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Adjusting to precarity: how and why the Roslin Institute forged a leading role for itself in international networks of pig genomics research

James W. E. Lowe

Science, Technology and Innovation Studies, University of Edinburgh, St John's Land, Holyrood, Edinburgh, UK, EH8 8AQ.

james.lowe@ed.ac.uk

Abstract

From the 1980s onwards, the Roslin Institute and its predecessor organisations faced budget cuts, organisational upheaval, and considerable insecurity. Over the next few decades, it was transformed by the introduction of molecular biology and transgenic research, but remained, however, a hub of animal geneticists conducting research aimed at the livestock breeding industry. This paper explores how these animal geneticists embraced genomics in response to the many-faceted precarity that the Roslin Institute faced, establishing it as a global centre for pig genomics research through forging and leading the Pig Gene Mapping Project (PiGMaP); developing and hosting resources, such as a database for genetic linkage data; and producing associated statistical and software tools to analyse the data. The Roslin Institute leveraged these resources to play a key role in further international collaborations as a hedge against precarity. This adoption of genomics was strategically useful, as it took advantage of policy shifts at the national and European levels towards funding research with biotechnological potential. As genomics constitutes a set of infrastructures and resources with manifold uses, the development of capabilities in this domain also helped Roslin to diversify as a response to precarity.

'We weren't joining a network, they were joining us'

Grahame Bulfield, Roslin Institute director, 1988–2002.[1]

This paper details institutional change in the context of changing funding, policy and institutional environments in the latter part of the twentieth-century. I focus on the Roslin Institute and its antecedents, such as the Animal Breeding Research Organisation (ABRO; until 1986) and the Edinburgh Research Station (ERS) of the Institute of Animal Physiology and Genetics Research (IAPGR; 1986–1993). I will mostly refer to this institution as the Roslin Institute or Roslin.

Roslin is most famous for the birth of Dolly the sheep in 1996, the first mammal to be cloned from an adult somatic (rather than germ-line) cell. Recent work has established that this was the culmination of a transgenics research programme dating back to the 1980s.[2] This paper will build on that research by focusing on the period from the late-1980s onwards. I will detail the importance of the advent of a genomics research programme to Roslin's strategic response to budget cuts and institutional change, a response which made use of the institute's long-held quantitative genetics expertise alongside newer molecular biology developments there. Through this programme of work, Roslin made itself indispensable to a wider scientific community through developing networks of the burgeoning field of livestock genomics, in particular pig genomics, and centrally-positioning itself within them. In examining the strategic response of lower-level actors such as individual institutions, this paper also speaks to the history of genomics, the role of the European Commission (EC) in the research ecosystem, and international collaboration.

Genomics, as a term and as a project, emerged from the mid-1980s onwards.[3] Developments in mapping methods and data infrastructures encouraged some administrators and researchers to begin advocating for the systematic mapping and sequencing of genomes, and in particular the human genome.[4] Genomic research on other species was also being pursued, such as on the nematode worm *Caenorhabditis elegans* and yeast (*Saccharomyces cerevisiae*), both of which are model organisms, studied to understand broader phenomena rather than purely for their own sake. It was against this background that genomics was seen as a possible domain that researchers and institutions working on other organisms could enter. In this paper I show how Roslin went about entering that domain, and in doing so helped to generate an ongoing programme of research centred on the mapping and then sequencing of the pig genome, the creation of infrastructures to create, collect, store and analyse genomic data, and the fashioning of a collaborative international network to coordinate the activity. Mapping the pig genome would allow Roslin to make use of the existing resources and skills it possessed, continue to develop the molecular biological capabilities it had been fostering since its strategic re-orientation in the early-1980s, and to access ever-increasing levels of funding for biotechnological research from sources such as the EC. It would allow them to produce data and knowledge to aid the identification and localisation of genes tied to key production traits that would be of use to the pig breeding industry, with whom the institution had ties dating back to the 1960s. Crucially, in building institutional capabilities to produce and analyse data on pig genomes, it could also make itself useful for other researchers and sectors with an interest in the pig beyond it being a source of food. Genomics, in its means of production and outputs, is polyvalent; it constitutes not so much a field in itself but a set of resources and infrastructures that can be used across the biological sciences, and enable forms of work and research that would not otherwise be possible. It was for this reason that heavy investments into genomics were made by public and charitable bodies, and why they were initially focused towards *Homo sapiens* and model organisms.[5] It was for this same reason that it was an attractive line of work for an institution needing to be flexible, to diversify and be adaptable while experiencing turbulent conditions.

Indeed, from the early-1980s onwards, Roslin experienced considerable upheaval and instability. There were significant shifts in: the level, source, stability, length and type of funding; the institute's location; relationships with its sponsoring research council and the nearby University of Edinburgh; leadership; and research direction. Just as important as the actual changes wrought were the constant examination, evaluation and audit of its organisation, management, activities and plans. This constant state of review and uncertainty persisted into the 1990s. This state was imposed by the Agricultural and Food Research Council (AFRC; as the Agricultural Research Council – the ARC – was reconfigured and renamed from 1983) and other governmental initiatives, including the eventual abolition of the AFRC.

I use the term precarity to characterise this situation, and aspects thereof. Precarity is most commonly used to capture the instability and uncertainty of the employment status of people without, for instance, permanent or fixed-hours contracts, or substantial job security. The parallels at an institutional level are evident when Roslin's situation is considered. Roslin may have experienced it more acutely than other facilities, but the rising precarity was widespread at all levels and in all parts of the publicly-funded agricultural research system. Indeed, however acute the circumstances of the Roslin Institute were, its situation was not unique. Institutions across Europe performing research relevant to animal breeding faced greater (e.g., Wageningen University in the Netherlands) or lesser (e.g., Institut National de la Recherche Agronomique, INRA, in France) changes to their management, organisation and funding over this period.[6] In the UK, as a consequence of the policy developments and shifting administrative regime set in train by the Thatcher and Major governments of the 1980s and 1990s, other AFRC institutes faced similar stresses to Roslin; some were abolished or privatised.[7]

I begin in section 1 by outlining the general background of changes in the funding and organisation of agricultural research in the UK from the 1980s, before focusing on how this impacted Roslin. This sets the scene for section 2, which details one strategy for coping with the circumstances laid out in section 1, the development of pig genomics research and capabilities.

