Religion and the Rise and Fall of Islamic Science

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May 2016

Abstract

Why did the surge of scientific production in the medieval Islamic world dwindle? To explore this question, I gather data on intellectual production from Harvard's library collection and a catalog of books from seventeenth century Istanbul. I document that the proportion of books dedicated to scientific topics declined in the medieval period, noting that the empirical patterns are most consistent with theories linking the decline to institutional changes. I discuss the role religious leaders played in generating these developments, concluding that the evidence is consistent with the claim that an increase in the political power of these elites caused the decline in scientific output.

*Harvard University, echaney@fas.harvard.edu. This paper is a substantially modified version of a chapter of my dissertation written under the direction of Barry Eichengreen, J. Bradford DeLong, Edward Miguel, Bob Powell and Gérard Roland. I thank many individuals and seminar participants for helpful comments, conversations and suggestions. Laura Morse provided invaluable assistance obtaining the Harvard Library data and Yazan al-Karablieh provided able research assistance. Part of this project was carried out while the author was a member of IAS Princeton, a Mellon Fellow at CASBS Stanford and a Furer Fellow at Harvard, whose support is gratefully acknowledged. I am responsible for all remaining errors.

"O Lord! Increase me in knowledge" -Quran (20:114)

"For indeed faith, with ignorance, is sound"[1] -Muslim Religious Elite, 12^{th} Century CE

Muslim-majority regions produce a disproportionately small share of world scientific output today.[2] During the medieval period, however, Islamic societies witnessed a spectacular flowering of scientific and technological production. For years, scholars have pointed to this "Golden Age" as evidence that Islam and science are not inherently incompatible. Scholars still struggle, however, to explain the low levels of scientific production in these regions today. One line of literature traces the current underproduction of science in the Islamic world to the medieval decline of scientific production and the concomitant rise of an obscurantist social equilibrium that has persisted to the present. Some have argued that external shocks such as the Mongol invasions brought about these changes, while others have pointed to endogenous factors. In recent years, scholars have challenged these interpretations, instead claiming that Islamic science did not decline in the medieval period and pointing to colonialism as the culprit (e.g. Saliba, 2007).

In this paper, I document the evolution of scientific production in the Islamic world over more than a millennium to explore whether scientific production in the Islamic world declined, to pinpoint when it declined, and to evaluate the validity of popular explanations for its decline. My primary measure of scientific production is derived from Harvard's library holdings, which are among the most extensive in the world. These data show a sustained drop in the proportion of books dedicated to scientific topics that becomes statistically significant in the twelfth century CE and persists through the end of the sample in 1800. This drop in scientific output is accompanied by a surge in books written on religious topics as well as an increase in derivative works (e.g. commentaries on previous works). Results using an alternative data set from seventeenth century Istanbul are qualitatively similar. Taken in unison, the results provide robust evidence that scientific production declined in the medieval Islamic world.

[1]Cited in Makdisi (1985, p. 47).

[2]See, for example, Dallal (2010, pp. 158-159) who discusses "the dismal state of scientific and technological production in the Muslim world" and notes that in one region of the Muslim world "the average output [of scientific publications...] per million inhabitants is roughly 2 percent of the output of an industrialized country."

The paper then evaluates possible explanations for this decline in scientific output. The empirical patterns cast doubt on hypotheses highlighting the role of colonialism or of the Mongol invasions as the observed decline predates these shocks. Among popular explanations for the decline, the data are most consistent with the “Sunni Revival” hypothesis (or Revival hypothesis for short) (Makdisi, 1973; Gibb, 1982). The classical version of this hypothesis claims that the Revival (which is believed to have begun in the eleventh century) marked a surge in the political power of religious leaders. This increase in political power was accompanied by the spread of institutions such as madrasas (educational centers where Islamic law was taught) that decreased the relative payoff to producing scientific knowledge. I hypothesize that as the payoff structure shifted in favor of the production of religious knowledge, talent increasingly flowed away from the study of scientific topics (Baumol, 1990; Murphy et al., 1991) leading to a decline in both the quality and quantity of scientific works produced.

I show that the available empirical evidence is consistent with the Revival hypothesis. First, trend-break algorithms locate robust breaks in both scientific production and the proportion of authors affiliated with madrasas that lie in the mid/late-eleventh century when madrasas began to spread across the Islamic world. Second, I provide evidence that the geography of the decline in scientific output spreads from East to West, roughly tracking the spread of madrasas.

Although data limitations preclude an empirical investigation of the fundamental causes of the Revival (e.g. whether the Revival was imposed from above or was a product of more bottom-up processes), the data do support the claim that the actions of religious leaders contributed to the decline of scientific production. I provide qualitative evidence that these newly empowered elites worked to restrict the production of scientific knowledge in the post-Revival institutions that they controlled because they believed that unrestrained scientific research led Muslims to disregard their teachings. In addition, I provide quantitative evidence that is consistent with this motive and weighs against the possibility that the results are a reflection of a post-Revival surge in religiosity. Thus, the available evidence is consistent with a conceptual framework in which religious leaders derive rents from their control over beliefs (Chaney, 2013), and work to restrict access to alternative world views unless otherwise constrained (Acemoglu and Robinson, 2000).

By providing evidence that the political empowerment of religious leaders was at the very least a proximate cause of the decline of scientific output in the medieval Islamic world, the paper adds to the growing literature arguing that "religion matters" in understanding differences in human capital formation rates (e.g. Mokyr, 2002; Botticini and Eckstein, 2005; Becker and Woessmann, 2009; Benabou et al., 2013) and thus economic outcomes (e.g. Barro and McCleary, 2003) across societies. While complementing such studies, the results in this paper also suggest the importance of better understanding the impact of actions taken by religious leaders in the political and institutional spheres (Benabou et al., 2013). Consistent with Cantoni and Yuchtman (2013), I argue that where religious elites hold more power they will favor an institutional and educational framework that discourages human capital accumulation that could detract from their control over the population (see Acemoglu and Autor, 2012, for a related discussion). This view predicts a negative correlation between the political power of religious leaders and scientific production that is consistent with the results presented in this paper. It also suggests that better understanding how and why religious leaders are constrained may help clarify variation in religious support for human capital formation both across religions and within religions over time.

The results also speak to the broader literatures on the economics of innovation and growth. Although there is a consensus that the production of ideas and human capital formation more broadly are at the "center of growth theory" (Jones and Romer, 2010, p. 226), the reasons why rates of innovation vary both across and within societies over time remain a topic of ongoing research. In recent years, research has stressed the importance of rent-seeking pressure groups in stifling technological progress (Mokyr, 1994; Krusell and Rios-Rull, 1996; Acemoglu and Robinson, 2000). This paper complements such studies, although it is novel in that it provides evidence that religious elites will thwart innovation unless otherwise constrained.

Finally, the paper contributes to scholarship investigating the economic rise of the Western World. This literature increasingly highlights the role of technological and scientific dynamism in the West as a key driver of the divergence both within the West and between the West and the rest of the world (e.g. Mokyr, 2005; Buringh and van Zanden, 2009). While studies generally recognize that China was technologically more advanced than Europe for much of the medieval period (e.g. Jones and Romer, 2010, p. 239) it is often forgotten that scientific and technological production in the medieval Islamic world "greatly surpass[ed] the West and China" for centuries (Huff, 2003, p. 48). The results challenge the claim that Islam as a religion is uniquely or inherently anti-science or anti-technology and suggest that future research investigating how the political equilibrium in the West placed constraints on religious leaders could provide insights into the scientific and technological development of the West in the run-up to the Industrial Revolution.

The remainder of the paper proceeds as follows: the first section provides a brief historical overview, presents the data and provides a simple formal framework within which to think about the potential biases in the data, a second section discusses the basic trends, a third section provides further evidence relating the decline to the Revival and discusses the role of religious leaders within the Revival and a fourth section concludes.

1 Historical Overview and Data

Scholars broadly agree that for much of the medieval period Islamic societies led the world in both technology and science (e.g. Huff, 2003, p. 48). While the factors that led to this surge in intellectual output remain a topic of debate, its timing is reasonably well known. From the rise of Islam in the seventh century until the start of the Abbasid Caliphate in 750 CE, the nascent Islamic world produced relatively little scientific output.[3] Abbasid Caliphs over the following century sponsored a translation movement aimed at rendering every available scientific text into Arabic (Gutas, 1998). This translation movement coincided with and

[3] In the century following the death of the Prophet Muhammad in 632 CE, Arab-Islamic armies conquered a vast territory reaching from modern-day France to Pakistan. The immediate successors to Muhammad (known as the Rashidun Caliphs) were followed by the Umayyad Dynasty in 661 which was replaced, in turn, by the Abbasid Dynasty in 750. Contrary to what is implied in many studies, this dynasty was relatively short-lived, at least in its ability to directly control territory. Generally speaking, after 945 the Abbasid Caliphs no longer controlled territory and primarily provided their blessing upon the true holders of power across the Islamic world. In 1258, this state of affairs came to an end when the last Abbasid Caliph was killed by the Mongols.

served as a catalyst for the explosion of scientific output that occurred in the Islamic world over the following centuries. Scientists during this period made important advances in fields as varied as astronomy, mathematics, medicine and optics (Kennedy, 1970, p. 337).[4] Indeed, many scientific works from the medieval Islamic world were eventually translated into Latin and are believed to have played a central role in the scientific development of Western Europe during the late medieval and early modern periods (e.g. Lindberg, 1978).

