments and the rule.

[38] More generally, Hotelling's work and readings on depreciation reveal a precious key to understanding his theoretical trajectory and privileged research topics, from the representation of competition (1929) to his work on welfare related to public utilities (1938).

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References

Akerman, Maria. 2003. "What Does 'Natural Capital' Do? The Role of Metaphor in Economic Understanding of the Environment." *Environmental Values* 12: 431–48.

Allison, James E. 1914. "Depreciation." *Annals of the American Academy of Political and Social Science* 53:198–213.

Arrow, Kenneth J. 1987. "Hotelling, Harold." In *The New Palgrave Dictionary of Economics*, vol. 2, edited by John Eatwell, Murray Milgate, and Peter Newman, 670–71. London: Macmillan.

Barbier, Edward B. 2010. *Scarcity and Frontiers: How Economies Have Developed through Natural Resource Exploitation*. Cambridge, MA: Cambridge University Press.

Barbier, Edward B. 2019. "The Concept of Natural Capital." *Oxford Review of Eco nomic Policy* 35, no. 1: 14–36.

Brazee, Richard J., and L. Martin Cloutier. 2006. "Reconciling Gray and Hotelling: Lessons from Early Exhaustible Resource Economics." *American Journal of Economics and Sociology* 65, no. 3: 827–56.

Canning, John Bennett. 1929. *The Economics of Accountancy: A Critical Analysis of Accounting Theory*. New York: Ronald Press.

Costanza, Robert, Rudolf de Groot, Leon Braat, Ida Kubiszewski, Lorenzo Fiora- monti, Paul Sutton, Steve Farber, and Monica Grasso. 2017. "Twenty Years of Eco- system Services: How Far Have We Come and How Far Do We Still Need to Go?" *Ecosystem Services* 28:1–16.

Crabbé, Philippe J. 1983. "The Contribution of L. C. Gray to the Economic Theory of Exhaustible Natural Resources and Its Roots in the History of Economic Thought." *Journal of Envi-*

ronmental Economics and Management 10, no. 3: 195–220.

Crabbé, Philippe J. 1986a. "Gray and Hotelling: A Reply." *Journal of Environmental Economics and Management* 13, no. 3: 295–300.

Crabbé, Philippe J. 1986b. "Unpublished Fragments on Natural Resources Economics and Excerpt from an Autobiography by Harold Hotelling." *Cahiers de Recherche Du GREEN* 8601.

Daily, Gretchen C. 1997. *Nature's Services: Societal Dependence on Natural Ecosystems*. Washington, DC: Island Press.

Daly, Herman E. 2020. "A Note in Defense of the Concept of Natural Capital." *Ecosystem Services* 41: 101051.

Darnell, Adrian C. 1988. "Harold Hotelling 1895–1973." *Statistical Science* 3, no. 1: 57–62.

Darnell, Adrian C. 1990. "The Life and Economic Thought of Harold Hotelling." In *The Collected Economics Articles of Harold Hotelling*, edited by Adrian C. Darnell, 1–28. New York: Springer-Verlag.

DesRoches, C. Tyler. 2015. "The World as a Garden: A Philosophical Analysis of Natural Capital in Economics." PhD diss., University of British Columbia.

DesRoches, C. Tyler. 2018. "On the Historical Roots of Natural Capital in the Writings of Carl Linnaeus." *Research in the History of Economic Thought and Methodology* 36, no. C: 103–17.

Duarte, Pedro Garcia. 2009. "The Growing of Ramsey's Growth Model." In *Robert Solow and the Development of Growth Economics*, edited by Mauro Boianovsky and Kevin D. Hoover. *History of Political Economy* 41 (supplement): 161–81.

Ely, Richard T. 1918. "Conservation and Economic Theory." In *The Foundations of National Prosperity: Studies in the Conservation of Permanent National Resources*, edited by Richard T. Ely, Ralph H. Hess, Charles K. Leith, and Thomas Nixon Carver, 1–92. New York: Macmillan.

Erreygers, Guido. 2009. "Hotelling, Rawls, Solow: How Exhaustible Resources Came to Be Integrated into the Neoclassical Growth Model." In *Robert Solow and the Development of Growth Economics*, edited by Mauro Boianovsky and Kevin D. Hoover. *History of Political Economy* 41 (supplement): 263–81.

Fenichel, Eli P., and Joshua K. Abbott. 2014. "Natural Capital: From Metaphor to Measurement." *Journal of the Association of Environmental and Resource Economists* 1, no. 1–2.

Ferreira da Cunha, Roberto P., and Antoine Missemer. 2020. "The Hotelling Rule in Non-Renewable Resource Economics: A Reassessment." *Canadian Journal of Economics* 53, no. 2: 800–20.

