

Time series of scientific growth in Spanish doctoral theses (1848–2009)

Antonio Fernández-Cano · Manuel Torralbo · Mónica Vallejo

Received: 4 June 2011 / Published online: 15 December 2011
© Akadémiai Kiadó, Budapest, Hungary 2011

Abstract This article analyses scientific growth time series using data for Spanish doctoral theses from 1848 to 2009, retrieved from national databases and an in-depth archive search. Data are classified into subseries by historical periods. The analytical techniques employed range from visual analysis of deterministic graphs to curve-fitting with exponential smoothing and Autoregressive Integrated Moving Average models. Forecasts are made using the best model. The main finding is that Spanish output of doctoral theses appears to fit a quasi-logistic growth model in line with Price's predictions. An additional control variable termed year-on-year General Welfare is shown to modulate scientific growth, especially in the historical period from 1899 to 1939.

Keywords Time series · Scientific growth · Doctoral theses · Exponential smoothing · ARIMA models · Spain · Modulatory variable

Introduction

There is a long-standing debate in scientometrics regarding the value of scientific growth models and indicators. Indicators of scientific growth are numerous, including number of articles published, citations, research centres, journals, expenditure, scientists and doctoral

A. Fernández-Cano (✉)
Department of Research Methods in Education, University of Granada,
Campus de Cartuja, Granada 18071, Spain
e-mail: afcano@ugr.es

M. Torralbo
Department of Mathematics, University of Córdoba,
Calle Alfonso XIII, 13, Córdoba 14071, Spain
e-mail: ma1torom@uco.es

M. Vallejo
Department of Didactics, University of Murcia,
Campus de Espinardo, Murcia 28071, Spain
e-mail: monicavr@um.es

dissertations or theses. A long list of scientometric indicators relating to the Spanish educational research system is included in a study by Fernández-Cano and Bueno (1999); most take their lead from de Solla Price's seminal work (1978). Further indicators continue to emerge, some of very recent vintage. Examples include Moed's (2010) source-normalized impact per paper (SNIP); the multidimensional-metric approach combining qualitative and quantitative methods (Schmoch et al. 2010); the multidimensional non-radial data envelopment analysis (DEA) model and a nonradial Malmquist index put forward by Guan and Chen (2010); and robust nonparametric methods in efficiency analysis used by Bonaccorsi et al. (2006).

The debate on indicators has been matched by a parallel debate regarding scientific growth models based on seminal studies by de Solla Price (1961, 1986). Fernández-Cano et al. (2004) carried out an integrative review using retrieved empirical studies which revealed the complexity and diversity of models of scientific growth and the absence of consistent patterns.

Analysis of scientific growth models based on R&D input and output data has continued. Huang, Varum and Gouveia (2006) measured the scientific productivity of China's S&T institutes using a polynomial distributed lag model. Sharma and Thomas (2008) examined the relative efficiency of the R&D process across a group of 22 countries using constant returns to scale (CRS). Tseng et al. (2009) used several trend indexes for time series with a view to detecting hot topics of research. Szydłowski and Krawiec (2009) analysed a series of 2,000 papers on symbolic logic published between 1666 and 1934, observing an overall exponential pattern, together with a number of oscillations prompted by the emergence of new ideas, and exogenous fluctuations due to wars and other non-scientific events. Other studies have focused on growth patterns in particular disciplines: Celeste et al. (2011) analysed trends for topics relating to the social determinants of health, obtained from a search of the PubMed database covering the period 1985–2007. Casson and Al-Qureshi (2010) examined the growth of ophthalmological research.

The debate surrounding scientific growth, and specifically scientific knowledge, has taken place not only within scientometrics—from a quantitative standpoint—but also within the history and philosophy of science, in the more qualitative sense (Munz 1985; Popper 1963; Sterman 1985; Lakatos and Musgrove 1970); in fact, these approaches, both the metric and the historico-philosophical, should be viewed as complementary rather than mutually exclusive, although efforts to bring them together remain a work in progress.

Modulatory theories of scientific growth

Discussion of scientific growth is important because it enables us to describe, explain and even monitor the progress of science. Over time, the discussion triggered initially by de Solla Price's model (1986) has grown richer and more complex. de Solla Price (1986) designed an endogenous bivariate model that plotted growth against time; this somewhat reductionist approach has gradually become more sophisticated, through the introduction of an increasing number of explanatory variables—both endogenous and exogenous—which serve to fine-tune, explain and shape the model (see Braun and Schubert 1988; Szydłowski and Krawiec 2001; Shelton 2008). With the inclusion of explanatory variables that might influence, regulate and even, to some extent, manipulate a research system, de Solla Price's underlying static model—overparsimonious and over-deterministic—is rendered at once richer and more dynamic. For the inexorable, fateful, onward March of time is not the only factor shaping patterns and cycles of scientific growth; nor are the linear, exponential and logistical cycles of de Solla Price's model (1986) as rigid as Giambattista Vico's *ricorsi* (2005) of three ages: the divine-mythological, the heroic, and the human.

Szydłowski and Krawiec (2001) examine two contrasting modulatory theories of scientific growth: the economicist view that science is the work of a special kind of economic sector, versus the personalist view that the progress of knowledge is the work of extraordinary talented individuals.

Indeed, two major modulatory macrotheories of scientific growth can be discerned: one focussing on endogenous factors (e.g. the personalist approach, the approach based on sometimes-spurious publication practices) and the other focussing on exogenous factors (imperatives of the “publish or die” kind; the introduction of accountability-based evaluation systems; or the purely economicist approach taking into account both human resources and economic resources). As Szydłowski and Krawiec (2001) rightly noted, we do not yet know to what extent the exogenous factors may dominate.

For that reason there is a need for studies like this one, which explore the relevance of new factors. A major failing of research conducted hitherto into the factors governing scientific growth has been its somewhat pretentious claim to establish causality (“if factor *X*, then growth *Y*”) using correlation and regression models. We would do well to remember that: “correlation does not imply causation”. In order to establish well-grounded evidence of causality, scientometrics needs to complete the loop: description-explanation-experimentation-metaanalytical integration. But since pure experimentation is extremely difficult in scientometrics, we are obliged to make use of quasi-experimental intra-group methods (Osuna et al. 2011) or predictive research like the present study, with an *ex post facto* design supported by powerful analytical techniques such as the Autoregressive Integrated Moving Average (ARIMA) model, widely used in econometrics but largely ignored in scientometrics; Vasileiadou (2009) has used this method to investigate the dynamics of research collaboration.

The question of method is by no means irrelevant in the sciences. While new methods enable a discipline to progress, we should not be tempted into methodolatry; some of the greatest aberrations have been perpetrated by researchers using an “imposing” method.

Doctoral theses as an indicator of scientific growth

Notwithstanding the many variations and senses attaching to the term, which vary from country to country, there appears to be a general consensus that a doctoral thesis is a report on an original piece of research which, once approved, bestows upon its author the academic distinction of a doctorate.

Doctoral theses represent a channel for scientific and academic expression both for novice researchers and for the research community to which they belong; for the new researcher, they constitute a rite of passage governed by a scientific *ethos*, which paves the way to a scientific career and at the same time confers social legitimacy (Ben-David 1991). The production of a doctoral thesis brings together the three core functions of a university: tuition through mentoring and supervision, research by the doctoral student, and management of the resulting information.

Doctoral dissertations or theses—these terms will be used interchangeably—also constitute a rich and valuable source of data reflecting the achievements of a whole scientific discipline, of a national research system and of individual researchers (i.e. the author and the supervisor of the thesis); as such, doctoral theses constitute a scientometric indicator. Until now, these have taken the form of a written account of research, ostensibly original and unpublished and of varying scientific quality, requiring the approval of acknowledged specialists in the field, but rarely published in its entirety; collectively, they make up that vast miscellany commonly labelled “grey literature”.

It would be wrong to treat doctoral theses as an exemplary scientific indicator; yet nor should their value as a scientific and scientometric phenomenon be underestimated. While one might question the rationale of using them as a measure of scientific growth, an increasing number of scientometric studies have taken the doctoral thesis as their basic unit of analysis and as a valuable indicator of scientific output. Liang et al. (2004) studied name-order patterns of graduate candidates and supervisors in Chinese publications. Schmoch et al. (2010) drew particular attention to the importance of sufficient numbers of PhD graduates and of their contribution to the infrastructure of the scientific community. The declining impact of Belgian theses as a source of scientific information was investigated by Lariviere et al. (2008). Chang et al. (2010) studied 2,089 degree theses from all of the 20 social work and social policy institutes in Taiwan. Chen et al. (2011) analysed a tiny sample of 383 studies published between 2000 and 2009 on Taiwan's National Health Insurance.