According to Brentjes (2009, p. 305) there were "two major periods for the patronage of scientific knowledge," the first spanning roughly the eighth to the twelfth centuries and the second running from the twelfth to the nineteenth century. During the first period, rulers and wealthy urban groups funded scientific output and also established institutions such as libraries where scientific topics were studied (e.g. Brentjes, 2009, p. 305). Rulers and other wealthy individuals patronized scientists for both prestige (David, 2008) and for the "practical benefits promised by the practitioners of medicine and astronomy and astrology and applied mathematics" (Sabra, 1996, p. 662).

In the second period, funding for intellectual pursuits shifted to religious institutions such as madrasas.[5] Unlike the direct patronage system of the first period, in the second period rulers and wealthy individuals endowed religious institutions dedicated to knowledge production. Prospective scholars who wished to be appointed to these posts generally had to specialize in the production of religious knowledge (Makdisi, 1981, p. 285).

One line of scholarship implies that the transition from the first type of patronage to the second occurred during a period of institutional change, often referred to as the Sunni Revival, that began sometime in the eleventh century. Traditionally, scholars linked these changes to tensions between rationalist and traditionalist interpretations of Islam. Makdisi (1962, p. 38) concisely sums up the differences between these two camps by noting that "the traditionalists rel[ied] on faith and shun[ned] reason; the rationalists glorif[ied] reason

[4] The term scientist is, admittedly, anachronistic. Throughout, I use this term in place of others such as natural philosopher for expositional ease.

[5] While for expositional ease in the text I use the word madrasa as short-hand for the religious institutions founded during the Revival, in addition to madrasas the Revival also witnessed a surge in institutional support for Sufi mystics. These institutions, known as khanaqahs (khanqahs), zawiyas, tekkes or ribats were routinely founded alongside madrasas and were often controlled by the same individuals. Indeed, recent scholarship has stressed "the fluidity of the boundary [...between] the madrasa and the khanaqah" during this period (Safi, 2006, p. 156).

and ha[d] little use for faith." Whereas rationalists criticized traditionalist interpretations for intransigence vis-à-vis the use of reason, traditionalists claimed that rationalist interpretations could lead to a loss of belief (e.g. Kraemer, 1986, p. 72). Religious doubt may have partly stemmed from the fact that rationalists encouraged the believer to approach God directly without interference from religious elites (Crone, 2006, p. 26). Traditionalist religious elites were opposed to such rationalist interpretations as well as to the scientific mindset believed to be at their root (Goldziher, 1981, p. 187).[6]

The Revival marked the final triumph of traditionalist religious leaders in their battle against rationalism (Makdisi, 1973, p. 168). During this period, madrasas replaced institutions focused on scientific research (Makdisi, 1981, p. 10).[7] Although some scientific research continued to be produced in madrasas, after the Revival "an instrumentalist and religiously oriented view of all secular and permitted knowledge" emerged where scientific research was constrained to "very narrow, and essentially unprogressive areas" (Sabra, 1987, pp. 240-241). Indeed, the goal of these institutions was "not to create critical or substantially new knowledge" (Brentjes, 2009, p. 319) and their establishment is believed to have been accompanied by a surge in derivative works such as commentaries on previous works (e.g. Talbani, 1996, p. 70). One interpretation attributes these changes in intellectual output to the desire of newly-empowered traditionalist religious leaders to limit the study of scientific topics as part of a broader effort to eliminate the religious skepticism that threatened their societal influence.

Despite claims that the Revival ushered in an institutional framework that has characterized many Islamic societies for much of their post-Revival history (Lambton, 1968, p. 203), our understanding of these societal changes remains at a "rudimentary stage" (Safi, 2006, p. 35). While it is beyond the scope of this paper to conclusively determine the causes of the Revival, I weigh some of the most common explanations against the available data in

[6]It was also believed that the unrestricted study of science could lead individuals to deism and even atheism. Consistent with this view, Stroumsa (1999) provides examples of the deist/atheist figures that emerged during the Golden Age. Also, see Glaeser and Sacerdote (2008) for evidence of a negative relationship between religious beliefs and human capital formation.

[7]While there are isolated examples of madrasas solely dedicated to funding scientific endeavors most available posts were dedicated to the production of religious knowledge (e.g. Brentjes, 2009, p. 313).

Section 3.1.1.

Other explanations for the medieval decline of scientific output compete with the Revival hypothesis in the literature. For centuries, scholars have stressed the role that the Mongol invasions of the thirteenth century played in bringing about the medieval decline. Although the mechanisms through which these shocks affected scientific output remain a topic of debate, the existing scholarship often stresses the importance of the destruction of physical and human capital as well as institutional and cultural changes (for one critical review of this hypothesis, see Saliba, 2007, p. 235).

In recent years, a new line of scholarship has emerged challenging the decline narrative. For example, Saliba (2007) provides overwhelming evidence that important advances continued to be produced in the Islamic world long after the supposed decline of scientific production. He suggests that the decline did not begin until the sixteenth century and tentatively attributes this decline to the European discovery of the New World. Thus, an intellectual stalemate has arisen between those who argue for a medieval decline and their detractors.[8] Much of this stalemate seems to be the product of a lack of systematic empirical evidence regarding the evolution of intellectual production in the Islamic world historically.

1.1 Measuring the Evolution of Scientific Output in the Islamic World

To measure the evolution of intellectual output in the Islamic world, I would ideally observe the population of all books written in the Islamic world throughout its history. Such a data set would allow me to empirically measure the evolution of intellectual production in the Islamic world over time. As an approximation to this ideal, in this paper I construct a data set containing every book written by authors with an Islamic-sounding name in Harvard's library collection.[9]

It seems reasonable to assume that Harvard's library collection provides an approximation

[8] For an introduction to this debate, see Huff (2003) and Saliba (2007).

[9] Thus, the sample includes many non-Muslims. For example, Hunayn ibn Ishaq is classified as having an Islamic-sounding name even though he was Christian because his name "sounds" Arab.

to the collection of surviving books considered important in the West today. First, Harvard's library is the largest university library in the world and the oldest in the United States.[10] Second, Harvard's historical and present-day strengths in history, the humanities and regional studies make it likely that the world's most prominent thinkers will be represented in the database.[11]

Despite the strengths of Harvard's collections, using any modern-day collection of works to assess the historic evolution of scientific output in the Islamic world is full of pitfalls. While the corpus of books in Harvard libraries is a sample from the unobserved population of all works produced in the Islamic world, it is probably not a random sample. For example, certain regions and time periods may be over-represented due to spurious scholarly consensus or the preferences of Harvard scholars.[12] Furthermore, even abstracting from the issue of Harvard and/or Western-specific biases in book collection, the (unobservable) corpus of all surviving works across the world is, in itself, unlikely to be a random sample from the population of works ever produced. This could be due, for example, to the destruction of historical manuscripts by invaders in certain regions and time periods but not in others.

Given these complications, I will focus on describing how the proportion of books on scientific topics varies over time rather than working with the total number of works on science. I do this primarily because I do not know how the selection probabilities vary over time, and thus changes in the observed number of works on science may be reflective of changes in these unobserved probabilities. Fortunately, a decline in the proportion of works dedicated to scientific topics is one of the key implications of the Revival hypothesis.

However, given that I also lack information on how selection probabilities vary both within and between sub-populations, it is impossible to know the extent to which changes in the proportion of books on scientific topics will provide consistent estimates of their population counterparts. To make this clear in the context of the baseline regressions run throughout

[10]See, for example, http://news.harvard.edu/gazette/1998/06.04/CountingLibrari.html.

[11]The collection policy of Harvard libraries is explained here: http://hcl.harvard.edu/collections/. In particular, this policy states that "[t]he collections aspire to comprehensive coverage of the record of scholarship, from all countries and in all relevant fields."

[12]Given the historic and present-day influence of Harvard scholars across disciplines, however, it is likely that the preferences of these scholars and those of the broader scholarly community are similar.

the paper consider the estimating equation (omitting all authors who died prior to 800 CE):

$$s_i = \gamma + \sum_{h \geq 1100} \beta_h D_h + \epsilon_i \tag{1}$$

where s_i is an indicator equal to one if book i is on a scientific topic and D_h is a dummy equal to one if the author of book i died in hundred year bin h. The β_h are the proportion of all books written on scientific topics by authors who died in century h relative to the omitted baseline which covers the interval [800,1100) which I use as a proxy for the "Golden Age" of scientific production. Define the dummy variable I_i equal to one if Harvard holds a book in its collection and zero otherwise.[13] Furthermore, and without loss of generality, assume that $E[s_i|t < 1100, I_i = 1] = \alpha E[s_i|t < 1100]$ and $E[s_i|h, I_i = 1] = \delta E[s_i|h]$ where I place no restrictions on α or δ aside from those necessary to keep $E[s_i|g, I_i = 1]$ on the unit interval. Then it is straightforward to show that

$$\text{plim}(\hat{\beta_h}) = \delta \beta_h + (\delta - \alpha) E[s_i|t < 1100] \tag{2}$$

Sensibly, equation 2 shows that if the Harvard collection is a random sample from the underlying population ($\delta = \alpha = 1$) then the point estimate is consistent. In addition, this equation yields a few insights. First, if Harvard libraries are sampling in a way that inflates the proportion of science by the same factor in both the Golden Age and in the post period ($\delta = \alpha$), then the estimated β_h will be too large (in absolute value). Conversely, if Harvard libraries sample in such a way that deflates the proportion of science by the same factor then the estimated β_h will be too small (in absolute value). Thus, even in the unlikely case when $\delta = \alpha$, I can only hope to recover the sign (and not the magnitude) of the change in the proportion of works dedicated to scientific topics over time.