Key to this strategy were the collaborative relationships that crystallised through the two successive Pig Gene Mapping Projects (PiGMaP) funded by the EC, PiGMaP I (1991–1994) and PiGMaP II (1994–1996), and which persisted in subsequent collaborations. PiGMaP involved genetic and physical mapping, with the intention of producing integrated genome maps. It was intended to help the livestock breeding industry make more effective selective breeding decisions, to improve knowledge of the relationship between pig genomes and those of cattle, mice and humans, to seed comparative genomics and aid 'the development of porcine models of human disease which are amenable to experimental manipulation.'[8] It involved the production of high-density maps incorporating well-spaced genetic markers, tools for the identification of quantitative trait loci (QTL, parts of the genome associated with variation in phenotypic traits of interest), and the creation of databases, software and statistical methods.

Accompanying this was the formation of stable and permanent networks or platforms that had strong industry involvement and even leadership. In this way, Roslin adroitly capitalised on the opportunities for increased collaboration in scientific research created by the EC, paralleled by the wider rising internationalisation of collaboration.[9] In addition to the increased funds provided by the EC, its directorate-general responsible for research (DG-XII) developed new models for the organisation of research.[10] They encouraged (and often mandated) cross-border, multi-national collaborative projects, the mobility and networking of researchers, industry involvement, and the sharing of data and materials.[11] As well as the role of the EC here, the internationalisation of research was supported by improvements in information and communications technology (ICT), the advent of databases, the geographical dispersion of key research materials, lagging domestic public funding of research and greater researcher mobility.[12]

Roslin's shaping and involvement in collaborative projects translated into a way of adjusting to precarity through the capabilities that they established, and the networks they forged. A crucial aspect of this was in constituting itself as a centre of calculation.[13] As well as producing and mobilising resources of its own, it coordinated the mobilisation of resources produced by others, notably genotyping data. It then stabilised this data and made it combinable by developing the capacity to produce and interpolate new data and forms of data, creating new and progressively more refined genomic resources as a result. Roslin was able to leverage these resources and this position to play a key role in further international collaborations, including the eventual sequencing of the whole pig genome.

1. The Challenging Background

1.1. Changes in the wider research system

By the close of the 1970s, agricultural research in Britain faced two main challenges that would force it to alter direction. The post-Second World War focus on increasing agricultural production had led to surpluses. Consequently, there was pressure to shift from a model of agriculture based on increasing output, towards ensuring that livestock production was competitive, economically sustainable, and (from the 1990s), environmentally sustainable.[14] This had implications for the kinds of research that the ARC/AFRC would be expected to support. Higher-level changes in funding arrangements would make agricultural research establishments more subject to shifts in policy at the governmental level. In 1971, former ARC chairman Lord Rothschild made a decisive intervention in long-running disputes over the independence and governance of agricultural research funded by the state, and its relationship to practical or applied problems. Among other recommendations in his 1971 report 'The Organisation and Management of Government R&D', he introduced the customer-contractor principle into the funding of applied science in agricultural research. The customer would be the Ministry of Agriculture, Fisheries and Food (MAFF), which would define research programmes based on perceived practical needs and contract this work to the research councils. This principle was founded on a strict but pragmatic distinction between basic/pure and applied science, based on the intended practical application of the research. Having established substantial freedom to direct its own research programming at its foundation in 1931, and gaining more control over the direction of agricultural research at the expense of MAFF in the 1956 Agricultural Research Act, the ARC now faced losing a huge part of its portfolio – and budget (53% eventually being transferred to MAFF).[15] The implications of this were not fully realised until accompanied by multiple additional changes that were initiated by the Thatcher government (1979–1990), and consolidated and extended by the subsequent Major government (1990–1997). I detail more specific consequences in the following sections; here I provide a broader contextual outline.

In his examination of science policy in the Thatcher era, Jon Agar foregrounds a number of shifts that are particularly pertinent to this study, which occurred in two main phases of her premiership. The first, lasting until 1987, involved cost-control, a concern with accountability and responsiveness, and deep disquiet with perceived failures to commercially exploit the findings of state-funded research. The push to encourage a more entrepreneurial culture among research scientists working in publicly-funded institutions and effect more technology-transfer to industry accompanied a more general aim to replace the jobs lost due to the accelerated de-industrialisation provoked by the government's policies.[16] One of the areas earmarked for this purpose was the nascent biotechnology sector. A raft of reforms encouraged the growth of venture capital and investment in start-up biotechnology firms; and an increasing array of incentives and rewards were provided to scientists and publicly-funded research institutions aimed at improving their engagement with industry, the acquisition and licensing of intellectual property on research advances, and the creation of spin-off companies.[17] This policy thrust also encouraged attempts to exploit research on livestock for biotechnological purposes, including at Roslin.[18]

The second phase began in 1987, with an abrupt shift that was intended to resolve the frustrations with the outcomes of the prior policies. The conventional tri-partite division of scientific work into 'basic', 'strategic' and 'applied', with a role for publicly-funded research in each division, gave way to a distinction between two new formulations: 'curiosity-driven' and 'near-market' research. The state was to support 'curiosity-driven' research, with funding for 'near-market' research cut; the private sector was expected to pick up the tab instead.[19] This led influential science policy advisors within government to extend the logic of the Rothschild reforms to encourage competition between publicly-funded research establishments for winning research contracts. This implied a change in the institutional status of these establishments. While there were advocates for widespread privatisation, a range of other outcomes were pursued as well, including making institutions into government agencies or legally-independent bodies supported by the state in some (diminished) way.[20] Throughout, these shifts all accompanied – and in many cases caused – changes in the mode, extent and stability of funding. These changes have been associated with the introduction and implementation of an administrative vision called New Public Management, which promoted changes in the relationship between government (and other public bodies such as research councils) and publicly-funded institutions such as research institutes, to encourage the formation of customer-contractor relationships. This entailed institutions developing a wider customer base and the public-sector making use of a wider array of contractors on a competitive basis. The removal of the security of receiving guaranteed support, and the imposition of certain managerial and administrative standards, were intended to aid this transition and make the institutions that were subject to them more flexible and responsive.[21]

The policy shifts detailed above were reflected in the changing programme, funding policy and organisation of the ARC and AFRC. There was a move from longer-term structural funding to shorter-term project-based funding; this has been characterised as a ‘projectification of science’.[22] In 1994, the dissolution of the AFRC and the founding of the Biotechnology and Biological Sciences Research Council (BBSRC) further shifted focus away from agricultural research. The increasing precarity of funding and support, and of institutional status, characterises the challenge to Roslin in this period. At the outset of the 1980s, the mission of one of Roslin’s main precursors – ABRO – was to aid production in the private sector. The imposition of a regime of precarity can be understood as a way of making an institution responsive to additional sectors beyond those with which they have established relationships. In the context of attempts to retool science to aid in the development and competitiveness of new biotechnology industries, this introduction of changes to the nature and behaviour of individual institutions was crucial.[23] An institution can respond to precarity by enhancing its capability to be responsive, even entrepreneurial, or struggle to continue to exist.[24] Indeed, from the early-1980s onwards, the situation for animal genetics research at ABRO was one of institutional and financial flux. To capture what this involved in the period this paper focuses on, I first outline the Roslin's changes in institutional form and location. Then, in successive sections, I illustrate: the difficult relationship with its partner institution near Cambridge; changes in funding arrangements; and the frequent reviews that threatened cuts, further reorganisations and alterations in institutional status.