Analysis of the growth of doctoral theses in a well-defined national research system may prove revealing, especially since it has not hitherto been investigated. The potential benefits of such a study are twofold: first, it highlights scientific, educational and cultural activity; second, it serves to verify the extent to which the output of doctoral theses in a national research system fits scientific growth models.

The aim is to gather evidence which will provide a firmer footing for disciplines, universities and national research systems as a whole, by recognising their achievements, their efforts, the general state of research in the country over a given historical period and the growth and development of a discipline within a specific context.

Research questions and their rationality

It should be noted that the research questions proposed follow to some extent the pattern of scientific method: description (through the provision of numerical and graphical data and a priori categorization of the cycle-based description) followed by explanation (model fitting, forecasting, relevance of an exogenous explanatory variable and relevant features of the underlying model). Clearly, these questions are primarily of theoretical, academic, literature-related interest; their immediate practical implications are few. The drafting of rules and policies for the development, monitoring and modulation of scientific growth lies beyond the power of the present researchers.

In this study, concretely, research sought to carry out and verify the following tasks:

- A graphic and numerical quantitative description of the time series of doctoral theses submitted in Spanish universities over the 1848–2009 period. Table 1, containing numerical data, is included in the next section.
- Division and description of the time series into partial subseries according to well-defined historical criteria.
- Selection of the best-fitting model (exponential smoothing or ARIMA) underlying each time series to account for past values.
- Computation of forecasts for a future 7-year interval (2010–2016) using the complete time series (1848–2009), the partial historical series (1976–2009) and a recent series (1989–2009), according to the best-fitting model.
- Significance of a dichotomous dummy covariate (general welfare) as a predictor for both the general and partial time series.
- Identification of the breakpoint-years in the series.

Table 1 Data related to the variables: date, number of theses and dummy variable (general welfare)

	0	1	2	3	4	5	6	7	8	9
184#									2 (1)	2 (1)
185#	16 (2)	16 (2)	14 (2)	34 (12)	13 (1)	5 (1)	10 (2)	3 (2)	13 (2)	18 (1)
186#	33 (1)	13 (12)	13 (2)	24 (2)	45 (2)	46 (2)	45 (2)	19 (2)	65 (1)	8 (1)
187#	13 (1)	16 (1)	30 (1)	30 (1)	25 (1)	34 (1)	40 (1)	97 (1)	159 (1)	138 (2)
188#	144 (2)	156 (2)	162 (2)	143 (2)	115 (2)	81 (2)	83 (2)	37 (2)	66 (2)	60 (2)
189#	48 (2)	49 (1)	54 (1)	63 (2)	52 (2)	43 (2)	56 (2)	66 (2)	90 (2)	72 (1)
190#	93 (2)	138 (2)	135 (2)	156 (2)	176 (2)	176 (2)	145 (2)	160 (2)	137 (2)	139 (1)
191#	166 (2)	156 (2)	170 (2)	152 (2)	109 (2)	104 (2)	80 (2)	47 (2)	55 (2)	66 (2)
192#	78 (2)	61 (1)	56 (1)	73 (1)	60 (1)	84 (1)	112 (2)	133 (2)	87 (2)	69 (1)
193#	66 (2)	52 (2)	69 (2)	68 (2)	72 (1)	65 (2)	27 (1)	3 (1)	1 (1)	7 (1)
194#	29 (1)	24 (1)	37 (1)	45 (1)	50 (1)	48 (1)	52 (1)	50 (1)	48 (1)	50 (1)
195#	81 (1)	180 (2)	145 (2)	111 (2)	171 (2)	201 (2)	288 (2)	268 (2)	347 (2)	297 (2)
196#	368 (2)	373 (2)	356 (2)	365 (2)	380 (2)	445 (2)	428 (2)	391 (2)	418 (2)	422 (2)
197#	547 (2)	658 (2)	734 (2)	1127 (1)	996 (1)	1147 (1)	1118 (1)	1062 (1)	1178 (2)	1302 (2)
198#	1471 (2)	1681 (1)	1751 (2)	1227 (1)	994 (1)	2340 (2)	3352 (2)	3045 (2)	3317 (2)	4562 (2)
199#	4501 (2)	3750 (2)	4747 (2)	4849 (2)	5233 (2)	5943 (2)	6106 (2)	5737 (2)	5206 (1)	6103 (2)
200#	5906 (2)	6409 (2)	7001 (2)	7238 (2)	6198 (2)	6216 (2)	6224 (2)	6501 (2)	7011 (1)	7391 (1)

The present study could make a contribution to the study of scientific growth. Its strengths are manifold: it tests de Solla Price's theoretical model, operates with a large sample and long time series (1848–2009), uses a major scientific product (doctoral theses) as a unit of analysis largely ignored in earlier studies, and proposes the novel use in scientometrics of time series analysis techniques (ARIMA and ARIMAX).

Readers interested in the crucial scientometric question of scientific growth are offered insights based on the past, present and future of a particular scientometric product (the doctoral thesis) with a clearly-defined system (Spain). The paper seeks to explore the what, how and why of a scientometric time series. The doctoral thesis—albeit in scientometric terms a minor work of grey literature—should not be dismissed, and nor should research into its production, of the sort reported here.

A novel feature of this paper is that it introduces, explores and evaluates the relevance of a new exogenous explanatory variable: the general welfare (GW) of a national research system, taking the Spanish system as a model. GW is understood as a nation's political and social stability and economic health status. This variable is more comprehensive than mere economic indicators. Acting alone or in combination, events such as strikes, social conflict, war, invasion, famine, economic crises, poverty and political turmoil may have a negative impact on scientific growth. A further question arises relating to the operative implementation of this factor: the present study opts in favour of validation through consensus among experts (historians). This *rapprochement* of history and science provides the basis for forecasting studies, on the grounds that—as Leitner and Leopold-Wilburger (2011) have noted—the explanation and improvement of forecasting are interdisciplinary issues.

Method

Sources of data for Spanish doctoral theses

Three valuable secondary sources are available in Spain for investigating completed doctoral theses. One of the most important of these is TESEO (*TESis Españolas Ordenadas*—Ordered Spanish Theses—2011) which has been indexing the summaries of doctoral theses submitted in Spanish universities since 1976. This is undoubtedly the most consistent source, containing the most reliable and consequently most valid data relating to doctoral productivity in Spain.

For pre-1976 data it is necessary to use the *Catálogo Completo*—Complete Catalogue—and *Tesis UCM*—UCM Theses—held at the library of the Complutense University of Madrid (UCM), which until 1954 was the only Spanish university authorised to award doctorates. For the somewhat hazy period between 1954 (the year in which the institutional decentralisation of theses took place) and 1976 (the year in which TESEO was established), searches were made of the thesis records held by the major universities of the time: Barcelona (1,618 theses), Santiago (724), Valencia (664 theses), Granada (435), Zaragoza (151), Salamanca (135), Valladolid (62) and Seville (23). These were in addition to the 7,859 doctoral theses completed at the Complutense University over the period 1940–1975.

Records prior to 1954, dating back to 1848, are available only in the *Catálogo Completo* and *Tesis UCM*. Undertaking algorithmic searches of these records is no simple task; in the end, in fact, methodical year-by-year searches had to be performed in order to ascertain the number of indexed theses by visual inspection, because German and French theses from the nineteenth century had to be discarded, while care had to be taken not to double-count theses listed twice, once in manuscript and once in book form.

Rationale for the time series under analysis: Spanish doctoral theses, 1848–2009

Clearly a diachronic study such as this is inevitably influenced by historical vicissitudes; but it is not the intention here to undertake an historical study, rather to try to shed light on the scientometric models associated with time series of thesis output and account for any patterns observed. The period under investigation is 1848–2009; reasons will be given for this choice, and the key stages and cycles in the evolution of Spanish doctoral thesis production will be identified.

Placing limits on a time series is no easy task, since it must be based on a well-founded rationale: historical, economic and even paradigmatic. As part of the liberal reforms of the 1840s, the government introduced a homogeneous, secular model, wholly free of outside influences. It was a national system, with Spanish as the language for writing theses, and it was highly centralised, in that all theses were submitted and examined at the Central University of Madrid.

The time series under investigation here is 1848–2009,¹ and the subseries contained within it provide a longitudinal view of Spanish thesis output over a period of over 150 years, spanning three centuries (see Table 1); as will become clear, this output has not been immune from the historical vicissitudes of a country that has suffered more than its fair share of tensions and conflicts.

This study, focusing on a single country, obviously does not allow wider generalisations to be made. However, it could be replicated in other national research systems. A more comprehensive study, covering a large sample of countries, would clearly be of great value.