In the more realistic case in which δ and α differ, it is possible to obtain a spurious decline

[13] Throughout, I assume that scientific books are measured without error for expositional ease. This assumption is easily relaxed, and if the probabilities of not identifying a book on science and spuriously attributing a book to a scientific topic do not change over time the analysis is identical. As there is little reason to expect bias coming from measurement error to lead to spurious conclusions in this context, I henceforth abstract from this issue although I provide a more detailed discussion in the appendix.

in scientific output. The only way this can occur is if $\delta < \alpha$ or if Harvard oversamples scientific works produced by authors during the Golden Age relative to the sampling regime in later centuries. This could happen, for example, if scholars have assumed that there was a decline in scientific production after 1100 CE and have ignored studying scientific works after that date. Note, however, that the differential targeting of Golden Age scientific works for destruction historically (perhaps due to their heretical content) would work in the opposite direction attenuating or possibly even flipping the sign of a true drop in scientific output.

In sum, while there is some hope that I will be able to recover the correct sign of β_h using the Harvard library collection, the estimated magnitudes should be treated with caution. In addition, a negative β_h will be indicative of a decline in the population proportion of works dedicated to scientific topics unless Harvard is oversampling scientific works from the Golden Age relative to the sampling regime in later centuries.

2 Empirical Results

To estimate the coefficients in equation 1, I collapse the data down to the year level, limit the sample to authors who died on the interval [800,1800) and run a regression of the form:

$$\%Science_{th} = \gamma + \sum_{h \geq 1100} \beta_h D_h + \epsilon_{th} \tag{3}$$

where the variable $\%Science_{th}$ is the proportion of books written by authors who died in year t and in hundred year bin h on scientific topics (the list of subject strings used to define scientific works as well as a detailed description of the data are provided in the appendix) and the D_h are century dummies. In table 1, I provide estimates of the β_h and the constant γ.[14] Throughout unless otherwise stated, I provide results weighted by the number of books

[14]Throughout the paper, I limit analysis to observations with defined values of the dependent variable when relevant. Thus, regressions using the proportion of books written on scientific topics as the dependent variable are estimated on the sample of books with defined subjects. Similarly, regressions investigating the proportion of books written by secretaries are limited to those authors for whom I was able to identify a profession. In general, however, these results are qualitatively similar to those obtained when running the regressions on the entire sample.

in each year as the point estimates in such a specification are equivalent to those obtained when running the regressions at the book level (i.e. the $\hat{\beta}_h$ are the proportion of all books held by Harvard written by authors on scientific topics who died in a hundred year bin relative to the omitted baseline).[15] In addition, throughout I present Newey-West standard errors allowing for the error structure to be heteroskedastic and autocorrelated up to seven lags. Finally, where the dependent variable is a proportion, I multiply the coefficients by one-hundred for expositional ease.

The results in column 1 show that during the Golden Age (the omitted baseline of [800,1100)) roughly ten percent of books are on scientific topics.[16] This drops to five percent in 1100 and by 1700 has fallen to two percent. While these results are consistent with a decline in scientific activity in the medieval period, they also provide empirical confirmation that some science continued to be produced in the Islamic world long after the Golden Age.

In column 2 of Table 1, the dependent variable is the proportion of books written on religious topics that are believed to have been most affected by the Revival.[17] These results show that works on Revival-related religion follow an almost opposite trend to those on scientific topics, increasing from roughly 13 percent of intellectual output during the Golden Age to over twenty percent in subsequent centuries.

While these patterns are consistent with the "Revival" hypothesis, as noted above it is possible that Harvard's library holdings are reflective of a spurious scholarly consensus. In other words, if scholars have assumed that there was a decline in scientific production after 1100 CE and have ignored scientific works after that date, then Harvard would spuriously hold a smaller proportion of scientific works after 1100 CE.[18]

I investigate the empirical relevance of this concern in two waves. In the first wave, I gather

[15]While in my view such a specification is the most natural in this context, I show in the appendix that the results are robust to alternative weightings.

[16]In the appendix I provide results suggesting that the drop from [1000,1100) to [1100,1200) is generally abrupt across the dependent variables considered in the paper.

[17]A book is classified as being on a Revival religious topic if its subject matter contains the string "Fatwa", "Law" or "Sufi" given that madrasa's primary purpose was to teach religious law (e.g. Makdisi, 1961, p. 11) and that of the khanaqah to support Sufi mystics.

[18]Although I take this possibility seriously, it is worth noting that there is little consensus on the timing of decline even among those who argue for a medieval decline of scientific production. Thus, while some argue that the decline begins around 1100 (e.g. Starr, 2013, p. 524), others stress that such a decline did not occur until the thirteenth century (e.g. Huff, 2003, p. 47).

data on intellectual production from seventeenth century Istanbul. While this source (which I will subsequently refer as Khalifa in reference to the author's name) is not perfect and may be subject to some of the same biases as the Harvard data (such as those introduced by the historical destruction of manuscripts), it is not subject to the Western scholarly biases that may be driving the Harvard results. Moreover, as it was composed roughly four centuries ago it contains works which no longer survive. Indeed, it is generally recognized as one of the most important sources of information on the intellectual history of the Islamic world and contains information on approximately 14,500 books written over a period spanning more than a millennium. In the appendix I provide summary statistics for this source and discuss it in greater detail.

Unfortunately, Khalifa does not generally provide book topics, but this source does provide information on whether the book was derivative (e.g. a commentary on a previous work) rather than original. Recall that the Revival hypothesis implies that the decline in the proportion of works on scientific topics coincides with an increase in the proportion of derivative works. The results in columns 3 and 4 of table 1 are consistent with this prediction.

In column 3, I examine how the proportion of books classified in the Harvard libraries as derivative varies over time.[19] These results provide evidence of an increase in the proportion of works that are derivative starting in the twelfth century. In column 4, I perform the same exercise using Khalifa's data.[20] Although the magnitudes and levels of statistical significance often differ,[21] the broad increase in the proportion of derivative works is apparent in both data sets. This result provides evidence that Western biases are not driving the results.

In the second wave, in the spirit of Altonji et al. (2005), I examine how large time varying selection would have to be to completely explain away the results under the null that the true effect is zero. Setting β_h=0 and plugging point estimates into equation 2 yields $\alpha =$

[19]I classify a book as being derivative if its subject field contains the string "Comment" or "Interpretation." To be as conservative as possible, even if the book's subject entry contains one or both of these strings, I do not classify it as derivative if it also contains the string "Criticism."

[20]Throughout, to be as conservative as possible I limit the Khalifa data to the interval [900,1500) given that this sample seems to be most reliable on this interval. Thus, in the Khalifa data the omitted baseline is [900,1100) rather than [800,1100). As I show in the appendix, however, the results are generally qualitatively similar when the [800,1500) sample is used.

[21]Perhaps because Harvard carries fewer derivative works and/or I am measuring this proportion with greater error in the Harvard data.

2.5δ.[22] To better understand the implications of this relationship in the sample, suppose that $\delta = 1$ or that the proportions of scientific output in the centuries after 1100 are measured consistently (the point estimates suggest that this proportion is roughly 4%). Then to completely explain away the results Harvard would have be sampling in a way that increased the true proportion of scientific books by 2.5 times (as the sample size during the Golden Age is 6352 books, this implies that Harvard is including 381 too many books on scientific topics during this period).[23] Alternatively, suppose that $\alpha = 1$ (or the true proportion of scientific works in the post period is 10%), then Harvard would have to be sampling in the later periods in such a way that the observed proportion of scientific works is only 40% of its true value (as the post-Golden Age sample size is 16391, this implies that Harvard is including roughly 984 too few books on scientific topics for this later period). One might expect such a sizeable change in the sampling regime to leave a trace in other observables such as the number of books per author around the decline in scientific output.[24]

In columns 5-9 of table 1, I look for evidence of such a change in observables around the decline in scientific output. In column 5, I show that the average number of books remains roughly constant at 24 per year through the sixteenth century whereas column 6 shows that there is little evidence for a change in the average number of books per author prior to 1400. Column 7 shows that the number of authors does not follow a clear trend until the end of the sample, whereas columns 8 and 9 show that surges in the proportion of books whose author I was unable to geo-reference and the proportion of books with no identified subject in the Harvard dataset do not increase until centuries after the observed decline in scientific output. Thus, these data provide little support for the hypothesis that the results are an artefact of time-varying selection.[25]

[22] Here I round and set the probability limit of $\hat{\beta_h}$ to its mode of -0.06, and the Golden Age proportion of scientific output to 0.10.

[23] Here, I state these quantities assuming the sample size is held constant.

[24] Thus, if Harvard were carrying many copies of the same scientific work for Golden Age scientists this would appear in a greater number of books per author during the Golden Age.

[25] The regressions in columns 5 and 7 are not weighted, whereas that in column 6 is weighted by the number of authors. Regression 9 is weighted by the total number of books written by authors who died in that year.