1.2. Changes to Roslin's institutional form and location

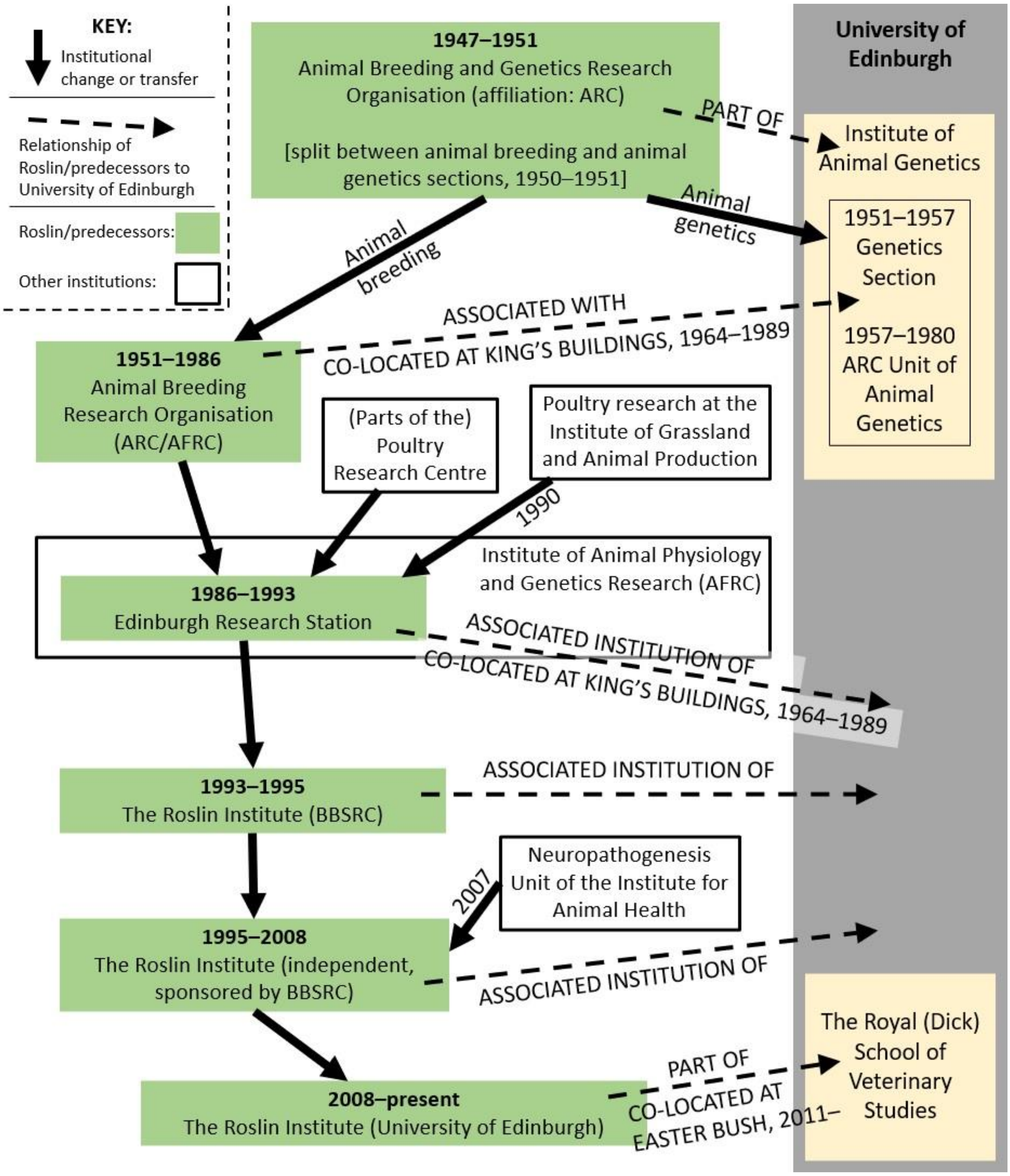

FIGURE 1 – Diagram depicting the key institutional changes experienced by the Roslin Institute and predecessor institutions, and the shifting relationship to the nearby University of Edinburgh.

From the 1980s onwards, Roslin has changed its institutional form several times (see Figure 1). A reorganisation of AFRC Institutes in the mid-1980s culminated in the merger of multiple institutes into so-called ‘super-institutes’. Among these were the IAPGR, which was a merger of: ABRO, parts of the Poultry Research Centre (PRC) based at a site near the village of Roslin (south of Edinburgh), and the Institute of Animal Physiology located in Babraham, Cambridgeshire. The merged institute was initially based on three sites, at Babraham, Roslin and the Kings Buildings in southern Edinburgh, the latter being where the science departments of the University of Edinburgh are situated. The Edinburgh Research Station (ERS, as the former ABRO and PRC elements of the IAPGR came to be known) still maintained links with the University as an Associated Institute. These links were weakened when the remaining ERS staff based at the Kings Buildings campus moved five miles outside the city to the former PRC site near Roslin. This move, and consolidation of the ERS on a single site, was completed in 1989.

In 1990, the rest of the poultry research that had been placed in the Institute of Grassland and Animal Production in the mid-1980s reorganisation became part of the ERS.[25] In 1993, the IAPGR was dissolved into its constituent entities. The Cambridge Research Station (CRS) comprising the Babraham-based portion of the super-institute became the Babraham Institute, while the ERS became the Roslin Institute. Upon independence, the Roslin Institute was initially an institute of the AFRC, and then BBSRC. In 1995, it became an independent institute (becoming a company limited by guarantee and a Scottish Charity), sponsored by the BBSRC. Since 1993, it suffered periodic funding crises ahead of its incorporation into the University of Edinburgh in 2008, moving to the University’s new Easter Bush campus in 2011.