Analyzing time series of doctoral theses

The scientometric approach, which is by its nature quantitative, is the most commonly used in studying a time series for doctoral thesis output (Fernández-Cano and Bueno 1999). Such studies vary in complexity and completeness, depending on whether they contain bivariate or multivariate data and on the extent to which they seek to verify and account for the fit of the chosen indicators to laws and patterns widely accepted in scientometrics; in this instance, to the models of scientific growth put forward by de Solla Price (1986).

Scientometric studies of this sort, using doctoral theses as an analytical unit, are becoming increasingly widespread and sophisticated. At an international level, Han et al. (2010) combined two time series from earlier studies (Thurgood et al. 2006; Falkenheim and Fiegenger 2008) focusing on the annual growth of doctorate degrees awarded in the USA; they observed the deadening effect of the world wars, a significant flattening of growth in the 1970s and an annual growth rate of 6.75% thereafter. The USA could be already very close to the saturation limit predicted by de Solla Price (1986).

The production of dissertations in eight research fields during 1950–2007 is studied by Andersen and Hammarfelt (2011) using the Gompertz function for analysing data and showing a decline in the growth of theses in all fields.

Most papers consulted, however, use a relatively simple approach, reporting numerical aspects of the series, plotting that data on graphs which are then analysed by visual interpretation, and finally either calculating correlation coefficients of growth (especially the multiple correlation coefficient, R^2 , between two variables: time-years and output) or inferring growth-rates or compound annual growth rates (CAGR) (see Fernández-Cano,

¹ The data shown in the Table 1 below include the following variables: date, number of theses and dummy variable (general welfare). All analyses were conducted using the data in Table 1.

Torrallbo and Vallejo 2004). These methods should not be dismissed on the grounds of their simplicity; as Makridakis and Hibon (2000) have rightly noted, complex analytical models such as ARIMA, exponential smoothing or deterministic models do not, merely by virtue of being sophisticated, necessarily provide better forecasts.

However, it was felt that these time series could usefully be subjected to a thorough and more complex examination. Two approaches were therefore adopted: simple models based on visual analysis by hindsight, focusing on deterministic linearity (linear, logarithmic, inverse, quadratic and so on); and a number of more sophisticated models: exponential smoothing (simple, damped, Brown's or Holt's linear exponential smoothing) as well as Box, Jenkins and Reinsel's (1994) ARIMA models. Each series will be investigated here using the most suitable model, as appropriate.

The IBM SPSS Statistics 19 (SPSS Inc. 2010) software package was used to calculate the exponential smoothing, ARIMA and ARIMAX models best fitted to each time series and related forecasts. The recent SPSS version 19 statistical package directly calculates the best-fitting model of the time series, exponential smoothing or ARIMA, and does not require parameter values (p , d , q) to be entered, as they are determined by prior autocorrelation functions and the corresponding correlograms. SPSS 19 was used to directly determine the best fit without additional steps.

The conventional or descriptive study of time series dates back to the second half of the nineteenth century; in 1970, however, analysis of time series made significant progress thanks to the work of Box and Jenkins and their development of what is known as ARIMA methodology, or Box-Jenkins models (Box and Jenkins 1970). This methodology is based on the theory of stochastic processes and provides improved results for, above all, short-term predictions. The final result is an autoregressive (AR), integrated (I) moving-average (MA) model known by the acronym ARIMA, with the respective generic estimates (p , d , q). Determination of the best-fitting model involves a complex four-phase process: identification, estimation, validation and prediction (see Makridakis, Wheelwright and Hyndman 1998). Forecasts will vary extensively depending on the type of series under consideration, and upper and lower limits will be provided at the usual 95% confidence level.

One section is dedicated to forecasts, focusing on the three available time series: the complete time series (1848–2009), using the criteria proposed by de Solla Price; the recent partial time series (1976–2009), matching the theoretical-historical period indicated earlier; and a more immediate or proximal time series (1989–2009), since a change in trends can be observed in the year 2000. Evidently, the underlying models and the predictions differ considerably depending on the series in question. Time series analysis in a sense resembles lenses, in that the type of lens used (the period studied) changes the focus (the results).

To explore the question of how wars and periods of economic instability impact on scientific growth, a dichotomous dummy variable has been employed called 'general welfare' where 1 represents a 'bad' year and 2 a 'good' year. It is not easy to introduce such a dummy variable on a yearly basis; this requires a reductionist approach derived from the consensual opinion of three experts. The significance of the GW dummy variable as a predictor is verified using the ARIMAX technique, specifically Ljung-Box's (1978) Q test and the Weibull test. The breakpoints of the complete time series are also identified in an attempt to determine structural changes.

A central assumption underlies this study: the authors make no claim to prophetic skills. It should be recalled that the complexity of a prediction within a dynamic and well-defined research system is subject to Poincaré's paradox (2002): a perfect error-free prediction

Table 2 Descriptive statistics for number of theses, analysed by time series and general welfare (GW)

Time subseries	GW	Mean	Std. Dev.	<i>N</i>
1848–1898	Bad	34.7	40.09	17
	Good	59.8	53.92	24
	Total	49.4	49.71	41
1899–1939	Bad	50.8	27.70	16
	Good	103.3	44.31	35
	Total	86.8	46.57	51
1940–1975	Bad	269.7	445.90	14
	Good	358.7	154.87	22
	Total	324.1	300.30	36
1976–2009	Bad	3491.8	2778.35	9
	Good	4609.7	1913.63	25
	Total	4313.8	2187.50	34
1848–2009	Bad	653.7	1658.40	56
	Good	1209.3	2111.27	106
	Total	1017.2	1979.105	162

requires an infinitely-precise knowledge of the past, which is evidently impossible. The authors are aware that all predictions are of the moment, provisional and fallible but inescapably necessary. Nor is it the authors' aim to generalise the findings to other geographical and historical spheres; however, partial studies such as this one, bound to a specific and clearly-defined context, may be transferable by replication to other countries, and it may indeed be feasible to combine and merge studies synthetically from different countries, incorporating contextual and idiosyncratic elements from each of the national research systems under investigation.

Results

Descriptive statistics

Using the database included in the footnotes (see Table 1), Table 2 (above) shows group values for the dependent variable (number of theses), differentiated in terms of the independent variables: the subseries (1848–1898; 1899–1939; 1940–1975 and 1976–2009) and GW (Bad; Good).

Considerable inter-group variability is apparent, with widely-differing standard deviations; this argues against using parametric statistics in particular, and the general linear model in general, given that the variances between the groups compared are manifestly heterogeneous; Levene's test, which measures the equality of error in variances, yields a highly significant value ($F = 47.2$; d.f. (7; 154); $p < 0.000$).

Analysing times series according to determinist models

The analytical results for the various series investigated are set out below, divided into series belonging to historical periods. Time series can be broken down into subseries. As an exercise in

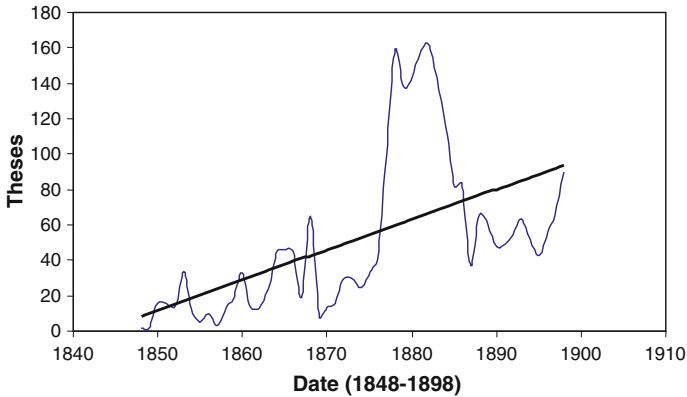


Fig. 1 Spanish doctoral thesis production, 1848–1898

analysis this can add to the richness of the conceptual landscape by addressing individual aspects and details that help to clarify the general series. A short series provides limited information, while a long one hides or dilutes some information. There is thus a kind of uncertainty principle involved. This is where the graphic representation of each series makes its contribution, through the deterministic model with its linear trend.

Deterministic graph patterns were generated using the *Regression → Curve Estimation* programme from the IBM SPSS 19 package and Excel (Microsoft 2010), showing the linear diagram and the trend line or best-fit line. Similar graphs were generated using the two packages, but those produced by Excel are used here due to their higher degree of definition and visual clarity.