2.1 Regional Variation

Beyond the proportion of derivative books, one would expect the Harvard and Khalifa data sets to yield similar results if both are approximately representative of the underlying population. While it is challenging to find variables that are comparable across data sets, in this section I investigate how the birth places of authors vary over time. In this section, I limit analysis to authors I was able to geo-reference who died on the interval [800,1500) and who were born inside the boundaries of the Islamic world as of 900 CE.[26] I limit the sample geographically to hold the region under analysis roughly constant over time. I limit the sample temporally both for expositional ease and due to the fact that there is evidence that Khalifa's data are less reliable after approximately 1500. In figure 1, I provide a map showing the geographic location of intellectual production during this period in the Harvard dataset. Larger dark circles denote higher numbers of books written by authors born in a location whereas larger white circles denote higher numbers of books on scientific topics. The boundaries of the Islamic world in 900 CE are shaded light grey. To examine the evolution of author location over time, I divide the Islamic world into 3 regions which I label East, Center and West. The first region includes authors born in Baghdad and east. The second includes those born in Alexandria and places east up to Baghdad whereas the third region includes those born to the west of Alexandria.[27]

To examine how the geography of intellectual production varies over time, I estimate equation 1 three times with the proportion of books written by authors who died in year t and were born in each of the three regions as the dependent variable (again, I weight by the number of books in year t). Note that as these three regressions completely describe the variation within and between regions, the baseline coefficients sum to one and the change coefficients sum to zero across regions (subject to rounding error). In columns 1-3 of table 2, I provide the results estimated using Harvard's data and columns 4-6 provide results estimated using Khalifa's data. The qualitative implications of the results are remarkably

[26] I choose the year 900 CE because these are the boundaries given by Kennedy in his Historical Atlas of Islam (available online at http://referenceworks.brillonline.com/browse/historical-atlas-of-islam). Most of these areas were under continuous Muslim control on the interval [800,1500). The main exceptions to this statement are the areas temporarily occupied by the Crusaders in the Levant and those permanently lost to Islam in Iberia.

[27] While there are other ways to divide the Islamic world, the basic trends documented in this section are robust.

similar across data sets. First, the eastern region produces the majority of intellectual output during the Golden Age. Second, starting in the thirteenth century there is a shift in the geography of intellectual production from the eastern to central regions. The timing of this shift roughly corresponds to the Mongol invasions and may be reflective of the widespread destruction caused by this military shock.[28]

When taken in unison, the results presented thus far weigh against the possibility that the Harvard data suffers from time-varying selection around the observed decline in scientific output. Furthermore, they are not consistent with claims that colonialism or the Mongol invasions are driving the results in the sense that these shocks postdate the beginning of the observed decline.

3 Science and the Revival

The evidence presented thus far suggests a decline in scientific output that becomes statistically significant in the twelfth century. In this section, I examine the extent to which the data are consistent with the Revival hypothesis. This hypothesis has implications for both the timing and the geography of the decline that can be taken to the data. Although I have already explored the timing of the decline to a degree, in this section I use the framework developed in Bai and Perron (1998, 2003) to search for breaks in the data. This strategy is motivated by claims by historians that the institutional changes that accompanied the Revival "transformed higher education" (Chamberlain, 1994, p. 69) marking "a significant change in Islamic social structure and Muslim community life" (Gilbert, 1980, p. 106). Specifically, I use the sample spanning the years [800,1799) and limit this sample to thinkers for whom I was able to find an Encyclopedia of Islam entry (see below for a more detailed discussion).[29] I then allow for up to five breaks in the "step-function" specification:

[28] These results also roughly coincide with those obtained by Bulliet (1979, pp. 7-9) from an independent historical source, further increasing confidence that these patterns are not spurious.

[29] While I obtain similar results when using the entire sample, the relatively few observations in the years before 800 make it difficult to locate the timing of the initial jump in scientific production (thus most trend break algorithms find no break prior to the Revival). I limit the sample to individuals for whom I was able to find an Encyclopedia of Islam entry for comparability between the science and madrasa results.

$$\%Science_t = \gamma_j + u_t \qquad t = T_j - 1 + 1, ..., T_j \tag{4}$$

where I follow the notation in Bai and Perron (2003) and use m to denote the number of breaks (m+1 regimes), for j=1,...,m+1. $\%Science_t$ is the proportion of works written by authors who died in year t on scientific topics and u_t is the disturbance term. The break points ($T_1, ..., T_m; T_0 = 0, T_{m+1} = T$) are treated as unknown. I weight these regressions by the number of books in each year.[30] This specification selects one break in 1048, with a 95% confidence interval covering the period 966-1149 and a 90% interval spanning 990-1119.[31]

This break is consistent with the Revival hypothesis in the sense that both confidence intervals contain major events that mark the emergence of the Revival institutional complex in both the central and eastern Islamic world (which, as shown above, constitute much of the sample through the twelfth century). For example, the establishment of the Niẓāmiyya Madrasa in Baghdad, which is often used to mark the start of the spread of madrasas across the Islamic world, occurred in 1065. In addition, the reign of the vizier Niẓām al-Mulk — often viewed as a pivotal figure in the institutional changes that accompanied the Revival— spans the interval 1064-1092.

Did the institutional changes of the Revival cause the decline in scientific production? For this to hold, the decline in scientific output would have to be accompanied by an increase in the proportion of authors affiliated with madrasas. To proxy for this quantity, I first look up every individual in the Harvard sample in the Encyclopedia of Islam.[32] Using a web grabber, I then download the entire Encyclopedia of Islam entry for each scholar and construct the proportion of books in each year for which madrasa is mentioned in the

[30] Although the GAUSS program described in Bai and Perron (2003) does not allow for weights, the unweighted algorithm can be used on the variables $\%Science_t\sqrt{n_t}$ in place of $\%Science_t$ and $\sqrt{n_t}$ in place of a vector of ones to obtain the weighted results.

[31] This break point is very robust. For example, I have also experimented with a specification of the form $\%Science_t = \gamma_j + \delta_j t + u_t$ and obtain qualitatively similar results although these are estimated less precisely. From a technical standpoint, I set m=5 and use 15% trimming although the results are robust to different trimming percentages. I allow for serial correlation in the error term, apply AR(1) prewhitening and allow for the variance of the residuals to be different across segments. The UDmax and WDmax test statistics are both significant at the 2.5 percent level and the BIC, LWZ and sequential procedures all find one break in 1048.

[32] In general, I use the second edition of the Encyclopedia although when an entry is not available in that edition but is available in the first or third edition (which is not complete) I use these alternatives. The exact encyclopedia entries used are available in an excel spread sheet that is available upon request.

Encyclopedia of Islam biography.[33] In figure 2, I provide the 50 year moving average of this proportion (marked madrasa) as well as the same moving average for the proportion of works on scientific topics.[34] The fitted values corresponding to the break in science are plotted and the vertical line marks 1071 (the break in the proportion of works for which madrasa is mentioned in the author's Encyclopedia of Islam entry).[35] In addition to the temporal proximity of the estimated breaks, the inverse relationship between the two moving averages is striking and shows that the decline in scientific output coincides with an increase in the proportion of authors affiliated with madrasas.

The Revival hypothesis also has implications for the geography of the decline. Scholars agree that madrasas —and the Revival institutional complex more broadly— spread across the Islamic world from east to west (Lapidus, 2014, p. 288). Although these institutions reached Egypt relatively quickly (by the early twelfth century), they did not reach Tunis (modern day Tunisia) until 1249, Fes (modern day Morocco) until 1271 and Islamic Iberia until 1349 (Shatzmiller, 1976, p. 115). This pattern provides an additional opportunity to investigate the extent to which the data are consistent with the Revival hypothesis.

To examine the geography of the decline in scientific activity, I further limit the sample to authors I was able to geo-reference who died on the interval [800,1500) and who were born inside the boundaries of the Islamic world as of 900 CE and run a regression of the form:

$$\%Science_{th} = \alpha + \gamma West + \sum_{h \geq 1100} \beta_h D_h + \sum_{h \geq 1100} \delta_h West \cdot D_h + \epsilon_{th} \tag{5}$$

where $\%Science_{th}$ denotes the proportion of intellectual output on scientific topics written by authors who died in year t and in hundred year bin h, the D_h are century dummies and West is a dummy equal to one if the author was born in the Western Islamic world.[36] In

[33] I code an author as associated with a madrasa if the words "madrasa", "medrese", "zāwiya", "tekke", "ribāṭ" or "k̲h̲ānḳāh" (upper or lower case) are mentioned in the biography.

[34] To calculate moving averages, for each year in the sample I regress the relevant proportion on a constant for the sample containing that year, the 25 previous years and the 24 future years and weight by the number of books.

[35] For the madrasa break, I use the same technical specifications as above. The UDmax and WDmax test statistics are both statistically significant at the 1% level. I present the one break selected by both the LWZ and sequential procedures although the BIC criteria selects two additional breaks in addition to the break in 1071.

[36] Due to data limitations, in these regressions I combine the Center and East regions into one Eastern region to gain statistical power. This strategy is also grounded in the historical record as following their emergence madrasas are

this "generalized differences-in-differences" specification, α is the proportion of works on science in the Golden Age in the non-Western Islamic regions, γ is the difference between this quantity in the West and that in the non-Western regions, the β_h are the change in the proportion of works on science relative to the Golden Age in the non-Western regions and the δ_h provide the differences-in-differences coefficients.

Point estimates from this specification are given in columns 3-6 of table 3. I begin in columns 1 and 2 by providing results from regression 3 on the restricted sample which I use to estimate equation 5. Column 1 shows that the proportion of works on scientific topics follows a similar trend to that in the entire sample, whereas column 2 documents the jump in the proportion of works written by authors affiliated with madrasas in the twelfth century. In columns 3 and 4, I examine how the decline in the proportion of works written on scientific topics varies geographically by examining the regression output from equation 5. Column 3 shows that during the Golden age 12% of intellectual output was on scientific topics in the Eastern Islamic world and that after 1100 CE this abruptly drops to 3%. Column 4 shows that the decline in the Western world came later. Indeed, the point estimates imply that in the twelfth century science represented 10% of output in Western regions and that this temporal difference in the decline of scientific output is statistically significant at the 10% level. Although the remaining differences-in-differences coefficients are not statistically significant, the point estimates suggest that the decline in scientific output did not begin in the West until the fourteenth century.