1.3. The relationship with CRS

After becoming part of the super-institute in 1986, ERS also had to deal with the challenges of being in the same institution as the CRS, 400 miles away. CRS had a larger budget and staff, roughly two-thirds of the overall IAPGR. The overall Institute Director (Sir Barry Cross 1986–1989, Sir Brian Heap 1989–1993) also served as head of the CRS, and the location of the Institute leadership in Babraham combined with the relative size of the two organisations led to the perception at ERS that decisions were chiefly made in the interests of the CRS.[26] Collaboration within the super-institute was weak. For instance, a 1992 Visiting Group (an external party of reviewers that monitors research council-funded institutes, often on a 5-year cycle) report noted that '[o]f the 174 and 145 external collaborations at CRS and ERS respectively, only 5 involved collaboration between CRS and ERS. The level of collaboration was no greater than might be expected between two separate UK research establishments of comparable size and complementary interests.'[27]

Substantial operational problems were created by the structure of the super-institute, and the distance between its two main component parts. Distrust of the overall Institute management by the ERS leadership was fomented by a perception that the leadership of the Institute and the CRS was not allocating resources fairly to ERS, that ERS was marginalised in the overall decision-making of the Institute, and that mooted re-organisations – ostensibly to make the Institute more functional and achieve the economies implied by the merger – were intended to concentrate further power (and resources) at CRS.

This came to a head in a 'discussion paper' circulated by the IAPGR Institute Secretary Philip Shaw in June 1991. Shaw proposed that new posts of Institute Finance Officer and Institute Engineer in the central Institute Office be created and based in Babraham, and that further responsibilities be added to the post of Institute Secretary, therefore centralising control over these functions at the Institute level; or, alternatively interpreted, at CRS. Shaw justified his proposed removal of budgetary competencies from stations as a means of circumventing conflicts engendered by 'the way finance is addressed' – disputes over the allocation of resources.[28]

ERS Head of Station (1988–1993) Grahame Bulfield responded swiftly to Shaw's proposals. He acknowledged Shaw's observations concerning ERS's perception of the 'unequal treatment of the two Stations and the goal post [sic] continually moving' and the difficulties 'of managing two sites 350 miles apart, with different scientific philosophies, and different management problems', but contended that these issues could not be resolved with a greater concentration of staff and decision-making powers in a central Institute Office.

Despite serious differences of opinion between Bulfield (and the ERS), Heap, and Shaw, Bulfield's characterisation of the fundamental cleavage in IAPGR was shared by Sir Brian, who has emphasised the significance of funding differences between ERS and CRS in shaping distinct cultures. At the time, CRS was largely dependent on AFRC funds, ergo on the commitment of the research council to funding it. ERS, however, was more dependent on periodic competitive MAFF funding. ERS had been conducting a great deal of 'near-market' research; CRS, far less.[29] The organisational configurations required to deal with these different funding regimes, and the distinct orientations of the work conducted as a result, meant that establishing IAPGR-wide ways of working would clash with the preferred arrangements of one or both of the stations.

Neither Shaw's proposal, Bulfield's rebuttal and counter-proposal, nor other schemes put forward to resolve the cultural and administrative contradictions between the two stations, were implemented.[30] Instead, in the light of the 1992 Visiting Group report, a Review Group (chaired by AFRC Council member Professor William V. Shaw) was commissioned by the AFRC Council to examine the options for the future of the Institute. The Group reported in September 1992, recommending that the IAPGR be split into two institutes, which became the Roslin Institute and the Babraham Institute on 1st April 1993.[31]

1.4. Funding changes

I have already indicated some of the general changes in levels and balance of funding. Here I outline the concrete impact that these had on Roslin. While the ERS was adapting to being the smaller partner in a super-institute and developing a research programme based more heavily on molecular biology, it also suffered the unexpected death of its Head, Roger Land, amid further changes in research policy and funding. Most notably, the Barnes Review applied the radical and largely unanticipated government decision to no longer fund 'near-market' research from 1987/1988 onwards to agricultural research.[32] ERS was still significantly oriented to performing the research that would be included in the vague designation of 'near-market', so this decision represented yet more destabilising news.

Throughout this, ERS was also having to reorient itself towards competing for more external and competitive funds. In a report issued to members of the Visiting Group ahead of their arrival at Roslin in 1992, the shift in funding was laid out in stark figures:

> On the amalgamation of ABRO and PRC to form ERS in 1986, the Station had approximately 50:50 funding from DES [Department of Education and Science – author] and MAFF. The MAFF funding is now about 42% and DES 30%, the

> remainder being made up of external and competitive funds of about 28%. Indeed, there has been a 5.5-fold increase in external funding since 1988 and together with collaborative grants with non-ERS institutions there are over 90 contracts/grants of total value £10.5M.[33]

The subsequent Review Group led by William V. Shaw critiqued some of the effects of recent policy changes, noting 'with concern the continuing decline in real terms in the volume of research commissioned by MAFF with AFRC Institutes following the withdrawal of Government funding for near market research.' Furthermore, they observed that:

> The need of [MAFF] Policy Divisions to respond in their commissioning decisions to economic and political pressures introduced instability within the system which had serious consequences for AFRC. […] The Group concluded that this instability threatened the structure of the science base, and made long term planning and resourcing of AFRC science programmes, and the supporting [of] facilities and expertise, very difficult.[34]

The precarity that Roslin faced did not therefore just manifest itself in concrete changes requiring a response, but in an environment in which prospective changes in the future could not necessarily be anticipated or prepared for.