The nineteenth-century period: 1848–1898

Diachronic graphic analysis begins with the period 1848–1898. These dates were not picked at random; 1848² was the year in which theses were first written in Spanish and the Central University of Madrid was by then firmly established after its move in 1836 from its previous home at Alcalá. The programme of liberal reform had modelled and defined university studies on the basis of the French system. At the other end of the period is 1898, a year of great political, economic and existential upheaval for Spain. This year marked the end of the Spanish Empire, with the loss of its last colonies, including Cuba. Theses from the Royal University of Havana were therefore excluded. This was the only institution, apart from Madrid, permitted to issue doctoral degrees following public examination of theses.

The pattern of thesis output by year is shown in Fig. 1.

Distinct cycles can be discerned in this graph.³ Two correlated observations may be drawn from this period: the moderately rising linear trend, with its striking cycles of highs and lows, appears to be linked—here this is put forward as a hypothesis and to a certain

² Two features characterise Spanish theses during the Ancien Regime; they had to be written in Latin and be approved (*nihil obstat*: ‘nothing hinders’) by the all-powerful Court of Inquisition; it was, moreover, an expensive, ceremonial and ostentatious ritual in which the newly-created doctor was forced to spend huge amounts of money on banquets, speeches, civic and religious processions and ruinous displays of generosity culminating in a bullfight.

³ In 1877, Santiago Ramón y Cajal, who was awarded the Nobel Prize in Physiology or Medicine in 1906, submitted his thesis: *Patogenia de la inflamación*—Inflammation pathogeny.

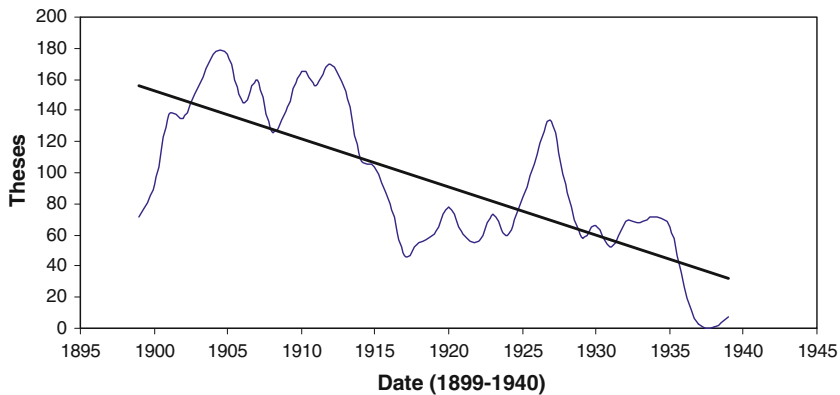


Fig. 2 Spanish doctoral thesis production, 1899–1939

extent confirmed—to political and social stability. It is quite clear that expenditure on R&D, the best predictor of scientific growth according to the biannual reports of the National Science Foundation (2010), increases in periods of social harmony and declines in times of upheaval and war; a variable referred to here as GW.

The period 1899–1939

In the wake of 1898, Spain underwent a period of regeneration affecting science, culture and life in general. The doctorate was reformed, with doctrinal discourse being replaced by a piece of research. This period marked the attainment of a major reform long championed by nineteenth-century liberals: the thesis ceased to be doctrinal, theoretical, compilatory and erudite, and became a practical and original piece of research. The progressives also made attempts to decentralise doctorates, so that they could be awarded by any university; furthermore any professor would be able to supervise theses, rather than just professors at the Central University of Madrid.

The singular production profile recorded over this 40-year period is shown in Fig. 2.

A number of clearly-defined cycles can be discerned: first, a period of growth from 1901 to 1915, coinciding with an era of relative social harmony, which saw the creation in 1907 of the *Junta de Ampliación de Estudios e Investigaciones Científicas*⁴ (Scientific Studies and Research Expansion Board), a body intended to encourage university postgraduate training.⁵ Then a series of negative impacts: a crisis in the socio-political model adopted by the liberal monarchy, colonial wars, a half-hearted military dictatorship (1923–1930), the economic crash of 1929, the ousting of the monarchy and the advent of the tumultuous Second Republic (1931–1939) which culminated in the horrors of the Spanish Civil War (1936–1939). All these factors account for the falling slope, indicating a clear state of

⁴ The *Junta de Ampliación de Estudios* (Scientific Studies and Research Expansion Board) was a body founded in 1907 with the aim of promoting scientific research and education in Spain, in an attempt to emulate European models. Its influence, in terms of arranging exchanges with Europe and sending scientists to Latin America, was notable. The institution was modified in 1939 with the advent of General Franco's regime.

⁵ In 1934, Severo Ochoa de Albornoz, the Spanish-born scientist and naturalised citizen of the USA, who was awarded the Nobel Prize in Physiology or Medicine in 1959, submitted his thesis: *Los fenómenos químicos y energéticos de la contracción muscular en la insuficiencia adrenal experimental* (Chemical and energetic phenomena of muscle contraction in experimental adrenal failure).

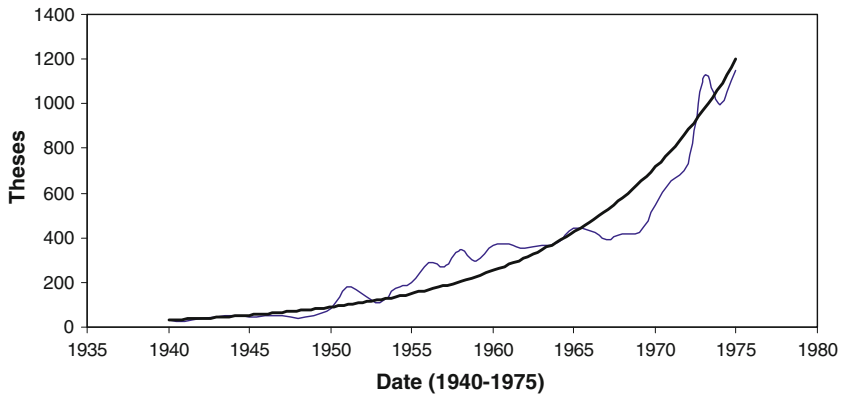


Fig. 3 Spanish doctoral thesis production, 1940–1975

involution. Three theses were submitted in 1937, one in 1938 and seven in 1939. These events lend support to the hypothesis that scientific growth, as measured by doctoral theses, is linked to periods of social and political harmony; Szydłowski and Krawiec (2009) prefer to talk of wars and other events far removed from science, but confirming such a correlation requires a closer contrast, which will be addressed below.

The period 1940–1975

After the fateful Spanish Civil War (1936–1939), Spanish doctoral thesis output fell to virtually zero. This period exactly coincides with the autarky regime established under General Franco. The Central University of Madrid—now the Complutense University—continued to enjoy the sole right of providing doctoral training. This privilege was curtailed in 1954 and, in one of the ironies of history, the decentralising aims of the Spanish liberals were finally attained under the iron rule of a conservative dictatorship.

The doctoral thesis time series graphs for this period, 1940–1975, are shown in Fig. 3.

Thesis output grew exponentially over this period, although a number of internal cycles can be discerned, with a marked contrast between the paucity of the 1940s, when output dropped to levels not seen since the previous century, and the uninterrupted growth in output from the 1940s onwards. Due to the academic decentralisation of the doctoral thesis system in 1954, each university now had its own collection of theses. As time went by, the realisation that information was becoming scattered led to the decision to set up a national state record; towards the end of this period, therefore, the TESEO thesis archive came into being, with the aim of bringing some order to the indexing and retrieval of theses submitted at all Spanish universities.

It is clear that the exponential growth in thesis production over this period is linked to the increase in the number of universities authorised to award doctorates.

The TESEO era: 1976–2009

The start of this period was marked not only by major political changes but also by the creation of the TESEO doctoral thesis archive, administered by the Ministry of Education and Science for the Spanish central government. This provided an improved, comprehensive approach to indexing, based on thesis summaries, which enabled more valuable

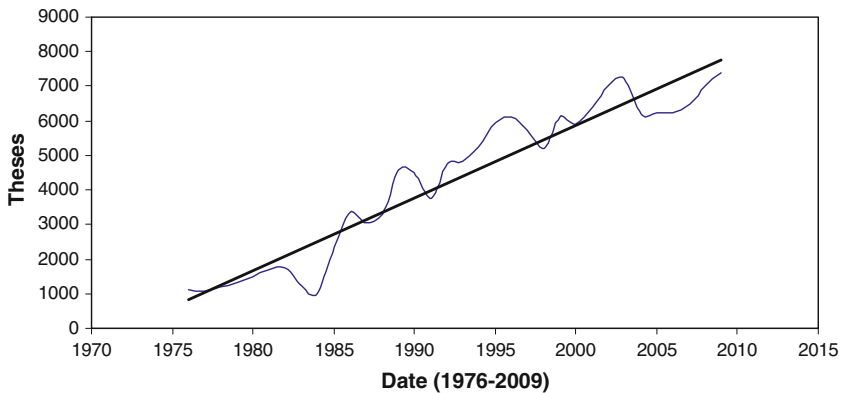


Fig. 4 Spanish doctoral thesis production, 1976–2009

data to be readily retrieved; however, while the submission of summaries to TESEO was recommended, it did not become compulsory until the early 1990s. Figure 4 shows the linear increase in Spanish doctoral thesis output over this period.