Franco, Marco P. V., Marion Gaspard, and Thomas M. Mueller. 2019. "Time Discounting in Harold Hotelling's Approach to Natural Resource Economics: The Unsolved Ethical Question." *Ecological Economics* 163: 52–60.

Gaspard, Marion, and Antoine Missemer. 2019. "An Inquiry into the Ramsey-Hotelling Connection." *European Journal of the History of Economic Thought* 26, no. 2: 352–79.

Gaspard, Marion, and Thomas M. Mueller. 2021. "Building Comparative Spaces: Harold Hotelling and Mathematics for Economics." *Journal of Economic Methodology* 28, no. 3: 255–73.

Gaudet, Gérard. 2007. "Natural Resource Economics under the Rule of Hotelling." *Canadian Journal of Economics* 40, no.4: 1033–59.

Giocoli, Nicola. 2018. "'Value Is Not a Fact': Reproduction Cost and the Transition From Classical to Neoclassical Regulation in Gilded Age America." *Journal of the History of Economic Thought* 40, no. 4: 445–70.

Gray, Lewis C. 1913. "The Economic Possibilities of Conservation." *Quarterly Journal of Economics* 27, no. 3: 497–519.

Gray, Lewis C. 1914. "Rent under the Assumption of Exhaustibility." *Quarterly Journal of Economics* 28, no. 3: 466–89.

Hands, D. Wade, and Philip E. Mirowski. 1998. "Harold Hotelling and the Neoclassical Dream." In *Economics and Methodology: Crossing Boundaries*, edited by Roger E. Backhouse, Da-

niel M. Hausmann, and Andrea Salanti, 322–97. New York: St. Martin's Press.

Hartwick, John M. 1999. "L. C. Gray on Exhaustibility, 1916." Working paper.

Helm, Dieter. 2015. *Natural Capital: Valuing the Planet*. New Haven: Yale University Press.

Hotelling, Harold. 1925. "A General Mathematical Theory of Depreciation." *Journal of the American Statistical Association* 20, no. 151: 340–53.

Hotelling, Harold. 1929. "Stability in Competition." *Economic Journal* 39, no. 153: 41–57.

Hotelling, Harold. 1931. "The Economics of Exhaustible Resources." *Journal of Political Economy* 39, no. 2: 137–75.

Hotelling, Harold. 1936. "Little Known Applications of Mathematics." *Mathematics Teacher* 29, no. 4: 157–69.

Hotelling, Harold. 1938. "The General Welfare in Relation to Problems of Taxation and of Railway and Utility Rates." *Econometrica* 6, no. 3: 242–69.

Hotelling, Harold. 1948. "Western Hotelling and Allied Families: An Epic of Migration." Box 52, HHP.

Hotelling, Harold. Papers. Rare Book and Manuscript Library, Columbia University. Catalogue: ndingaids.cul.columbia.edu/ead/nnc-rb/ldpd_4078401.

Ise, John. 1925. "The Theory of Value as Applied to Natural Resources." *American Economic Review* 15, no. 2: 284–91.

Johnston, Bruce F. 1998. "The History of the Food Research Institute as Seen through Its Publications: A Long View." web.stanford.edu/dept/humsci/FRI/fri/html/history.html.

Karp, Larry. 2017. *Natural Resources as Capital*. Cambridge, MA: MIT Press.

Kula, Erhun. 1998. *History of Environmental Economic Thought*. London: Routledge.

Livernois, John. 2009. "On the Empirical Significance of the Hotelling Rule." *Review of Environmental Economics and Policy* 3, no. 1: 22–41.

McClintock, Thomas C. 1962. "J. Allen Smith, a Pacific Northwest Progressive." *Pacific Northwest Quarterly* 53, no. 2: 49–59.

Missemer, Antoine. 2017. *Les Économistes et La Fin Des Énergies Fossiles* (*1865–1931*). Paris: Classiques Garnier.

Missemer, Antoine. 2018. "Natural Capital as an Economic Concept, History and Contemporary Issues." *Ecological Economics* 143: 90–96.

Missemer, Antoine, and Franck Nadaud. 2020. "Energy as a Factor of Production: Historical Roots in the American Institutionalist Context." *Energy Economics* 86: 104706.

Moritz, Robert E. 1919. "On the Relations of Mathematics to Commerce." *School Science and Mathematics Association* 19, no. 4: 350–57.

Moritz, Robert E. 1932. "A New Theory of Depreciation of Physical Assets." *Annals of Mathematical Statistics* 3, no. 2: 108–25.

Nadal, Alejandro. 2016. "The Natural Capital Metaphor and Economic Theory." *Real-World Economics Review* 74:64–84.