1.5. Frequent reviews

In addition to the regular Visiting Group reports and internal IAPGR reviews and proposals that occasioned much back-and-forth debate between the two stations, the ERS also experienced regular reviews and reports by the AFRC's Management Audit Unit (MAU), which had been formed in 1985.[35] The increased role for auditing of management and performance within the AFRC was a reflection of the wider adoption of regimes of performance audits as part of the implementation of New Public Management from the late-1970s in the UK and elsewhere.[36] In June/July 1988, September/October 1989 and January 1992, the MAU conducted 'fieldwork' at ERS, interviewing staff, issuing questionnaires, receiving reports, and touring the facilities. Each time, the MAU made sweeping recommendations concerning staff cuts, redeployments and regrading. ERS leadership believed that the motive for this was to downgrade posts rather than offer the constructive managerial and operational advice that was supposedly the MAU's remit.[37]

In addition to the internal AFRC and Institute reviews mentioned above, Roslin also faced further uncertainties due to the Government's launch of a series of reviews into the future of publicly-funded research institutions in the wake of their 1993 white paper, *Realising our potential: A Strategy for Science, Engineering and Technology*. The initial review, the 'Multi-Departmental Scrutiny of Public Sector Research Establishments', was rapidly conducted by the Government's Efficiency Unit in 1994.[38] The follow-up 'Prior Options Review of Public Sector Research Establishments' was then set in motion to examine the institutions not privatised by the previous review, and only concluded in 1997. Both looked at Roslin, among other institutions. The Prior Options Review considered 'the scope for privatisation', that is, the removal of direct Government support, and introducing 'flexibility' in the form of fixed-term contracts for new hires to prepare institutes for privatisation.[39] While full privatisation did not occur for Roslin, their core funding from the BBSRC continued to decline in real terms, and their reliance on short-term (typically, 3-year) research commissions from MAFF instituted at least some of the 'flexibility', or instability, that it would have entailed.

For Roslin, an evolving regime of precarity was set in train in the 1980s. There was no one moment of crisis precipitating the multiple dimensions of this, but the ongoing introduction of a series of changes to policies, and the embedding of new organisational and managerial logics into institutions upon which Roslin relied. The ongoing manifestation of precarity therefore required a response well into the 1990s and beyond.

2. Adjusting to precarity: establishing and leading an international collaboration to map the pig genome

While still part of the super-institute, one of the ways in which Roslin navigated the challenges specified above was by adopting a programme of transgenics research with allied commercialisation, which culminated in the birth of Dolly.[40] However, it also adopted another strategy for responding to the precarity it was facing, which I will now explore. Internal strategic reviews identified genome mapping as an opportunity for the ERS that could build upon existing lines of research, capabilities and material resources, be of interest to industry, and attract European funding. This led to Roslin forging and leading an international network to map the pig genome, and creating new informatics resources, materials and tools to make itself an attractive collaborative partner. As a result, it positioned itself at the centre of pig genome research networks in Europe and beyond, from the late-1980s to the present, opening up new and varied funding opportunities.

2.1. Launching genomics research

A tradition of conducting genetics research relevant to the problems of animal breeding, and ties with the livestock breeding industry, persisted at the ERS.[41] In addition to the nascent transgenics work in the mid-1980s, there were two main lines of genetic research. The first was molecular, characterised by the work of Alan Archibald, who had come to animal genetics from a biochemistry background. The second line of research was quantitative, and was typified by the work of Chris Haley, who came to Roslin following postdoctoral research at the University of Birmingham.[42] Archibald spent 1982–1983 learning recombinant DNA techniques at the European Molecular Biology Laboratory in Heidelberg.[43] From the mid-1980s, he conducted work on the genetics of a condition called Porcine Stress Syndrome. This work concentrated on the establishment of the order of genes around a locus where the responsible mutated gene was hypothesised to reside. This was one of the lines of research that led him into pig gene mapping. He was joined in this work by livestock geneticists from around the world, from both quantitative and molecular backgrounds.[44] This research helped to consolidate links between some of the key actors who would participate in PiGMaP.

The intersection of both quantitative and molecular approaches underpinned pig genome research, and the establishment of Roslin as a centre of data, calculation, coordination and communication. The coming together of these two lines was facilitated by processes set in place by Grahame Bulfield when he became the Head of Station at the ERS in November 1988, taking advantage of the degree of autonomy that ERS had within the super-institute. In the months immediately after his appointment, he talked to all of the institute's scientists about their work. These conversations led to the delineation of possible future work, which fed into the creation of thirteen 'working parties'. The working parties allowed researchers to formulate the basis for new research programmes that better meshed with their skills and interests, within the overall framework of adapting the ERS's research strategy towards a changed funding environment.

Working party 7 on 'Genome Analysis', led by Archibald, decided on the basis of two reports and three meetings that creating a map of a livestock animal genome based on a kind of marker called Restriction Fragment Length Polymorphisms (RFLPs) would be both practically feasible and enable the identification and locating of quantitative trait loci, sites associated with phenotypic variation. Pigs were chosen due to the availability of reference families of crosses between imported Meishan pigs and members of the domestic Large White breed. Meishan pigs are a Chinese breed, and a population of them was imported to the UK in 1987, with animals going to pig breeding companies and Roslin itself. Their prolificacy was of interest to breeding companies because of the potential for increasing the number of piglets born to commercially-bred sows, and to Roslin for the reproductive research that could be conducted on them. For genomics, their value lay in their genetic distinctiveness from European domesticated breeds, as discussed below in section 2.4. The report of the working party noted that 'ERS has a unique ability to generate reference families for mapping, handle large number of DNA samples for RFLP mapping, and the theoretical geneticists and the databases for such analyses.' Although funding arrangements from the AFRC similar to the Transgenic Animal Programme already in place were mooted, it was acknowledged that '[i]nternational collaboration, possibly through the EEC [European Economic Community – author] might be necessary.'[45]

Wider collaboration was deemed to be important to gaining access to funds and different populations of pigs, but also because the scale of research required could not be carried out at the relatively small ERS. Genomics entailed a collaborative mode of work. The drive towards European cooperation was due to the paucity of institutions with which Roslin could collaborate on livestock genomics within the UK, the need for other institutions in Europe to collaborate beyond their own walls and borders, and the research agenda of the EC itself.

2.2. PiGMaP comes together

The first fruit of the strategy of working party 7 was a successful application for funds by Archibald and Haley from the Pig Science Programme of the AFRC. ERS received £159,774 of the total £243,000 for 'AG202/419 (PSP) "A molecular and physical map of the pig genome"' with CRS. The 3-year programme of research from 1990 to 1993 overlapped with the eventual tasks that ERS and CRS promised to fulfil as part of PiGMaP.