Nevertheless, as the trend line in Fig. 4 shows, the growth pattern was not clearly exponential: from 1984 to 2003, growth surpassed even the exponential model; thereafter, however, it fell back to a slower linear growth approaching a quasi-logistic model. In line with de Solla Price's models of scientific growth (see Fernández-Cano et al. 2004), the time series of Spanish doctoral theses could be said to have reached saturation point, suggesting a quasi-logistic growth model characteristic of a mature research system. It is unthinkable, as de Solla Price (1986) pointed out, that all series should grow indefinitely, since this would lead to the absurdity of an infinite number of theses and doctors. A similar finding is reported by Leydesdorff and Zhou (2005), who noted that data on doctoral degrees awarded in China and Korea were now displaying non-exponential growth.

After a certain point, moreover, the system may generate dysfunctions and become somewhat debased, as Fernández-Cano et al. (2008) have reported with regard to doctoral theses in educational sciences; evidence starts to emerge of unnecessary co-supervision, prolific supervision and theses of questionable methodological quality.

After 2002, when there was a strong demand and a need to complete theses, under political and administrative pressure to stabilise the university teaching profession, the growth curve returns towards a near-logistic stability.

The recent past: 1989–2009

Assuming that the pattern of growth in future will be lower, the most recent time series covers the last 20 years, even though part of it falls within the time series analysed above.

Note how the line of best fit is less steep compared to the earlier period and almost parallel to the X axis. This trend is a clear indication that the output of Spanish theses is settling into a logistic pattern (Fig. 5).

The general pattern for over 150 years of Spanish doctoral theses

The four previous periods were merged to create an overall pattern for the entire time span, 1848–2009; the result is shown in Fig. 6. An adjusted curve, calculated using a seventh-

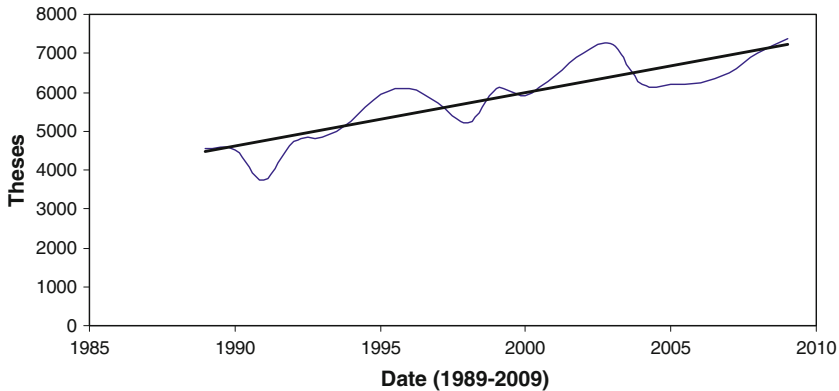


Fig. 5 Spanish doctoral thesis production, 1989–2009

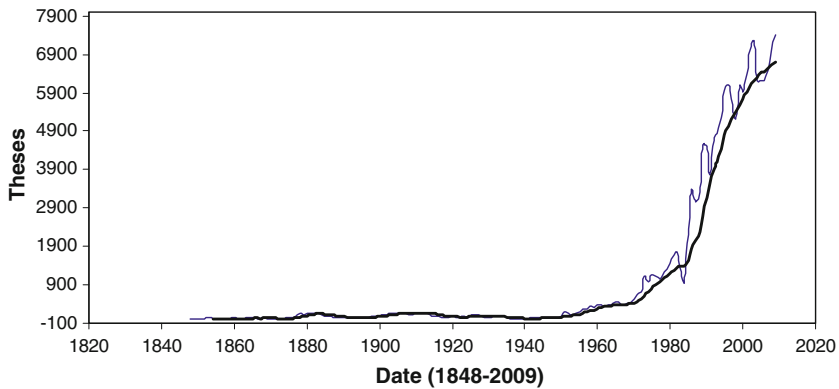


Fig. 6 Spanish doctoral thesis production, 1848–2009

order moving average, shows an incipient stabilisation post-2003 as forecast by the two earlier partial series. This can be seen quite clearly in Fig. 6.

It is quite clear that, in overall terms, the time series of Spanish theses from 1848 to 2009 fits a quasi-logistic growth model. Examination of the most recent phase (1976–2009) shows occasional dips, evident in the graph, which are later followed by a greater rise. The dips may be no more than a form of “reculer pour mieux sauter”. However, as becomes clear in what follows, when better models of fit are used, whether ARIMA or exponential smoothing, the numerical forecasts confirm the logistic tendency already evident in the deterministic graphs for the most recent partial series (1976–2009 and 1989–2009) and the complete series (1848–2009).

Fitting the doctoral thesis time series to exponential smoothing and ARIMA models

All the above observations were based on deterministic graph patterns calculated on the basis of hindsight. Using more powerful data analysis techniques—exponential smoothing and ARIMA models—the best fit can be determined for each case.

Table 3 Models of fit for Spanish doctoral thesis time series

Time series	R^2	R_E^2	Deterministic	Exponential smoothing	ARIMA
1848–1898	0.761	0.761	Linear rising	Simple	(1, 0, 0) ^a
1899–1939	0.807	0.807	Linear falling	Simple	(1, 0, 0) ^a
1940–1975	0.930	0.62	Exponential	Brown ^a	(0, 1, 0)
1976–2009	0.940	0.522	Linear rising	Holt ^a	(2, 1, 0)
1989–2009	0.763	0.619	Constant linear rising	Holt ^a	(0, 1, 0)
1848–2009	0.988	0.322	Quasi-logistic	Holt smoothing	(2, 1, 7) ^a

^a Best fitting

The exponential smoothing and ARIMA models of fit were calculated using the *Forecasting* programme from the IBM SPSS 19 package, with the instructions *Create Model* → *Expert Modeler*, selecting the best fit of the two. Two goodness-of-fit indicators were used: quadratic R and stationary quadratic R; values close to 1 indicate a better fit to the particular model for each time series. Table 3 above compares the models of fit for each series with earlier deterministic models. The ARIMA and exponential smoothing models obtained from numerical analysis of the above series using SPSS 19 fully agree with the deterministic models derived from the earlier graphs.

Table 3 shows the best-fitting model (exponential smoothing or ARIMA) underlying each series. It should be stressed that in the ARIMA model (2, 1, 7) for the complete series (1848–2009), the moving averages (MA) parameter ($q = 7$) indicates a 7-year “biblical cycle” in the growth of theses. The autoregression (AR) parameter of 2 ($p = 2$) shows that only two previous years could be affecting the following value. The value of the parameter of $d = 1$ shows that the series has to be log-integrated (I) once to eliminate the stationary trend. The main finding, however, is the evidence supporting de Solla Price’s (1986) theory regarding the general model of scientific growth: sustained linear growth → exuberant, exponential growth → logistic saturation.

Determining forecasts

Forecasts can be also developed based both on the last subseries (1976–2009), (1989–2009) and on the complete series (1848–2009). This ability to calculate future values predicted by the model is one of the most powerful features of exponential smoothing and the ARIMA models.

Shown below are the forecasts, in graph form, using the model of best fit for a future period of 7 years (2010–2016); this is not a case of adopting the Bible’s 7-year time frame, but rather of using the mid-term interval, probably the most widely used in prediction studies (Fernández-Cano et al. 2008). Every forecasting graph derived from the *Plots* feature of the IBM SPSS 19 package includes: the observed values of the series, adjusted and predicted values for the model of best fit and predicted values at a confidence interval of 95%, with upper (UCL) and lower confidence limits (LCL).

Taking the 1976–2009 temporal series and the model of best fit (Holt exponential smoothing) produces the graph shown in Fig. 7.

The pattern of central predicted values shows a straight rising line consistent with the earlier deterministic pattern.

Taking the 1989–2009 temporal series and the model of best fit (Holt exponential smoothing) produces the graph shown in Fig. 8.

