Jointly published by Akadémiai Kiadó, Budapest and Springer, Dordrecht

Scientometrics
DOI: 10.1007/s11192-007-2017-0

Is bigger necessarily better for environmental research?

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In restructuring environmental research organisations, smaller sites generally disappear and larger sites are created. These decisions are based on the economic principle, 'economies of scale', whereby the average cost of each unit produced falls as output increases. We show that this principle does not apply to the scientific performance of environmental research institutes, as productivity per scientist decreased with increasing size of a research site. The results are best explained by the principle 'diseconomies of scale', whereby powerful social factors limit the productivity of larger groupings. These findings should be considered when restructuring environmental science organisations to maximise their quality.

Introduction

In recent years, a wide range of environmental research organisations across Europe have been restructured, with smaller sites being closed or aggregated to form larger sites. The rationale behind such restructuring adheres to a single economic principle, 'economies of scale', whereby the average cost of each unit produced falls as output increases [1]. While this economic principle may be a functional guideline for industry, we demonstrate that it does not apply to the scientific performance of environmental research institutes. We found that neither publication rate nor its quality or use by the wider scientific community increased as predicted; on the contrary, all three measures

Received February 12, 2008

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0138–9130/US $ 20.00

decreased with increasing size of a research site. Moreover, the number of papers published per scientific staff member was greatest for groupings with up to 30 scientists, after which outputs declined. These findings are in line with a second, less well understood economic principle, that of 'diseconomies of scale', which posits that bureaucratic factors pose limits to the productivity of larger groupings [2]. We suggest that these findings should be taken into consideration when restructuring environmental science organisations, thereby providing configurations that maximise high quality scientific research.

Methods

We used publication statistics of the UK's Centre for Ecology and Hydrology (CEH), a geographically dispersed organisation currently in the process of restructuring [3, 4] with research sites of widely different size, to determine whether 'economies of scale' is a principle that helps to predict the academic performance of environmental science groupings. Publications were extracted from the Web of Science, making use of a range of key words, notably all postal codes and possible miss-spellings of those, to derive the total number of peer-reviewed scientific papers published per NERC Centre of Ecology and Hydrology (CEH) site. Cross-reference with CEH publication data bases were made to ensure that the data are a reliable representation of the scientific paper outputs of the individual sites. The years 2003–2005 were used to calculate an average annual publication output for eight sites. For a further two sites that have been recently closed, publications from the three years prior to closure (1999–2001 for one and 2000–2002 for the other) were used. Averages were divided by an index of the size of each of the research sites, the number of scientific staff per site (full time equivalent) as at April 2005 (or 2002 for the two sites that no longer exist), so that the average number of publications per scientist per year could be calculated. A second performance index, the number of times a paper is cited, was calculated for the eight current/recently existing sites. For this, the number of times a paper had been cited between the moment of publishing and the end of 2007 was obtained in the 2nd week of January 2008 from the Web of Science. Subsequently, the median number of times a paper had been cited was calculated per site for each of the three years separately. The average of the resulting three medians was used as the 'measure of central tendency' and related to the number of scientific staff of the respective sites. A third performance index, the total numbers of papers in *Nature* and *Science* per scientist, was calculated over the whole period of CEH existence (1999–2005) for the eight current/recently existing sites, again making use of the number of scientific staff (FTE) as of April 2005.

Results and discussion

Contrary to predictions from the economies of scale principle, the number of peer-reviewed ISI publications per scientist (a commonly used statistic to encapsulate scientific productivity) decreased with increasing number of scientists at a site, and appeared highest for groupings with around 30 scientists (Figure 1a). Annual variation in publication rate was noticeably greater for smaller sites, with the smallest site in particular having a mixture of productive and less productive years. The publication rate of the largest site was much more consistent, but also invariably below average. This suggests that increasing the size of very small groupings to around 30 scientists may help maintain consistently high scientific output. Further enlargement in size may further increase consistency but will be associated with net reductions in output per individual. That the concept of economies of scale has limited applicability in this context also becomes evident when inspecting both the number of times that a paper is cited (Figure 1b) and contributions to frontier journals such as *Nature* and *Science* (Figure 1c). Here, individual scientists from smaller (rather than larger) sites were most likely to push the boundaries of science through communication in these high-impact journals and also saw their work in general more used by the scientific community. Whereas one would like to relate scientific productivity to its financial cost, such data are rarely ever available. Based on the currently best available information provided by CEH management we have to conclude that the total net expenditure per scientist is unrelated to the size of a research unit.

Figure 1 compares one index of scientific productivity against staff numbers over a range in size of research sites. For such sites to be strictly comparable, we would assume 'all else being equal', yet here this is not the case. Although all sites are within CEH, they differ for example in the precise areas of their research, in the age structure and experience of their scientists and in the proportion of their work that involves externally commissioned projects or technical scientific services. Such factors likely impinge upon the output of scientific papers but cannot be controlled for in analysis. The statistics we give involve the whole population of CEH but each site is unique. Thus small sites *per se* might not cause high productivity, but their potential for high scientific output cannot be ignored when restructuring a research organisation.

Nevertheless, the single criterion 'economies of scale' appears to have a strong appeal to science management, perhaps because of its foundations in the rational choice paradigm. Economists, however, have long recognised that the 'economies of scale', which dictate that the ideal size of a firm [5] would be infinitely large, are off-set by 'diseconomies of scale', i.e. forces that cause larger firms to produce goods and services at increased per-unit costs [2].