In August 1989, Archibald began contacting leading pig geneticists around Europe about an application for a gene mapping project to the EC's BRIDGE programme. One of his correspondents was Louis Ollivier, a quantitative geneticist at the INRA Station de Génétique Quantitative et Appliquée, at Jouy-en-Josas near Paris.[46] Ollivier informed Joël Gellin of Laboratoire de Génétique Cellulaire at INRA Centre Recherches de Toulouse about these plans, and on 11th September, Gellin wrote to Archibald suggesting that they come together to formulate a common project.[47] Gellin noted that a 'round-table discussion on gene mapping […] with a EEC point of view' had been arranged at the CRS by Elizabeth Tucker for November 1989. This meeting took place on 11th November, and involved 40 participants from across Europe. A scientific staff member in DG-XII, Hervé Bazin, was present.[48] Bazin was 'a key supporting figure for getting the PiGMaP project funded', according to Archibald, and guided the mappers through the process.[49] In that same month, Archibald and Haley began receiving the contributions to the overall application from the prospective laboratories. These were soon integrated into an overall proposal, which was accepted for funding from BRIDGE in May 1990. It was funded as a 'N' (networked) project, with a 1.2 million ECU budget (approximately £850,000).[50]

Institutions involved in PiGMaP (I and/or II)	Institutions associated with PiGMaP
CRS/Babraham Institute (UK)	CEA, Fontenay-aux Roses (France)
Danish Institute of Animal Science Research Centre, Foulum (Denmark)	Christian-Albrechts-Universität Kiel (Germany)
INRA Castanet-Tolosan (France)	Humboldt University of Berlin (Germany)
INRA Jouy-en-Josas (France)	INRA Domaine Pluridisciplinaire du Magnerand (France)
Laboratoire mixte INRA-CEA de Radiobiologie Appliquée (France)	Institut de Biologie (France)
Norwegian College of Veterinary Medicine (Norway)	Institute of Animal Physiology and Genetics (Czech Republic)
ERS/Roslin Institute (UK)	Istituto di Allevamenti Zootecnici (Italy)
State University of Ghent (Belgium)	Iowa State University (USA)
Swedish University of Agricultural Sciences (Sweden)	National Institute of Animal Industry (Japan)
Royal Veterinary and Agricultural University (Denmark)	University of Edinburgh (UK)
University of Bologna (Italy)	University of Helsinki (Finland)
University of Hohenheim (Germany)	University of Sydney (Australia)
University of Leicester (UK)	
University of Ulm (Germany)	
University of Utrecht (Netherlands)	
Uppsala University (Sweden)	
Wageningen Agricultural University (Netherlands)	

FIGURE 2 – Institutions involved with PiGMaP. The left-hand column lists institutions that received EC funds as contractors. The right-hand column lists other institutions that contributed to publications produced by PiGMaP.

2.3. Collaboration in PiGMaP

Reflecting norms within livestock genetics communities, data generated within PiGMaP was shared only with those contributing data towards it. Through the sharing of data and materials, PiGMaP helped to strengthen the hitherto weak ties across the pig genetics community that had been established in the 1980s. It also contributed to the forging of links between institutions in European Community countries and those in non-Community countries in Europe and beyond (including Australia, Japan and the USA), through a wider collaboration centred on PiGMAP.

PiGMaP used the strengths and research interests of the participating laboratories, with some efforts to avoid duplication (e.g. the use of subsets of reference families of pigs rather than genotyping them all) and informally divided labour through ad hoc groups and meetings of relevant participants. Alan Archibald served as coordinator, and Roslin hosted a computer system and databases, as well as developing statistical tools for the analysis of data arriving from participating laboratories. There was no strict top-down direction of the dissemination of tasks or division of labour in PiGMaP. Roslin's status as coordinator meant, though, that new laboratories wanting to participate in PiGMaP II – or the wider collaborative network of which it formed the heart – went through Roslin, and more specifically, through Archibald. PiGMaP meetings were not open to any who wished to attend, but outside participants were invited to contribute, for example a regular attendee was the United States Department of Agriculture's (USDA) extramural pig genome coordinator Max Rothschild. In 1990, Archibald and Haley went to the Allerton conference in the USA that led to the development of two USDA-funded initiatives there. Before this meeting, many US actors were not aware of the British and European efforts and participants.

There was considerable incentive for European laboratories to work together. Each came to PiGMaP with their own support from national funding agencies and ministries, and in some cases from the private sector. The European funding, the collaboration, and the sharing and integration of outputs, constituted added value. As many non-European researchers and institutions wanted to work with European collaborators, Roslin's position at the centre of the European network was leveraged into a central role in international efforts.

2.4. Roslin at the centre of PiGMaP

In addition to using the reference family of Meishan-Large White crosses to perform linkage analysis, a crucial part of Roslin's programme of work within PiGMaP was to develop statistical and computational tools for the integration and analysis of the data being submitted to Roslin.[51] This multi-functional role was to be another hedge against precarity, in making itself useful in a variety of contexts, enabling it to take up and develop different opportunities as they arose.

Chris Haley at Roslin, together with (primarily) INRA and Wageningen University, led the work on the development of statistical tools and software. Haley was inspired to develop statistical methods for the mapping of genes and quantitative trait loci in pigs by a 1988 paper reporting the mapping of loci in tomatoes.[52] It was not a simple matter to adapt tools developed for plant genome mapping or human genome mapping to the mapping of genes in pigs. Pig populations are not inbred to anything like the same degree as tomatoes, and in contrast to humans, reference families comprising pigs with known pedigrees could be created.[53]

Reference families, at Roslin at least, consisted of three generations, the second generation being the result of crosses between Meishan and European Large White pigs of the first (grandparental) generation. These pig breeds are genetically and phenotypically distinct. The different breeds were hypothesised to be likely to carry different alleles for equivalent genes. Crosses between breeds should therefore regularly produce offspring heterozygous for those alleles, to provide data on linkage for mapping. Wild boar were used in crosses with Large White pigs by some other PiGMaP groups in order to achieve the same end.

Making use of data arising from crossing experiments conducted across Europe, however, required an informatics capacity that was not in place for pig genome mapping at the start of the 1990s. Acquiring the funds for a computer system that could host a database specifically designed for the requirements of pig genome mapping, was a capital spending priority for ERS for the 1991–92 financial year. An alternative suggestion from elsewhere in the super-institute that PiGMaP use the Genome Database (GDB) at the Medical Research Council's Human Genome Mapping Project Resource Centre, was rejected by ERS. Human genome mapping – for which GDB was designed – involved a different level of mapping resolution, and was not equipped to incorporate reference family pedigree information alongside the linkage data. Additionally, as the editing of the database would be under the control of the Human Genome Mapping Project, this would clash with the EC requirement that there should be a separate database for animal genome mapping.[54] Bazin had given Roslin an indication that they were the preferred home for this. He emphasised that setting up and hosting such a database would allow them to establish themselves as the centre for all mapping project data for farm animal genome projects, and therefore set themselves up for further capacity-building informatics funding from the EC's third framework programme. Roslin got the computer system they needed. This set them up to be able to develop and host two databases for PiGMaP: the more widely accessible PiGBASE holding mapping data, and ResPig for genotyping data sent by (and only accessible to) contributing members of the consortium and the wider collaboration around it. ResPig was the result of a suggestion by Bazin to seek funding to develop the databases being populated by PiGMaP data. This yielded 300,000