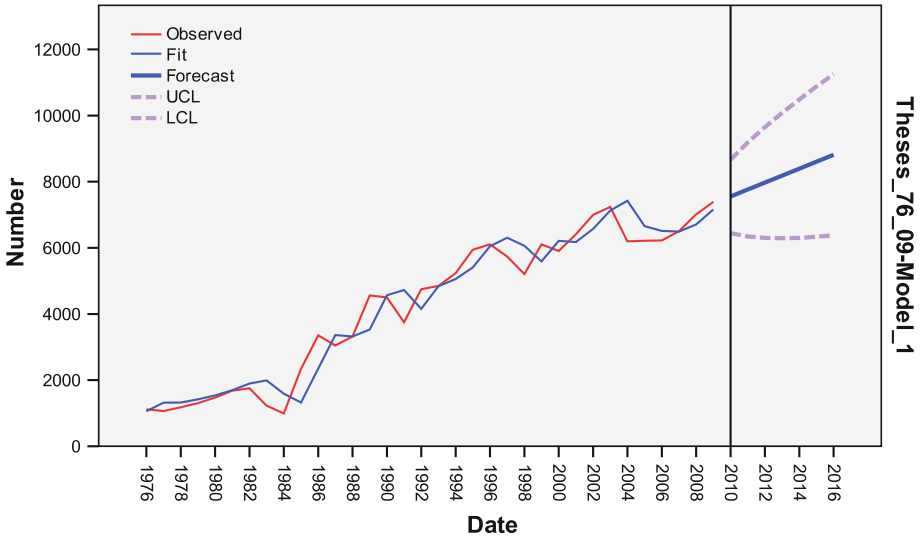


Fig. 7 Forecasting graph for Spanish thesis-production using the 1976–2009 series with Holt exponential smoothing

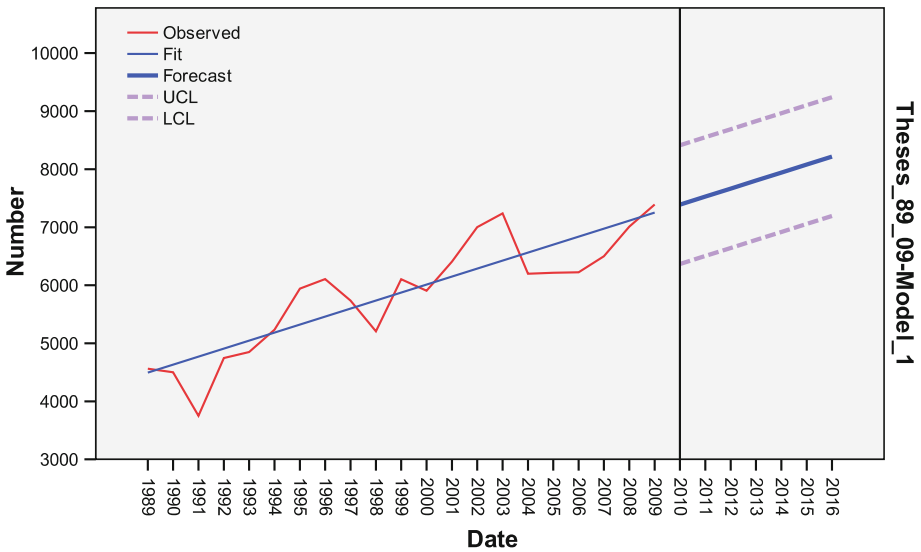


Fig. 8 Forecasting graph for Spanish thesis-production using the 1989–2009 series with Holt exponential smoothing

For this series, the pattern of the forecast is once again linear, but also constant. The upper and lower limits remain stable and unvarying; this indicates that, as well as having a better fit, the forecasts also approach a certain degree of stability, something that is more obvious when the findings for this series are compared with the previous one, inasmuch as the slope of the last section is shorter.

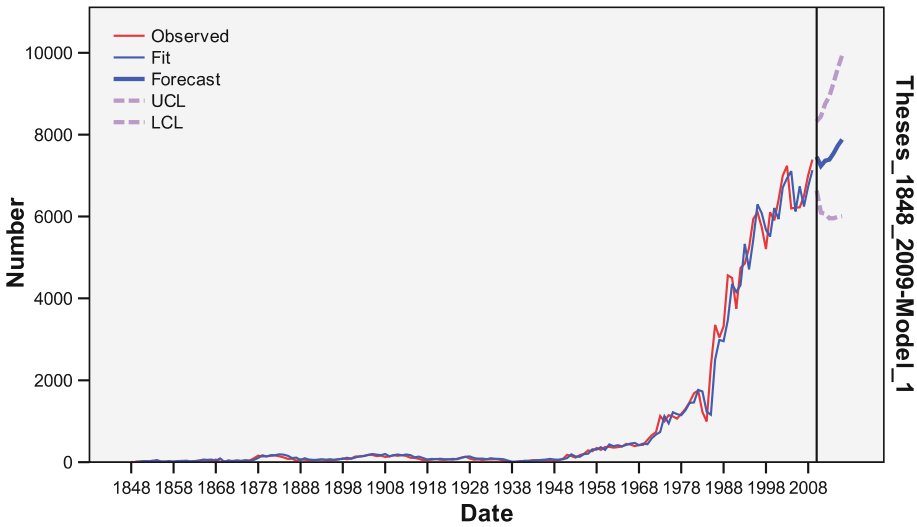


Fig. 9 Forecasting graph for Spanish thesis-production using the 1848–2009 series with ARIMA model (2, 1, 7)

Table 4 Growth forecasts for Spanish doctoral theses classified, by time series and corresponding models of best fit

Time series	Model		2010	2011	2012	2013	2014	2015	2016
1989–2009	Holt	Forecast	7,390	7,528	7,666	7,804	7,941	8,079	8,217
		UCL	8,413	8,551	8,689	8,827	8,965	9,103	9,241
		LCL	6,367	6,504	6,642	6,780	6,918	7,056	7,194
1976–2009	Holt	Forecast	7,555	7,765	7,975	8,186	8,396	8,606	8,816
		UCL	8,664	9,186	9,651	10,081	10,489	10,880	11,257
		LCL	6,446	6,345	6,300	6,300	6,302	6,332	6,375
1848–2009	ARIMA (2, 1, 7)	Forecast	<i>7,556</i>	<i>7,076</i>	<i>7,202</i>	<i>7,258</i>	<i>7,295</i>	<i>7,469</i>	<i>7,711</i>
		UCL	8,014	7,738	7,966	8,095	8,251	8,544	8,857
		LCL	7,098	6,413	6,438	6,420	6,340	6,394	6,565

UCL Upper Confidence Limit (95%), *LCL* Lower Confidence Limit (95%); best forecast in italics

Undoubtedly however, the most impressive forecast comes from using the complete time series—1848–2009—and its best model of fit: ARIMA (2, 1, 7).

The pattern shows a degree of stabilisation from 2004, something that had already been set in train with the decline recorded in 2000 (Fig. 9). The tendency towards stabilisation in Spanish thesis-production becomes more apparent with the calculation of the numerical values shown in Table 4 (above).

The 1989–2009 and 1976–2009 series do not predict linear growth in the number of theses. However, the 7-year forecast for the complete series (1848–2009) shows how Spanish thesis output stabilises around the interval from 7,076 forecast for 2011 and 7,711 for 2016. It is clear that as the prediction period increases, the forecast becomes less reliable, and the confidence limits become broader.

Significance of the general welfare predictor

It was earlier hypothesised that periods of economic instability could impact on scientific growth, and for this reason a dichotomous dummy variable called ‘general welfare’ was introduced. In order to establish the statistical significance of this variable as a predictor of doctoral thesis output, two analyses have been used. The first of these is the ARIMAX (F_Q) solution using Ljung-Box’s (1978) Q test, also known as the modified Box-Pierce statistic (1970). This test is included in IBM SPSS 19’s *Forecasting* programme. Treating GW as an independent variable yields the p values shown in Table 5 for each series, always using the model of best fit. Secondly, a life data analysis was performed life data using a reliability coefficient (W_{F-R}) for times-to-failure and Weibull’s (2011) test. The dichotomous nature of the dummy variable (Good/Bad) enables a calculation widely used in engineering and in ON/OFF systems.

It should be noted that this variable is predictive, using both the ARIMAX solution and the Weibull test, only in the complete series (1848–2009); it is also predictive in the 1899–1939 series when the latter test is used. Furthermore, for the complete series, a Kendall’s tau_b correlation coefficient (see Abdi 2007) calculated over 1,000 bootstrap samples yields a value of $\tau = 0.277$ ($p < 0.000$), which is highly significant. A non-parametric statistic such as the Wald-Wolfowitz (1940) run test generates an adjusted z value of 2.32 ($p = 0.0206$).

The lack of significance for the remainder of partial series, except that of 1899–1939, could be due to the nominal-dichotomous nature of this predictor and the fact that series are relatively short, providing scarcely 50 years of data. The very low values observed during the Spanish Civil War (three theses in 1937; one in 1938 and seven in 1939) may have contributed to the significance of the GW variable as a predictor.