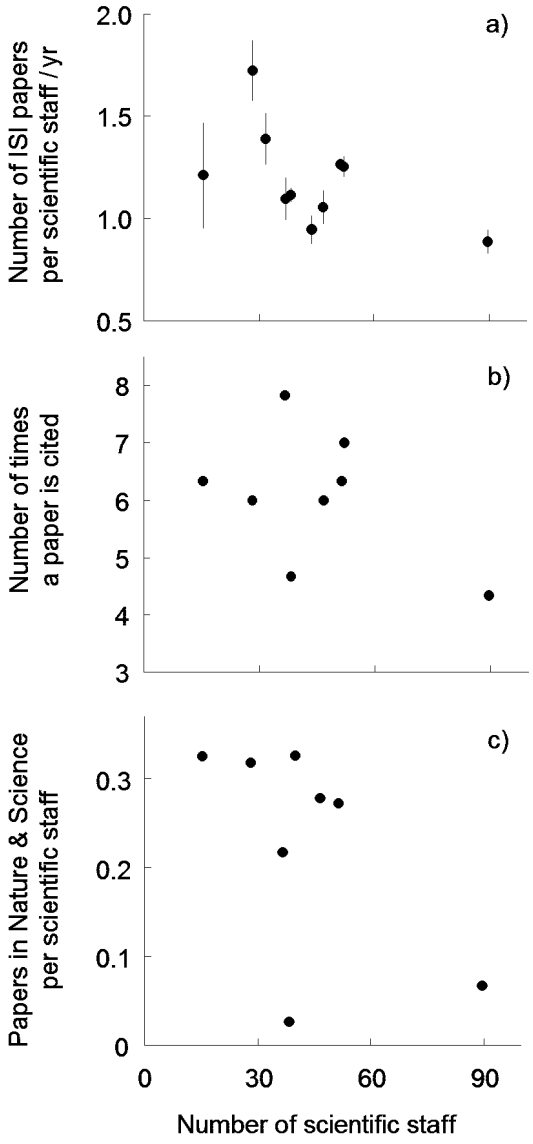

Figure 1. Publication rates per scientist in relation to the size of individual research stations of the NERC Centre for Ecology and Hydrology, UK. a) The number of ISI peer-reviewed scientific papers per scientific staff per year (mean ± population standard error). b) The median number of times a paper is cited within, on average, a 2-year time period. c) The total number of published papers in the journals *Nature* and *Science* per scientific staff between 1999 and 2005

A wealth of well-established economic and social scientific theories exists that helps explain the multitude of effects subsumed under the term 'diseconomies of scale' [6–8]. We propose that the decline in productivity of individual scientists with increasing size of a research site could be due to two central elements of the 'diseconomies of scale' concept: *i*) *atmospheric consequences* (2) and *ii*) *communication distortion* and associated costs (2). *Atmospheric consequences* are largely the result of reduced commitment on the part of employees because with increasing firm size, it becomes increasingly difficult for individual workers to understand the purpose of corporate activities, or even observe the value of their own contribution. As a consequence alienation can occur, concomitant with a decrease in individual performance. This principle may be of particular importance to scientists who are strongly intrinsically motivated and replacing this by extrinsic motivation offered through science management may be counter productive. This concept of 'crowding out' [9, 10] and related social scientific theories [8, 11, 12, 13] can help explain such *atmospheric consequences* as described by Williamson [2]. Dispersed organisations such as national environmental science institutes might minimise the risk of reduced productivity from alienation by sustaining a series of smaller (rather than fewer larger) sites to foster an environment in which individual scientists and support staff feel valued, commit to their remit, perceive themselves as having control over their actions and see their individual contribution having an impact. *Communication distortion* may derive from extra layers of management associated with larger sites and the resulting increase in transaction costs [5, 14]. Parkinson's Law [15] states that the costs of communication increase with the number of workers and its relevance to natural science organisations has previously been demonstrated [16, 17]. In short, with increasing numbers of staff in a given site, the number of communication transactions increases disproportionally, hence increasing the time and thus the costs of communication. Diseconomies of scale are predicted to lead to reduced research and strategic development in industry [18]. Similarly, they may help explain why optimal scientific performance is achieved in smaller, rather than larger, research sites.

From an economic perspective, if only diseconomies of scale were considered, then the ideal firm size may be one worker. If only economies of scale applied, than the ideal firm size would be infinitely large. However, when both apply, the firm must not be too small or too large for optimal performance. Whereas the ideal firm size may be relatively large in industry, our findings suggest that environmental research aimed at delivering innovative, high quality science, may be best carried out within multiple smaller sites rather than fewer larger sites, so that the 'diseconomies of scale' do not undermine the collective scientific productivity of a research organisation. This is in line with earlier findings within the Ecology division of the New Zealand Department of Scientific and Industrial Research [19]. We suggest that the principle 'smaller

environmental research sites are better' might apply widely and that the trade-off between economies and diseconomies of scale be considered in the restructuring of research institutes, to maximise high quality science.

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We thank NERC for the provision of staff numbers, CEH for information on running costs and Alison Odds for cross-checking publication data. Rob Brooker, David Carss, Phil Hulme and two anonymous referees provided valuable comments on an early draft.

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