ECUs to Roslin and INRA Jouy-en-Josas for the Genome mapping informatics infrastructure (GEMINI) project, as part of the BIOTECH 1 programme.[55]

The development of Roslin's calculative and analytical capacity depended on the adaptation of existing tools and approaches, to be able to deal with the kind of data produced by pig reference families, crosses and genotyping data. PiGBASE was developed from an existing database for mouse genetics, GBase, developed at the Jackson Laboratory in the USA. Roslin staff worked with the Jackson Laboratory's Alan Hillyard to ensure that PiGBASE was equipped for the kinds of data that would be entered into it either manually at Roslin or remotely from elsewhere. First Archibald, and then Archibald with Max Rothschild, edited the database. Another database (GEMMA) was established at the INRA station near Toulouse. While there was regular contact between researchers at Roslin (Archibald and Haley) and INRA (Denis Milan), the databases were never fully integrated. Roslin, nevertheless, was a key point of passage for the inclusion of data in the European side of the mapping effort. Through international contacts, Roslin was also involved in efforts to publish maps based on the data contained in these databases, including integrated maps such as those for swine chromosomes 2 and 5.[56]

PiGMaP participants would send genotyping data to Roslin based on the crosses they performed. This was not in a standardised form, as different data submissions demonstrate (see Figures 3 and 4). In the early years, these data would be manually checked by Archibald. Later, the Roslin bioinformatician Andy Law developed a system that spotted errors or inconsistencies in the results of linkage analyses performed using submitted data. Towards the end of the project, he also created means by which participants could remotely enter data. In addition to checking, entering and analysing data (using statistical tools built into software), the supply of data was monitored from Roslin.[57] PiGMaP participants were able to pursue their work in their own way to a considerable extent. Roslin, however, as the coordinator of the project responsible to the EC for the delivery of promised outputs, had the role of regulating the moral economy of the collaboration.[58] This entailed ensuring that the distribution of (prospective as well as actual) credit motivated and reflected the due sharing of data and contributions towards the overall outputs of the collaboration, as well as the aims and interests of the individual groups.

Locus = GRF

allele 1 = 4.3k

allele 2 = 3.8 k

GRF genotypes (*DraI*) in Edinburgh 2 reference family

	4.3	3.8	
227			?
1104	X	X	1|2
497	X	X	1|2
521		XX	2|2
9609	X	X	1 2
9818		XX	2 2
9810		XX	2 2
6111		XX	2 2
6112	X	X	1 2
6113			?
6114		XX	2 2
6115	X	X	1 2
6118		XX	2 2
6119		XX	2 2
6120	X	X	1 2
6122		XX	2 2
5204	X	X	1 2
5205	X	X	1 2
5206	X	X	1 2
5207	X	X	1 2
5208		XX	2 2
5209	X	X	1 2
5210		XX	2 2
5211		XX	2 2
5213	X	X	1 2
5214	X	X	1 2
5215		XX	2 2

FIGURE 3 – Genotyping data sent to Alan Archibald at the Roslin Institute by Vivi Hunnicke Nielsen at the National Institute of Animal Science Research Centre Foulum, Denmark, 4th June 1993. Source: Alan Archibald's personal papers, folder 'AA4_13 PiGMaP - Foulum'.

		S0066	S0069	S0072					
Ed.2	DK	CGT 16	CGT 19	CGT 22					
227	31	2/18	12/12	10/10					
1104	32	0/0	0/10	10/20					
9609	33	0/2	0/12	10/10					
497	34	0/4	0/8	0/20					
521	35	2/2	8/8	10/20					
9818	36	4/2	8/8	10/20					
9810	37	0/2	8/8	0/20					
6111	38	0/2	8/12	10/10					
6112	39	2/2	0/8	10/10					
6113	40	4/2	8/12	10/10					
6114	41	0/2	8/12	10/10					
6115	42	2/2	8/12	10/10					
6118	43	2/2	8/12	10/20					
6119	44	0/2	0/8	10/10					
6120	45	0/4	0/8	10/20					
6122	46		0/8	10/20					
5204	47		8/12	10/20					
5205	48		0/8	10/20					
5206	49		0/8	0/10					
5207	50		0/8	10/20					
5208	51		0/8	0/10					
5209	52		8/12	10/20					
5210	53		0/8	10/20					
5211	54		0/8	10/20					
5213	55		0/8	10/20					
5214	56		0/8	0/10					
5215	57		8/12	0/10					

31 + 32 = 33
34 + 35 = 36 og 37
33 + 36 = 38 - 46
33 + 37 = 47 - 57

from Trine
30-8-93

FIGURE 4 – Genotyping data sent to Alan Archibald at the Roslin Institute by Trine Winterö at The Royal Veterinary and Agricultural University, Copenhagen, 30th August 1993. Source: Alan Archibald's personal papers, folder 'AA4_4 PiGMaP - Copenhagen'.

Funding support for databases and software was time-limited: PiGBASE expired in 2002. Subsequently, Archibald secured BBSRC grants for the development – led again by Andy Law – of a new database to host data for a range of farmed animals: ArkDB.[59] Roslin was not alone in trying to secure funds to establish and maintain these community resources, and to develop tools to aid researchers in exploiting them as fully as possible.[60] They are, however, fine examples of how Roslin made itself a dynamic attractor for data and mapping analyses over this period, from a standing start in 1989.

As a key location for the development and the hosting of databases and statistical and software tools for the reception and integration of data sent in various forms, Roslin functioned as a centre of calculation for data and its interpretation. Centres of calculation are key actors in creating and maintaining circulations of resources and people; and in analysing, classifying and inscribing data in abstract representative forms like mapping relations stored on a database.[61] In Roslin's case, the existing relationship with the breeding sector had contributed two facets of this before PiGMaP: it was a training centre for geneticists who would go on to work in industry and in other publicly-funded research institutes, and it had access to reference families of pigs that were a valuable genetic resource. Roslin also led the forging of the network that would enable linkage experiment data to feed into it. This allowed Roslin staff to calculate linkage relationships and then hypothesise relative map positions of genetic markers across the genome. A progressively greater resolution of different kinds of markers across the map could then be used in the hunt for 'candidate genes', the characterisation of which was intended to provide a more targeted base for selective breeding. The charting of these markers, in turn, iteratively allowed ever finer-grained mapping as the database entries and inferred linkages between markers flowed out of Roslin alongside DNA samples from their reference families. This allowed the other institutions in the network to generate more data, and to begin to test associations between what was mapped and the data they had collected on the phenotypes of their animals. The results could then be combined with – and tested against – subsequent mapping, data derived from new kinds of genetic markers, data produced using different methods (including physical mapping methods such as radiation hybrid mapping) and maps produced by other projects, such as the one based at the USDA Meat Animal Research Center in Nebraska.[62] Through this activity and these circulations, the strength and connectedness of the networks Roslin had helped to foster was enhanced, as was Roslin's own prominence within them.