The finding for the complete series (1848–2009) corroborates Szydłowski and Kra-wiec’s (2009) assertion that the occurrence of conflicts correlates negatively with doctoral thesis output, in a general research system such as that investigated in the Polish study or in a national system such as Spain’s, provided that the time series used is a long one: from 1666 to 1934 in the case of the Polish study, and from 1848 to 2009, in the Spanish study.

It should be stressed here that the predictive-correlational connection observed does not imply a causal relationship. Correlation, after all, is never synonymous with cause.

Table 5 ARIMAX solution and Weibull test for statistical significance of general welfare (dummy) as a predictor of number of theses by periods-subseries

Time series	F_Q	d.f.	p	W_{F-R}	p
1848–1898	13.46	17	0.705	0.723	0.165
1899–1939	23.74	17	0.168	0.853	0.005
1940–1975	13.54	18	0.758	0.810	0.472
1976–2009	16.45	16	0.422	0.409	0.522
1989–2009	24.62	18	0.136	0.890	0.201
1849–2009	40.45	9	0.000	0.792	0.005

F_Q ARIMAX value in Q Ljung-Box’s test, *d.f.* degrees of freedom, p probability value, W_{F-R} reliability coefficient in Weibull’s test

Table 6 Breakpoints in the general time series (1848–2009)

Types of breakpoints	Years in the time series 1848–2009	Years in the time series 1848–2009 with predictor (GW)
Additive	1973–1983–1984–1985–1988–1998–2004	1973–1983–1984–1985–1994–1995–1998
Innovational	1985–1992–1993–1994–1995–2001–2004–	1981–1985–1988–1989–2001–
Local trend	1969	1905–2007
Transient		1992
Level shift		2004

Breakpoints in the complete time series (1848–2009)

In order to determine the breakpoints of the series it is not appropriate to use the Chow or Andrews tests, which involve linear regression, given that the lines of best fit for each series are curves rather than straight lines. It should also be remembered that the distributions of the number of theses relating to each series are highly heteroscedastic, i.e. have highly- heterogeneous variances, and should therefore not be used in the general linear model.

It is then possible to assimilate the breakpoints to the outliers, which the IBM SPSS 19 *Forecasting* programme identifies once the model of best fit has been ascertained. This can only be done for the time series, or including the GW predictor which has attained a certain level of statistical significance (see Table 6).

One conclusion can be drawn from the breakpoints identified: the partial series used have no stochastic basis, since none of the start or end points appear to be breakpoints. It would thus appear that the partial series examined here have a historical, but not scientific, justification; however, if the data are subjected to the general linear model, statistically significant differences emerge between the intercepts of each line of regression (time series: number of theses by date).

Even so, it is worth highlighting certain breakpoints as especially significant landmarks in the complete 1848–2009 series; namely:

- 1969, which marks the start of the exponential growth in the number of theses.
- 1973, when thesis production rises 51.8% compared to the previous year.
- 1992, when output rises by almost 1,000 theses (26%) compared to the year before, making this year a pronounced transient and innovational breakpoint.
- 2004 with its level shift, which may be the turning point of the series in its conversion to a logistic trend.

Conclusions

This paper has looked at both the past and future of Spanish thesis production. Well-founded responses have been provided to the research questions, and are summarised as follows. The time series of Spanish doctoral theses from 1848 to 2009 has been graphically and numerically expressed and broken down into subseries that are theoretically and historically well-defined but are not consistent with a stochastic model. Patterns and trends in the historical development of Spanish doctoral thesis production have emerged, with four distinct phases becoming historically but not stochastically apparent.

The model of best fit for the complete series (1848–2009) was an ARIMA model (2, 1, 7) visible in an incipient logistic curve, something which corroborates de Solla Price's (1986) predictions concerning scientific growth. In other words, the future seems to point to a somewhat slower linear increase or quasi-logistic growth.

Seven-year forecasts were generated using the best-fitting model. A dichotomous dummy covariate (general welfare) attained statistical significance as a predictor for the general series. Finally, the relevant breakpoint-years in the complete time series (1848–2009) were identified.

A number of final considerations deserve mention. The fallibility of forecasts should be acknowledged, despite the apparently complete availability of data and the mathematical sophistication of prediction techniques using exponential smoothing and ARIMA models. Scientometric analyses of scientific growth time series identify patterns and general trends, but they are not immune from error. Forecasts are provisional; predictions that presume to be exact are meaningless, since any unforeseen event or “black swan” can cause output to fall, unexpectedly destroying a trend that had been developing for years.

Scientific growth as measured by thesis output is not immune to the historical factors of political and social harmony, as a dummy variable (general welfare) has demonstrated. That said, the authors have no wish to introduce a simple-minded historicist bias into their explanation of scientific growth. A case could be made, however, for thesis production being linked to a whole range of factors: political factors, such as the political future of Spain as it faces the prospect of a possible secession of its regions; economic factors arising from the worsening of a still-prevailing crisis; and psychological factors, such as the boredom associated with research among young people today, and the very deterioration of the system, which renders the production and accumulation of doctoral theses futile and redundant. Additional research is required to verify the significance of these factors; concretely further research in this area could usefully include an integrative review of the exogenous and endogenous factors determining scientific growth.

Looming on the horizon are a number of considerations which could also affect the growth of Spanish thesis production. They are potential factors which could have a far-reaching impact: at present, the vagueness of European guidelines on postgraduate study, the lack of European harmonisation regarding use of the title of doctor, the growing professional importance of Master's degrees and the imprecision of the European Credit Transfer System (ECTS) vis-à-vis theses all raise doubts regarding the ability of the Spanish academic system to generate and disseminate knowledge through the training of new researchers. What is really needed, and long-awaited, is a consistent European educational policy on doctoral studies capable of overcoming the vagueness and lack of regulation in the current system, of stressing methodological rigour and of alleviating the many legal and regulatory pressures to write theses and publish, all of which give rise to dysfunctions of the sort previously outlined by Fernández-Cano, Torralbo and Vallejo (2008).

Finally, echoing de Solla Price's (1986) thoughts, there is no sense in indefinitely pursuing “growth for growth's sake”, like rabbit colonies. This leads to the admittedly gloomy reflection that, in the light of the evidence set out here, the halcyon days of development, at least insofar as the doctoral theses in a research system such as Spain's is concerned, are over. Perhaps the time has come to pause and consider whether it makes sense to continue growing regardless of scientific quality, in the absence of any type of checking, ignoring the wider needs of society, leading to a “breakthrough model” which tarnishes the academic environment and gives rise to striking inequalities. Sometimes, faced with the prospect of a huge amount of scientific activity (papers, theses, researchers,

R&D expenditure), the melancholy image that comes to mind is that of the dung beetle condemned to build an ever-growing ball of waste. The dream, or myth, of unlimited scientific growth seems to be crumbling.