In column 5, I perform a similar exercise with the proportion of books written by authors affiliated with madrasas as the dependent variable. These regressions are a bit more powered and are consistent with the historical record that madrasas spread from East to West in the Islamic world. Thus, through the thirteenth century almost no authors were affiliated with madrasas in the West. This quantity begins to jump in the fourteenth century (the sum of the fourteenth century coefficients in columns 5 and 6 is statistically significant at the 10% level) and by the fifteenth century has reached levels comparable with those in the East.

In sum, although not always as highly powered as they would be in the ideal world, the

believed to have spread quickly across both the Center and Eastern Islamic regions.

regression results are broadly consistent with the geographic implications of the Revival hypothesis.

3.1 Mechanisms: the Revival, Religious Elites and Science

The Revival hypothesis can be schematically summarized as: $\uparrow$ Political Power of Religious Elites $\Rightarrow$ Institutional Changes $\Rightarrow$ $\downarrow$ Payoff to Production of Science $\Rightarrow$ $\downarrow$ Science. In this section, I focus on providing evidence in support of this causal sequence. Note, however, that I do not attempt to pinpoint the reasons behind the increase in political power of religious leaders during the Revival (although a few possibilities are discussed below).

Did the Revival coincide with an increase in the political power of religious elites? Throughout, I follow Acemoglu and Robinson (2006, p. 173) defining political power as "a measure of how influential a particular group (or individual) is in the political arena when there is conflict over which policy should be implemented" and further assume that religious leaders always desire to control a larger share of resources.[37] If one admits this definition and premise, then the institutional changes of the Revival suggest an increase in the political power of religious elites.

Prior to the Revival, religious leaders sustained themselves primarily through secular occupations (Gilbert, 1980, p. 118). The advent of madrasas changed this state of affairs and led religious leaders to exchange "nonprofessional status for full-time scholarly employment" (Gilbert, 1980, p. 126).[38] Rulers and private individuals funded madrasas through *waqf*s or Islamic trusts.[39] While the founder had considerable liberty over the activities supported by their endowment, the law of *waqf* stipulated that "there be nothing in the foundation that could be construed as inimical to the tenets of Islam." Religious leaders were the "sole judges of what was inimical" to Islam (Makdisi, 1981, p. 283) and presided over all *waqf* endowments (Hodgson, 1974, p. 124). Thus, the surge in *waqf* endowments during this period (Hodgson, 1974, p. 51) represents an increase in the share of resources under the

[37] Of course, I also assume that other groups will resist decreases in the share of resources that they control.

[38] As above, I continue to use the word madrasa as shorthand for the religiously oriented institutions that emerged during the Revival.

[39] See Kuran (2001) for an overview of the *waqf* in the Islamic world historically.

control of religious leaders, providing evidence for an increase in their political power.

To provide empirical support for the Revival hypothesis and the increase in political power of religious leaders, I turn to the data to perform several exercises. First, I examine the extent to which the data are consistent with the claim that religious elites gained social influence following the Revival. While this is difficult to measure, I generate the variable $\%Elit_{th}$ equal to the proportion of books written by authors that died in year t whose subject field contains the string "Muslim scholars" or "Ulama" (both of which are used to refer to Muslim religious leaders in the Harvard database). I do this because it is reasonable to expect more books to be written about religious leaders (e.g. biographies) as they gained societal influence. In column 1 of table 4, I present results obtained using estimating equation 3 with $\%Elit_t$ as the dependent variable. These results provide at least some support for an increase in the political power of religious leaders that roughly coincides with the decline in scientific output.

As religious leaders gained political power, they could have continued to support scientific research in madrasas or other *waqf* institutions had they desired. The available evidence, however, suggests that while some employed in madrasas continued to work on scientific topics, the sciences were "banished from the regular course of institutionalized education" under the law of *waqf* (Makdisi, 1981, p. 283). At the same time, institutions solely dedicated to the study of science disappeared in the twelfth century as resources shifted to religious leaders (Makdisi, 1981, p. 10).

The evidence suggests that religious elites used their increased influence to limit the study of science because they believed that the unrestricted study of science led to religious skepticism.[40] To prevent such skepticism, many religious leaders advocated restricting the study of science to individuals who could be trusted to not go astray (in practice, primarily religious elites themselves).[41] This desire to eradicate skepticism appears to have guided the

[40] Al-Ghazālī (1058-1111), one of Islam's most renowned religious leaders, provides an example of this view when noting that "he who studies mathematics is amazed by its precision and proofs. He then takes a more positive view of philosophy and reckons that all of the rational sciences are as clear and trustworthy as mathematics [...] and he says: if religion were true, then philosophers would have proved its veracity with their precise methods [...] we have seen many deviate from [Islam] in this manner" (al-Ghazālī, 1111 [1971], pp. 21-22).

[41] For example, al-Ghazālī notes that those who study sciences (in this case geometry and arithmetic often) "have gone beyond their study into innovations (i.e. non-orthodox beliefs) and thus the weak (in faith) should be barred from their

crafting of the post-Revival education system. Thus, in addition to limiting the study of science, this system is believed to have discouraged "questioning, verifying, criticizing, evaluating and making judgements" while encouraging "the uncritical acceptance of authority" (Halstead, 2004, p. 526). These institutional changes appear to have been successful in eliminating or suppressing religious skepticism, as after the emergence of madrasas "evidence for skepticism, relativism, and unbelief begin to peter out" (Crone, 2006, p. 33).

While I am unable to empirically measure the evolution of religious skepticism over time, here I use the data to examine the evolution of the proportion of works written on rationalist veins of Islam. In column 2 of table 4, I provide empirical evidence that rationalist interpretations of Islam lost influence in the centuries following the Revival. In this column, I provide point estimates from equation 3 with the proportion of books containing the string "Motazilites" in the subject matter as the dependent variable. The term Motazilites referred to Muslims who along with philosophers "emphasized the centrality of reason as an ordering principle in God's being, in the human understanding of the universe, and in the governing of human behavior" (Lapidus, 2014, p. 245). The point estimates are all negative and often statistically significant. If rationalist interpretations of Islam were a source of religious skepticism, this decline in rationalism provides some evidence for a post-Revival decline in skepticism, and also evidence of a decline in the scholarly expression of rationalism.

As mentioned above, the Revival hypothesis also implies that after the rise of madrasas, authors working on scientific topics were primarily religious elites. To examine the extent to which authors working on science were more religiously-oriented after the Revival, I limit the sample to individuals who wrote at least one book on a scientific topic and estimate regression 3 with the proportion of scientific and Revival-related religious works as the dependent variable.[42] The results, presented in columns 3 and 4 of table 4 are broadly consistent with the claim that the works of scientists were more oriented towards religious

study like the boy is barred from the bank of the river so that he does not fall in" (al-Ghazālī, 1111 [2005], p. 31). Sabra (1987, p. 237) notes that after the Revival, scientists "were imbued with Muslim learning and tradition."

[42]It is straightforward to show that these coefficients are in general different in magnitude (and perhaps even in sign) from those obtained using the entire sample. To see this, note that (using identical notation to that used above) $E[s_i|h] - E[s_i|t < 1100] = (E[s_i|h; s_i > 0] - E[s_i|t < 1100; s_i > 0])Pr(s_i > 0|h) + (Pr(s_i > 0|h) - Pr(s_i > 0|t < 1100))E[s_i|t < 1100; s_i > 0]$.

topics after the Revival. In other words, this result is consistent with claims by historians that the most productive scientists after the Revival were "all religious men [..that] held official religious positions" and "wrote extensively on religious subjects" (Saliba, 2007, p. 243).[43]

In further empirical support of the Revival hypothesis, I use Khalifa's dataset to determine whether scientific works were more difficult to access than other scholarly works in seventeenth century Istanbul. To do this, I create an index of "undercitation" ($UnCit_i$) which is the number of books Khalifa lists for an author minus the number of books Harvard holds for that author.[44] I then examine the extent to which Khalifa is underciting scientists by estimating the regression:

$$UnCit_i = \gamma_h D_h + \sum_h \beta_h D_h \cdot Scientist_i + \epsilon_i \tag{6}$$

where i indexes authors. Column 5 presents estimates of the β_h or the differences in the mean of UnCit between scientists and non-scientists by century.[45] In the row labeled p-value I provide the p-value corresponding to the null hypothesis that the β_h are jointly equal to zero. These results show that Khalifa included fewer books written by scientists and are consistent with the hypothesis that it was more difficult to access works written by authors on scientific topics in seventeenth century Istanbul.[46]

As a final empirical test of the Revival hypothesis, I investigate whether madrasas encouraged the production of religious knowledge at the expense of scientific research. To do so, I regress the share of works written on religious and scientific topics on an indicator variable equal to one if the author was affiliated with a madrasa. Authors affiliated with madrasas

[43]Although Saliba (2007, p. 243) uses this fact to argue that there was no conflict between science and religion, he fails to note how the fact that these elites "wrote extensively on religious subjects" would have worked to crowd out scientific research. In addition, he does not address the possibility, raised in this paper, that science was limited to religious elites precisely because they could be trusted not to lapse into rationalistic interpretations of Islam and skepticism.

[44]I use the Harvard data set as the baseline and match the Khalifa data by author name. In other words, the sample size is determined by the Harvard data set. In addition, I assign the value zero to the Khalifa data for Harvard authors that I could not match.

[45]I define scientists as authors who have at least one work on a scientific topic in a Harvard library. In addition, in this regression, I cluster standard errors by the author's year of death.