Pottier, Antonin. 2014. "L'économie Dans l'impasse Climatique. Développement Matériel, Théorie Immatérielle et Utopie Auto-Stabilisatrice." PhD diss., École des hautes études en sciences sociales, Paris.

Princeton University Archives, Graduate School Alumni Records, Rare Books and Special Collections Library, Princeton University. Catalogue: rbsc.princeton.edu/.

Ramos Gorostiza, Jose Luis. 2003. "Ethics and Economics: From the Conservation Problem to the Sustainability Debate." *History of Economic Ideas* 11, no. 2: 31–52.

Ramsey, Frank P. 1928. "A Mathematical Theory of Saving." *Economic Journal* 38, no. 152: 543–59.

Richardson, R. G. D. 1924. "The Thirtieth Annual Meeting of the Society." *Bulletin of the American Mathematical Society* 30, no. 5: 199–216.

Riggs, Henry Earle. 1922. *Depreciation of Pu-*

blic Utility Properties and Its Relation to Fair Value and Changes in the Level of Prices. London: McGraw-Hill.

Robinson, Tim J. C. 1980. "Classical Foundations of the Contemporary Economic Theory of Non-Renewable Resources." *Resources Policy* 6, no. 4: 278–89.

Robinson, Tim J. C. 1989. *Economic Theories of Exhaustible Resources*. New York: Routledge.

Saliers, Earl A. 1912. *The Coal Miner. A Study of His Struggle to Secure Regulated Wages in the Hocking Valley*. Bethlehem, PA: Bethlehem Printing Company.

Saliers, Earl A. 1915. *Principles of Depreciation*. New York: Ronald Press.

Saliers, Earl A. 1922. *Depreciation: Principles and Applications*. New York: Ronald Press.

Samuelson, Paul A. 1960. "Harold Hotelling as Mathematical Economist." *American Statistician* 14, no. 3: 21–25.

Skinner, Ernest B. 1924. *The Mathematical Theory of Investment*. Boston, MA: Ginn.

Slade, Margaret E., and Henry Thille. 2009. "Whither Hotelling: Test of the Theory of Exhaustible Resources." *Annual Review of Resource Economics* 1:239–60.

Smith, Gerald Alonzo. 1982. "Natural Resource Economic Theory of the First Conservation Movement (1895–1927)." *History of Political Economy* 14, no. 4: 483–95.

Smith, Gerald Alonzo. 1986. "Gray and Hotelling: A Comment." *Journal of Environmental Economics and Management* 13, no. 3: 292–94.

Smith, J. Allen. 1907. *The Spirit of American Government*. New York: Macmillan.

Smith, J. Allen. 1914. "Effect of State Regulation of Public Utilities upon Municipal Home Rule." *Annals of the American Academy of Political and Social Science* 53:85–93.

Solow, Robert M. 1974. "The Economics of Resources or the Resources of Economics." *American Economic Review* 64, no. 2: 1–14.

Special Collections Library, University of Washington. Catalogue: archives-west.orbiscascade.org/search/results.aspx?t=i&q=wauar&f_repo=wauar.

Stearns, Frederic P., Charles S. Churchill, William G. Raymond, Henry Earle Riggs, Jonathan P. Snow, William J. Wilgus, and Leonard Metcalf. 1917. "Final Report of the Special Committee to Formulate Principles and Methods for the Valuation of Railroad Property and Other Public Utilities." *Transactions of the American Society of Civil Engineers* 81: 1311–1620.

Sullivan, Sian. 2017. "On 'Natural Capital,' 'Fairy Tales,' and Ideology." *Development and Change* 48, no. 2: 397–423.

Sweeney, James L. 1993. "Economic Theory of Depletable Resources: An Introduction." In *Handbook of Natural Resource and Energy Economics*, edited by Allen V. Kneese and James L. Sweeney, 3:759–854. Amsterdam: Elsevier.

Taylor, James S. 1923. "A Statistical Theory of Depreciation Based on Unit Cost." *Journal of the American Statistical Association* 18, no. 144: 1010–23.

Turnbull, Thomas. 2017. "From Paradox to Policy: The Problem of Energy Resource Conservation in Britain and America, 1865–1981." PhD Thesis, University of Oxford.

Victor, Peter A. 2020. "Cents and Nonsense: A Critical Appraisal of the Monetary Valuation of Nature." *Ecosystem Services* 42: 101076.

Webster, George N. 1920. *Theoretical Depreciation: A Menace to the Public and the Investor*. New York: n.p.

Weintraub, E. Roy. 2002. *How Economics Became a Mathematical Science*. Durham, NC: Duke University Press.

Zeff, Stephen A. 2000. "John B. Canning: A View of His Academic Career." *Abacus* 36, no. 1: 4–39.