References

- Abdi, H. (2007). Kendall rank correlation. In N. J. Salkind (Ed.), *Encyclopedia of Measurement and Statistics*. Thousand Oaks, CA: Sage.
- Andersen, J. P., & Hammarfelt, B. (2011). Price revisited: On the growth of dissertations in eight research fields. *Scientometrics*, *88*(2), 371–383. doi:10.1007/s11192-011-0408-8.
- Ben-David, J. (1991). *Scientific growth: Essays on the social organization and ethos of science*. Berkeley, CA: University of California Press.
- Bonaccorsi, A., Daraio, C., & Simar, L. (2006). Advanced indicators of productivity of universities. An application of robust nonparametric methods to Italian data. *Scientometrics*, *66*(2), 389–410. doi:10.1007/s11192-006-0028-x.
- Box, G. E. P., & Jenkins, G. M. (1970). *Time series analysis: Forecasting and control*. San Francisco: Holden-Day.
- Box, G. E. P., Jenkins, G. M., & Reinsel, G. C. (1994). *Time series analysis: Forecasting and control* (3rd ed.). Englewood Cliffs, NJ: Prentice Hall.
- Box, G. E. P., & Pierce, D. A. (1970). Distribution of the autocorrelations in AutoRegressive Moving Average time series models. *Journal of the American Statistical Association*, *65*(332), 1509–1526.
- Braun, T., & Schubert, A. (1988). World flash on basic research: Scientometrics versus socio-economic indicators. Scatter plots for 51 countries. 1970–1980. *Scientometrics*, *13*(1), 1–9.
- Casson, R. J., & Al-Qureshi, S. H. (2010). Scientific information, journal impact factors and editorial policy. *Clinical and Experimental Ophthalmology*, *38*(7), 655–656.
- Celeste, R. K., Bastos, J. L., & Faerstein, E. (2011). Trends in the investigation of social determinants of health: Selected themes and methods. *Cadernos de Saude Publica*, *27*(1), 183–189.
- Chang, Y-F., Ku, Y-W., & Hsu, C-Y. (2010). Social policy study in Taiwan. An analysis of postgraduate degree theses, 1990–2008. *Asia Pacific Journal of Social Work and Development*, *20*(1), 95–110.
- Chen, Y. C., Yeh, H. Y., Wu, J. C., Haschler, I., Chen, T. J., & Wetter, T. (2011). Taiwan's National Health Insurance research database: Administrative health care database as study object in bibliometrics. *Scientometrics*, *86*(2), 365–380. doi:10.1007/s11192-010-0289-2.
- de Solla Price, D. J. (1978). Towards a model of science indicators. In Y. Elkana, J. Lederberg, R. K. Merton, A. Thackray, & H. Zuckerman (Eds.), *The advent of science indicators* (pp. 69–95). New York: Wiley.
- de Solla Price, D. J. (1986). *Little science, big science...and beyond*. New York: Columbia University Press.
- Falkenheim, J. C., & Fiegner, M. K. (2008). *2007 Records fifth consecutive annual increase in U.S. doctoral awards*. Arlington, VA: National Science Foundation.
- Fernández-Cano, A., & Bueno, A. (1999). Synthesizing scientometric patterns in Spanish educational research. *Scientometrics*, *46*(2), 349–367. doi:10.1007/BF02464783.
- Fernández-Cano, A., Torralbo, M., & Vallejo, M. (2004). Reconsidering Price's model of scientific growth: An overview. *Scientometrics*, *61*(3), 301–321. doi:10.1023/B:SCIE.0000045112.11562.11.
- Fernández-Cano, A., Torralbo, M., & Vallejo, M. (2008). Revisión y prospectiva de la producción española en tesis doctorales de Pedagogía (1976–2006) [Review and prospective of the Spanish production of doctoral theses in Pedagogy (1976–2006)]. *Revista de Investigación Educativa*, *26*(1), 191–207.
- Guan, J. C., & Chen, K. H. (2010). Modeling macro-R&D production frontier performance: An application to Chinese province-level R&D. *Scientometrics*, *82*(1), 165–173. doi:10.1007/s11192-009-0030-1.
- Han, C. S., Lee, S. K., & England, M. (2010). Transition to postmodern science-related scientometric data. *Scientometrics*, *84*(2), 391–401. doi:10.1007/s11192-009-0119-6.
- Huang, C., Varum, C. A., & Gouveia, J. B. (2006). Scientific productivity paradox: The case of China's S&T system. *Scientometrics*, *69*(2), 449–473. doi:10.1007/s11192-006-0153-6.
- Lakatos, I., & Musgrove, A. (Eds.). (1970). *Criticism and the growth of knowledge*. Cambridge: Cambridge University Press.
- Larivière, V., Zuccala, A., & Archambault, E. (2008). The declining scientific impact of theses: Implications for electronic thesis and dissertation repositories and graduate studies. *Scientometrics*, *74*(1), 109–121. doi:10.1007/s11192-008-0106-3.

- Leitner, J.-R., & Leopold-Wilburger, U. (2011). Experiments on forecasting behavior with several sources of information. A review of literature. *European Journal of Operational Research*, 213(3), 459–469. doi:10.1016/j.ejor.2011.01.006.
- Leydesdorff, L., & Zhou, P. (2005). Are the contributions of China and Korea upsetting the world system of science? *Scientometrics*, 63(3), 617–630. doi:10.1007/s11192-005-0231-1.
- Liang, L. M., Liu, J. W., & Rousseau, R. (2004). Name order patterns of graduate candidates and supervisors in Chinese publications: A case study of three major Chinese universities. *Scientometrics*, 61(1), 3–18. doi:10.1023/B:SCIE.0000037359.22151.6f.
- Ljung, G. M., & Box, G. E. P. (1978). On a measure of a lack of fit in time series models. *Biométrica*, 65(2), 297–303. doi:10.1093/biomet/65.2.29.
- Makridakis, S., & Hibon, M. (2000). The M3-competition: Results, conclusions and implications. *International Journal of Forecasting*, 16(4), 451–476. doi:10.1016/S0169-2070(00)00057-1.
- Makridakis, S., Wheelwright, S. C., & Hyndman, R. J. (1998). *Forecasting. Methods and applications*. New York: Wiley.
- Microsoft Inc. (2010). *Microsoft Excel 2007 version 12*. Seattle: Microsoft Inc. Available at <http://office.microsoft.com/en-us/>
- Ministerio de Educación. (2011). *Tesis doctorales: TESEO*. Available at <https://www.educacion.es/teseo/irBusquedaAvanzada.do>
- Moed, H. F. (2010). Measuring contextual citation impact of scientific journals. *Journal of Informetrics*. doi:10.1016/j.joi.2010.01.002.
- Munz, P. (1985). *Our knowledge of the growth of knowledge: Popper or Wittgenstein?*. London: Routledge.
- National Science Foundation. (2010). *Science and engineering indicators: 2010*. Arlington, VA: National Science Foundation. Available at <http://www.nsf.gov/statistics/seind10/>
- Osuna, C., Cruz-Castro, L., & Sanz-Menéndez, L. (2011). Overturning some assumptions about the effects of evaluation systems on publication performance. *Scientometrics*, 86(3), 575–592. doi:10.1007/s11192-010-0312-7.
- Poincaré, H. (2002). *La ciencia y la hipótesis*. Madrid, Espasa. Original French title: *La science et l'hypothèse (1902)*. Paris: Flammarion.
- Popper, K. R. (1963). *Conjectures and refutations: The growth of scientific knowledge*. London: Routledge.
- Schmoch, U., Schubert, T., Cansen, D., Heidler, R., & von Gortz, R. (2010). How to use indicators to measure scientific performance: A balanced approach. *Research Evaluation*, 19(1), 2–18. doi:10.3152/095820210x492477.
- Sharma, S., & Thomas, V. J. (2008). Inter-country R&D efficiency analysis: An application of data envelopment analysis. *Scientometrics*, 76(3), 483–501. doi:10.1007/s11192-007-1896-4.
- Shelton, R. D. (2008). Relations between national research investment and publication output; Application to an American paradox. *Scientometrics*, 74(2), 191–205. doi:10.1007/s11192-008-0212-2.
- SPSS Inc. & IBM Company. (2010). *IBM SPSS statistic 19*. Chicago: SPSS Inc. Available at <http://www.spss.com>
- Sterman, J. D. (1985). The growth of knowledge: Testing a theory of scientific revolutions with a formal model. *Technological Forecasting and Social Change*, 28(2), 93–122. doi:10.1016/0040-1625(85)90009-5.
- ReliaSoft Inc. (2001). *Reliability growth and repairable system data analysis online referente*. ReliaSoft. Available in <http://www.weibull.com/relgrowthwebcontents.htm>
- Szydlowski, M., & Krawiec, A. (2009). Growth cycles of knowledge. *Scientometrics*, 78(1), 99–111. doi:10.1007/s11192-007-1958-7.
- Szydlowsky, M., & Krawiec, A. (2001). Scientific cycle model with delay. *Scientometrics*, 52(1), 83–95. doi:10.1023/A:1012751028630.
- Thurgood, L., Golladay, M. J., & Hill, S. T. (2006). *U.S. doctorates in the 20th century*. Arlington, VA: National Science Foundation. Available at <http://www.nsf.gov/statistics/nsf06319/pdf/nsf06319.pdf>
- Tseng, Y. H., Lin, Y. I., Hung, W. C., & Lee, C. H. (2009). A comparison of methods for detecting hot topics. *Scientometrics*, 81(1), 73–90. doi:10.1007/s11192-009-1885-x.
- Vasileiadou, E. (2009). Stabilisation operationalised: Using time series analysis to understand the dynamics of research collaboration. *Journal of Informetrics*, 3(1), 36–48. doi:10.1016/j.joi.2008.11.002.
- Vico, G. (2005). *New science: Principles of a new science concerning the common nature of the nations (3er rev. ed.)*. London: Penguin Classics. Original Italian title as *Principi di scienza nuova d'intorno alla comune natura delle nazioni (1744)*.
- Wald, A., & Wolfowitz, J. (1940). On a test whether two samples are from the same population. *The Annals of Mathematical Statistics*, 11(2), 147–162. doi:10.1214/aoms/1177731909.
- Weibull (2011). *Life data analysis (Weibull analysis) software tool*. Reliability software. Tucson, AZ: ReliaSoft Corporation. Available at: <http://www.reliasoft.com/Weibull/index.htm>.