[46]An alternative explanation is that Khalifa's personal preferences led him to systematically undercite scientists. The fact that Khalifa seems to be attempting to provide a comprehensive overview of intellectual production as well as the fact that he includes a significant number of books on scientific topics weighs against this hypothesis.

dedicated 13 percentage points more of their intellectual output to Revival-related religious topics (from a base of 0.15, the standard error is 0.04) and this jump is 11 percentage points when century dummies are included (standard error of 0.04).[47] The results for the proportion of books on scientific topics move in the opposite direction. Thus, authors affiliated with madrasas dedicate 5 percentage points less of their intellectual output to scientific output (from a base of 0.10 percent, the standard error is 0.02) and this drop is 3 percentage points when century dummies are included (standard error of 0.02).[48] In general, then, these correlations are consistent with the claim that madrasas encouraged the production of intellectual works on religious topics at the expense of scientific ones.

3.1.1 What Caused the Revival?

While it is beyond the scope of this paper to convincingly pinpoint its causes, in this section I discuss the relevance of some of the most plausible explanations for the Revival. It is important to note, however, that I view this discussion as exploratory in light of both data limitations and the relatively underdeveloped state of scholarship on this period of Islamic history (e.g. Safi, 2006, p. 35).

A first explanation attributes the Revival —and the surge in the political power of religious leaders— to an increase in religiosity due to climatic shocks or military shocks. This interpretation posits that religious leaders responded to popular demand for traditionalism when establishing madrasas and limiting scientific production. A geographically differentiated climatic shock large enough to explain the patterns in the data would presumably leave a trace in the evolution of the birthplace of authors during the twelfth century. For example, Bulliet (2009, p. 136) argues that an economic crisis in eleventh-century Iran led to an economic decline which manifested itself, among other things, in a migration of scholars westward.[49] Yet, results in table 2 show that there is little evidence in support of

[47]In these regressions (which are run at the author level) I cluster standard errors by death year.

[48]It is worth noting that the Revival hypothesis implies that after the Revival institutions solely dedicated to the study of the sciences disappeared, which may help explain why the science results with century dummies are not statistically significant. In other words, after the Revival there was a decline in science, but science to the extent that it was produced was as likely to be produced in madrasas as in other locations.

[49]It is worth noting, however, that this is a minority view among historians who in general do not see "a major break in the general continuity of rural prosperity" during this period (Lambton, 1973, p. 116).

this prediction as the drop in the proportion of authors born in the Eastern Islamic world does not become statistically significant until the thirteenth century.

Some have attributed the Revival to a surge in religiosity driven by the start of the Crusades, which may have pushed the inhabitants of the lands most affected by this military shock towards "a less tolerant version of Islam" (Gutas, 1998, pp. 170-171). While the timing of the drop in scientific output roughly corresponds to this military shock, the geography does not. Thus, the twelfth-century decline is primarily driven by the regions east of Baghdad.[50] It seems somewhat unlikely that the beliefs of those in the Eastern Islamic world were affected by military shocks that never directly threatened them. The conclusion that military shocks are insufficient to explain the decline is also supported by the experience of the Western Islamic world. Although this region was also subject to significant military pressures from Christian polities during this period (e.g. Islamic Iberia) it did not witness a decline in scientific production. In any case, explanations attributing the decline of scientific output to an increase in religiosity while holding the proportion of Muslim population constant would require any surge in religiosity to continue unabated for centuries. This seems unlikely, although it is impossible to completely rule out the role increased religiosity might have played in the initial surge in the political power of religious leaders which may have then been institutionalized and thus perpetuated over the centuries.

A related explanation highlights the importance of increases in demand for religious services, perhaps due to an increase in the proportion of the population adhering to Islam during the Revival. Such an increase could have led to the emergence of madrasas, the services provided by religious elites and a decline in the proportion of works on scientific topics. However, such an increase would presumably also be reflected in a jump in the proportion of intellectual output dedicated to religious topics beyond those incentivized in madrasas. To proxy for this proportion I generate the variable $\%ORel$, which is the proportion of books containing the strings "God", "Islam", "Muhammad", "Prayer" or "Quran." Results with this proportion as the dependent variable are reported in column 6 of table 4 and show no clear pattern in the evolution of the proportion of books on religious topics in the

[50]This can easily be seen by noting that in table 2 the eastern region is dominant through the twelfth century.

centuries after the Revival. In other words, while Revival-related religious works did go up, as would be expected as religious leaders gained political power, the proportion of general works on religion that might reflect an increase in popular demand for religious topics did not increase.

A third explanation argues that an increase in the popularity of mystical Islam —not the political empowerment of religious leaders— was the most consequential aspect of the Revival. Thus, for generations scholars have argued that mystical interpretations of Islam (Sufism) gained popularity during this period and that the rise of such interpretations can help explain the decline in scientific output (e.g. Dallal, 2010, p. 154). In column 7 of table 4, I provide evidence that is consistent with this view in the sense that the proportion of works on mysticism increases in the twelfth century. Yet recent scholarship increasingly links the rise of Sufism to the institutional changes of the Revival, suggesting that the surge in Sufism after the Revival should be viewed as a downstream outcome of the political empowerment of traditionalist religious leaders rather than as an independent event.[51] For example, Crone (2006, p. 37) suggests that mystical interpretations of Islam were pushed by religious elites to prevent "reason from running wild in skepticism" and played an instrumental role in keeping the use of reason firmly in support of Islam after the Revival. Indeed, the rise of Sufism seems linked to the emergence of a new 'orthodoxy' that incorporated mysticism following the Revival (Lapidus, 2014, p. 237).[52] Such scholarship argues that the rise of Sufism may have been an effect of the empowerment of traditionalist religious leaders after the Revival.

A fourth explanation stresses the top-down actions of the Turkish tribes (Seljuks) that spread across much of the Eastern Islamic world in the twelfth century in generating the Revival. While historians of the period now generally agree that the Revival "occurred

[51]While historically many scholars viewed traditionalist interpretations of Islam and mysticism as being at odds prior to the Revival, more recent scholarship has highlighted the link between traditionalist religious leaders and mysticism (e.g. Makdisi, 1973, p. 161).

[52]Many have claimed that the religious thinker al-Ghazālī (1058-1111) single-handedly created this new ideology and dealt a death-blow to scientific inquiry through his writings. Although Ghazālī was undoubtedly an influential figure, I argue that the success of his teachings are ultimately a product of the Revival. In other words, I suggest that Ghazālī should be viewed as a kind of "cultural entrepreneur," generating an ideology for which there was latent demand (I thank Joel Mokyr for suggesting this phrase).

independent of the Seljuks" (Ephrat, 2000, p. 2), it is impossible to completely rule out this hypothesis due to data limitations. However, the eventual spread of Revival institutions from east to west cast some doubt on the Seljuk hypothesis as Turkish rule did not reach the Western Islamic world in the medieval period.

A final view attributes the Revival to the culmination of bottom-up historical processes within Islamic societies over the previous centuries. While scholars differ regarding the exact nature of these processes, there is broad agreement that the Revival coincided with the militarization of the governing power, the contraction of pre-Islamic governmental structures (e.g. the secular bureaucracy) and the emergence of Muslim religious leaders as the primary representatives of civil society and providers of public goods (e.g. Lapidus, 2014, p. 224). Although this view implies that the political power of religious leaders increased during this period, it also suggests that their empowerment should be viewed as a proximate cause of the decline in scientific output.[53]

While this hypothesis is not sufficiently developed to be convincingly tested from an empirical standpoint, column 8 of table 4 provides some preliminary empirical evidence in its support. In this column, the dependent variable is the proportion of books written by authors that Khalifa identifies as belonging to the secular bureaucracy (i.e. those identified as a secretary or *kātib*). Results show that after the Golden Age fewer books were written by authors identified as belonging to this bureaucracy. To the extent to which this result is indicative of a weakening of the secular bureaucracy, it suggests that future research investigating this political process may further our understanding of the timing of the Revival.

Regardless of Revival's fundamental cause(s), the data and the historical evidence all support the claim that religious were empowered during this period and that the actions of these religious leaders contributed to the observed decline in scientific output.

[53]Recent research suggests that the introduction of slave soldiers across the Islamic world centuries earlier may have led to a gradual weakening of pre-Islamic state structures (Blaydes and Chaney, 2013, 2016). This process, combined with conversion to Islam, would have eventually led to both the emergence of religious leaders as the primary representatives of civil society and the militarization of government. In this view, the abrupt institutional changes under the Seljuks should be seen as the product of the fact that the Shi'i dynasties that preceded the Seljuks across much of the Islamic world found it difficult (perhaps due to ideological constraints) to implement these changes earlier and more gradually.

4 Conclusion

While the Islamic world stood at the vanguard of scientific and technological production during the medieval period, today it produces a disproportionately small share of world scientific output. This paper contributes to our understanding of this reversal by providing the first large-scale empirical investigation of the evolution of scientific output in the Islamic world over a millennium. The empirical patterns suggest that a surge in the political power of religious leaders in the mid/late eleventh century CE caused a decline in scientific production and the patterns cast doubt on the most prominent alternative explanations for the decline.

I hypothesize that these newly empowered religious leaders worked to limit the study of scientific topics because they believed that the unrestricted study of science led Muslims to both embrace rationalistic interpretations of Islam and to disregard their teachings. Thus, religious leaders altered the institutional framework in order to develop an education system that both discouraged scientific research and rewarded obedience to authority. I provide empirical evidence consistent with this motive and argue that the evidence suggests that religious elites, like any elite, will rent-seek unless otherwise constrained.

While the causes of the surge in the influence of religious leaders remain a topic for future research, the available evidence suggests that this increase in political power may have been part of the emergence of a broader institutional framework in which religious leaders had a larger degree of influence over civil society than they possessed in the pre-Revival period.

Finally, the analysis in the paper suggests important interactions between institutions, religious beliefs and human capital that seem fruitful areas for future research. During the Golden Age, many Muslims adhered to an interpretation of Islam based on reason which has been viewed as a precursor to the 'natural religion' espoused by some Enlightenment thinkers (e.g. Dupré, 1999, p. 2). Such interpretations seem to have lost favor after the Revival. I have provided some preliminary evidence that religious leaders discouraged these rationalistic interpretations and worked to define a new 'orthodoxy' emphasizing obedience to authority, mysticism and faith. This evidence suggests that religious leaders preferred this new interpretation because it enhanced their societal influence.

The existing literature suggests that Europe's unique political equilibrium generated more enduring constraints on European religious elites than that in the Islamic world after the Golden Age (Ben-David, 1965; Mokyr, 1994; Landes, 1998, p. 52). While examining the extent to which this is true remains a topic for future work, recent research (Blaydes and Chaney, 2013; Chaney, 2012, 2013; Blaydes and Chaney, 2016) suggests that a deeper understanding of these political developments may shed light on the reasons behind the abnormal rates of human capital accumulation in Europe in the run-up to the Industrial Revolution.

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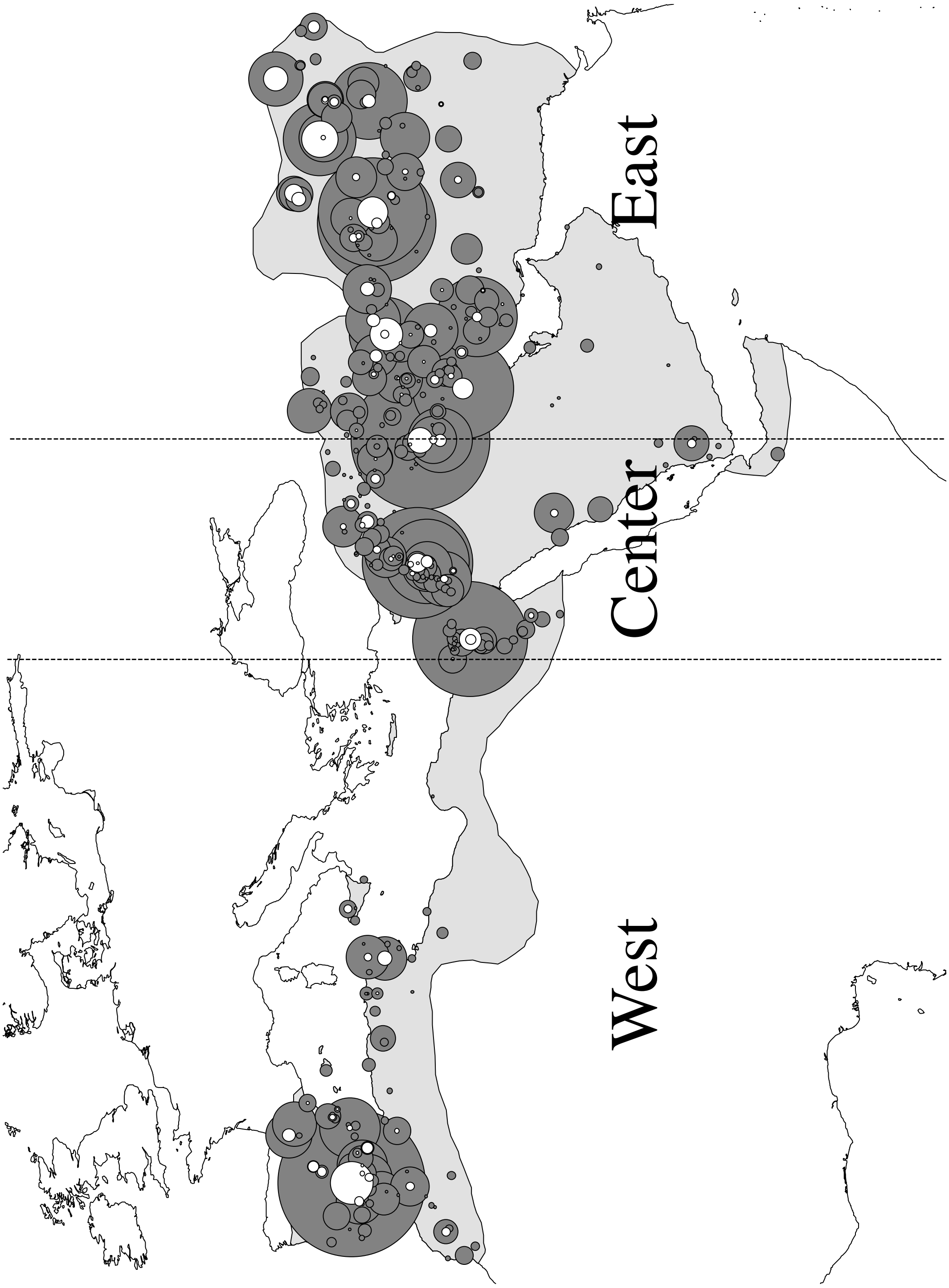

Figure 1: **Centers of Intellectual Production Prior to 1500 CE**
Larger circles denote more books written by authors born in location, white circles denote scientific works

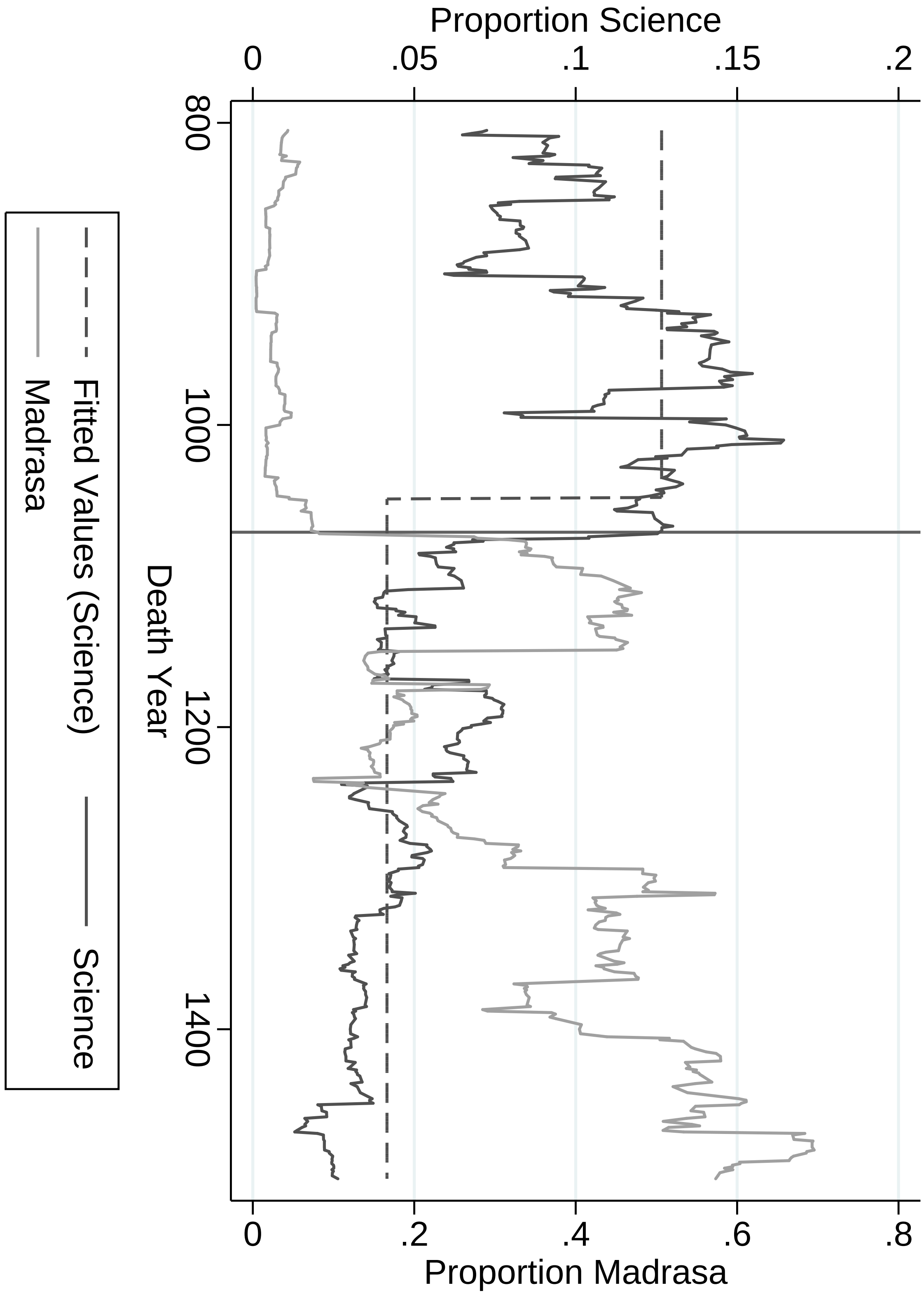

Figure 2: **Madrasas and the Fall of Islamic Science 800-1500**
50-year moving average, solid vertical line denotes break in madrasas.

Table 1: **The Decline of Scientific Production in the Islamic World: 800-1800 CE**

	Relative to Average on the Interval [800, 1100)*								
	%Sci	%Rel	%Com	%Com2	Books	Books2	Authors	%NoPlace	%NoSub
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
[1100, 1200)	-4.58**	10.18***	3.78*	5.58***	2.14	-0.21	0.51	0.43	4.53
	(2.25)	(3.04)	(1.98)	(2.02)	(5.24)	(1.39)	(0.72)	(4.67)	(7.23)
[1200, 1300)	-4.51**	15.19***	1.51	15.14***	14.55	1.04	1.48**	-1.21	1.31
	(2.02)	(3.58)	(1.05)	(2.34)	(9.49)	(1.86)	(0.66)	(4.45)	(3.18)
[1300, 1400)	-6.28***	11.73***	5.21***	24.10***	9.73	0.15	1.49**	4.45	-2.15
	(1.81)	(3.17)	(1.75)	(2.08)	(6.66)	(1.04)	(0.75)	(4.50)	(2.81)
[1400, 1500)	-5.61***	11.25***	2.60**	29.21***	-3.49	-2.03***	1.14	10.50**	1.77
	(1.88)	(3.65)	(1.27)	(2.16)	(3.77)	(0.68)	(0.95)	(4.10)	(3.00)
[1500, 1600)	-6.47***	11.27**	2.85***		-4.10	-2.27*	1.30	12.74***	4.71
	(1.89)	(4.70)	(0.93)		(5.49)	(1.17)	(0.89)	(4.51)	(3.21)
[1600, 1700)	-6.21***	9.62***	4.20***		-6.59**	-3.42***	2.66**	11.87***	9.63***
	(1.80)	(2.73)	(1.45)		(2.79)	(0.62)	(1.11)	(4.34)	(2.86)
[1700, 1800)	-7.61***	8.90***	5.34**		-7.62***	-3.72***	3.07***	16.02***	9.60***
	(1.83)	(2.62)	(2.50)		(2.69)	(0.53)	(0.86)	(3.98)	(2.91)
[800, 1100)	9.68***	13.08***	4.20***	12.95***	23.70***	6.01***	3.94***	34.31***	26.57***
	(1.73)	(1.51)	(0.67)	(1.20)	(2.22)	(0.47)	(0.33)	(2.06)	(1.51)
N	942	942	942	571	942	942	942	942	964

Notes: *results obtained from the Harvard sample are all calculated on the sample [800,1800). Those in column 4 are from the Khalifa dataset which uses the sample covering [900, 1500) and thus in this sample the omitted period is [900,1100) rather than [800,1100). The dependent variable in column 1 is the proportion of books written on science, that in column 2 is the proportion on religion, that in columns 3 and 4 is the proportion of "derivative" books, in column 5 the number of books, in column 6 the number of books per author, in column 7 the number of authors, in column 8 the proportion of books with no identified place of birth of author and in column 9 the proportion with no subject. Regressions in columns 1-3, 5-8 are estimated on the sample of books with an identified subject whereas the regressions in columns 4 and 9 are estimated on the entire sample. The regressions in columns 1,2,3 and 8 are weighted by the total number of books with an identified subject in each year. The regressions in column 5 and 7 are not weighted, whereas that in column 6 is weighted by the total number of authors. Regressions 4 and 9 is weighted by the total number of books written by authors who died in that year. Newey-West standard errors allowing for the error structure to be heteroskedastic and autocorrelated up to seven lags are presented in parentheses. ***, **and *indicate significance at the 1%, 5% and 10% levels.

Table 2: **Location of Intellectual Production: 800-1500**

	Relative to Average on the Interval [800, 1100)*					
	Harvard			Khalifa		
	East	Center	West	East	Center	West
	(1)	(2)	(3)	(4)	(5)	(6)
[1100, 1200)	-15.07	-4.02	19.09	-6.85	-0.08	6.93
	(12.50)	(4.78)	(11.93)	(8.11)	(5.88)	(5.12)
[1200, 1300)	-30.86***	10.88	19.98	-27.48***	19.47***	8.02
	(8.51)	(9.80)	(12.36)	(6.99)	(5.60)	(5.40)
[1300, 1400)	-34.41***	39.31***	-4.90	-41.34***	39.62***	1.72
	(11.37)	(12.81)	(6.12)	(6.13)	(6.37)	(3.93)
[1400, 1500)	-30.31**	27.39**	2.91	-40.68***	49.53***	-8.85***
	(14.49)	(13.45)	(8.95)	(7.69)	(7.49)	(2.49)
[800, 1100)	73.18***	12.67***	14.15***	70.61***	17.45***	11.95***
	(5.46)	(3.06)	(4.78)	(3.76)	(3.30)	(2.30)
N	554	554	554	590	590	590

Notes: *results obtained from the Harvard sample are calculated on the sample [800,1500). Those in columns 4-6, are from the Khalifa dataset which uses the sample covering [900, 1500) and thus in this sample the omitted period is [900,1100) rather than [800,1100). The dependent variable is the proportion of books written by authors born in each geographic region as denoted above each regression. All regressions are limited to books whose authors were born within the boundaries of the Islamic world in 900 CE and are weighted by the number of books written by authors who died in a given year. Newey-West standard errors allowing for the error structure to be heteroskedastic and autocorrelated up to seven lags are presented in parentheses. ***, **and *indicate significance at the 1%, 5% and 10% levels.

Table 3: **Geographic Variation in the Decline of Scientific Output and the Rise of Madrasas: [800-1500)**

	Relative to Average on the Interval [800, 1100)					
	%Sci	%Mad	%Science		%Madrasa	
			East	Dif.	East	Dif.
	(1)	(2)	(3)	(4)	(5)	(6)
[1100, 1200)	-6.19**	32.50*	-9.39***	10.18*	52.74**	-52.66**
	(2.89)	(18.58)	(2.56)	(6.08)	(21.42)	(21.44)
[1200, 1300)	-5.83**	15.96**	-7.54***	5.63	27.54***	-24.73**
	(2.57)	(6.97)	(2.76)	(5.62)	(10.20)	(10.93)
[1300, 1400)	-8.46***	39.89***	-8.87***	2.88	43.23***	-30.41*
	(2.29)	(13.27)	(2.56)	(5.54)	(14.84)	(16.39)
[1400, 1500)	-8.37***	52.70***	-8.46**	1.34	48.51***	18.64
	(2.72)	(12.33)	(3.41)	(5.78)	(17.40)	(21.01)
[800, 1100)	11.42***	4.55***	11.79***	-2.46	5.18**	-4.19*
	(2.24)	(1.76)	(2.51)	(5.24)	(2.22)	(2.37)
N	455	455	546	546	546	546

Notes: the dependent variable in column 1 is the proportion of books written on science, that in column 2 is the proportion of books written by authors affiliated with madrasas. Columns 3 and 4 provide regression output from a regression of the form: $\%Science_{th} = \alpha + \gamma West + \sum_{h \geq 1100} \beta_h D_h + \sum_{h \geq 1100} \delta_h West \cdot D_h + \epsilon_{th}$. Column 3 provides estimates of the β_h whereas the row labeled [800, 1100) provides the estimate of α. Column 4 provides estimates of the δ_h whereas the row labeled [800, 1100) provides the estimate of γ. The results in columns 5 and 6 present the results in an identical manner using the proportion of works written by authors affiliated with madrasas as the dependent variable. All regressions are limited to books whose authors were born within the boundaries of the Islamic world in 900 CE and have an entry in the Encyclopedia of Islam. Newey-West standard errors allowing for the error structure to be heteroskedastic and autocorrelated up to seven lags are presented in parentheses. ***, **and *indicate significance at the 1%, 5% and 10% levels.

Table 4: **Mechanisms**

	%Elit	%Mot	%Sci	%Rel	UnCit	%ORel	%Sufi	%Sec
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$[900, 1000)$					-7.90**			
					(3.18)			
$[1000, 1100)$					-13.80**			
					(6.82)			
$[1100, 1200)$	0.99**	-0.40	-12.00	9.89*	-36.93*	9.73	7.30**	-6.08*
	(0.45)	(0.31)	(7.75)	(5.18)	(20.19)	(8.46)	(2.98)	(3.67)
$[1200, 1300)$	0.46	-0.62**	-13.29**	16.81**	-29.95*	-3.89	10.33**	-4.99
	(0.31)	(0.27)	(5.26)	(7.05)	(16.61)	(4.95)	(5.23)	(3.46)
$[1300, 1400)$	1.26***	-0.49*	-16.60***	10.53**	-24.69*	16.85***	3.86**	-6.48**
	(0.43)	(0.28)	(5.20)	(5.23)	(12.97)	(5.14)	(1.93)	(3.20)
$[1400, 1500)$	1.84***	-0.39	-9.70*	4.02	-8.52	2.90	6.09*	-7.56**
	(0.45)	(0.32)	(5.52)	(4.50)	(5.28)	(3.31)	(3.16)	(3.13)
$[800, 1100)$	0.54***	0.65**	25.19***	9.90		34.73***	3.45***	9.07***
	(0.13)	(0.27)	(4.71)	(2.82)		(1.89)	(0.79)	(3.01)
p-value					[0.00]			
N	650	650	249	249	2386	650	650	412

Notes: the dependent variable in column 1 is the proportion of books written on religious leaders, that in column 2 is the proportion on rationalistic interpretations of Islam, that in column 3 the proportion of books on science, in column 4 the proportion of books on Revival-related religious topics, that in column 5 a proxy for undercitation, in column 6 the proportion of "other" religious works, in column 7 the proportion of works on Sufism and in column 8 the proportion of works written by authors who were members of what I refer to as the "secular bureaucracy." As results in columns 5 and 8 rely on the Khalifa sample they are estimated on the interval [900, 1500), whereas the remainder of the coefficients are estimated on the [800, 1500) sample. Columns 3 and 4 are restricted to authors who wrote at least one work on a scientific topic. Newey-West standard errors allowing for the error structure to be heteroskedastic and autocorrelated up to seven lags are presented in parentheses aside from those in column 5 where the standard errors are clustered by the author's death year. The row p-value provides the p-value for the test that the coefficients in the column are jointly equal to zero. ***, **and *indicate significance at the 1%, 5% and 10% levels.