2.5. Post-PiGMaP

In terms of specific projects, the EC framework programmes were no less ephemeral than domestic funding sources. In the early-1990s, delays in the approval of the fourth framework programme created uncertainty around funding. Furthermore, funded projects ran for relatively short periods of 2–4 years, and the demands placed on collaborators were inconsistent. EC funding for research did, however, still serve as a buffer against precarity. Partly, this was through the addition of a new source of funds, although these were never a significant proportion of Roslin's income. Mainly, though, it was through new capabilities developed through EC-funded projects (for instance, leading to Roslin developing software such as QTL Express and GridQTL that became significant internationally-used tools), and the platforms and networks that were established from the collaborations that Roslin had helped to forge.

Roslin played a role in securing funding for – and leading – European-funded collaborations beyond PiGMaP. These involved the further identification and mapping of genetic markers, and the continued development of maps, statistical methods, software tools and databases.

These methods and resources were then deployed, for example, in EC-funded collaborations throughout the rest of the 1990s and into the 2000s to study pig genetic diversity, help identify candidate genes or quantitative trait loci relevant to livestock production, and to develop the means to introgress (transfer) an allele from one breed to another.

Roslin was also involved in the creation of genome libraries, in which fragments of DNA are stored in viruses or microorganisms. Genome libraries can be used to search for and analyse particular markers, genes or sequences of interest, to enable the mapping and characterising of genes. A library was created using the P1 bacteriophage during PiGMaP. Later, over 1997 and 1998, Roslin constructed and evaluated a Bacterial Artificial Chromosome library (PigEBAC).

From the late-1990s onwards, efforts were made to obtain backing to sequence the whole pig genome. Initially, attempts to get the USDA and the US National Institutes of Health to fund this were unsuccessful. But from 2000, Archibald acquired funds to begin the process of systematically constructing a physical map of the whole genome, to form the basis for subsequent sequencing. When the sequencing project finally commenced, Archibald and Roslin were key players. This time, they did not host a database or conduct the sequencing, but functioned as a community node, and an organisational and intellectual contributor. The pig genomics community that had developed in the 1980s, and strengthened ties through collaborations throughout the 1990s, conceived and managed the sequencing project through the Swine Genome Sequencing Consortium. The Sanger Institute in Cambridgeshire, UK, was contracted to perform key, technology-intensive parts of the physical mapping and sequencing. Four genome libraries were used, including PigEBAC. Archibald frequently visited and liaised with the Sanger Institute. Once the initial stages of assembly were conducted at the Sanger Institute and The Genome Analysis Centre in nearby Norfolk, further assembly was performed at Roslin by Archibald, and Roslin scientists also contributed towards the genome annotation.[63]

In 2017, a new high-quality version of the swine reference genome was published. This project was led by Archibald and Tim Smith of the USDA Meat Animal Research Center – and significant portions of the work took place at Roslin. This demonstrates how what had begun as one strategy among many to cope with new forms of precarity, actually resulted in the establishment of Roslin as an indispensable centre of communication, circulation, calculation and integration within 21st century livestock genomics. Through developing itself as a centre for genomics research, it has also been able to take advantage of the polyvalence of genomics to establish collaborations beyond livestock genomics. From the 1990s onwards, it has leveraged its capabilities, resources and reputation to participate in projects to assess the diversity and evolutionary relations of the pig, as well as collaborating on more biomedical areas of research, diversifying its research portfolio and opening itself up to more and different kinds of funding and support as a result.[64]

3. Conclusion

Grahame Bulfield has recounted that running Roslin 'was like riding bareback on a wild horse.'[65] His predecessor died suddenly. Regular threats to the funding and status of the institution caused ongoing strife to those working there. The merger with a distant and culturally-distinct institution was still bedding down, funds for 'near-market' research were withdrawn, and core non-competitive funding was declining. New, untested, regimes of audit and measurement of scientific activity augmented existing external monitoring processes.

One strategy to adjust to all this was to target the new opportunities opened up by European funding. This was no less short-term than domestic sources, and its consequences remained: ephemeral jobs (and skills), ephemeral databases, ephemeral data. It did, however, offer another stream of funding, and the opportunity to forge and shape international networks, and to position itself advantageously within them. In this, Roslin were able to take advantage of improved ICT, but they had to fight to secure it, aided by Bazin's guidance, and to demonstrate the worth of the database and software resources they produced. They made use of their existing resources such as the Meishan pigs, augmented these with new resources such as PigEBAC, and coordinated the production and circulation of materials and data from other centres. Roslin encouraged and made use of researcher mobility and the cultivation of new connections with collaborative potential. It achieved this through the training of researchers, contacts with industry and other academics, and the development and coordination of PiGMaP. Roslin's activity therefore demonstrates how an institution can not only respond to changes in the research environment that encourage collaboration, but also construct new niches, thereby modifying that environment to further enhance their collaborative links and embed their own indispensability.

With partners across Europe, through pig genome mapping Roslin was able to build stable configurations of research collaborators, successive research projects, and permanent networks dedicated to promoting livestock genomics research. This has created a centre of gravity that has guaranteed continued support for this research.[66] The EC actors, at the level of DG-XII and Bazin, were interested in capacity-building. This meant identifying certain institutions that could help with this, and aiding the construction of collaborative networks that would provide the impetus for continued development. This took a different form in pig genomics, compared to other contemporary European genomics programmes, such as the

Yeast Genome Sequence Project (YGSP, 1989–1996). For example, in the YGSP, while sequencing was distributed among many laboratories, the project was formally organised in a top-down and hierarchical way. A designated bioinformatics coordinator (the Martinsried Institute for Protein Sequences) collated, analysed and published sequencing data from all participants, and each chromosome or part thereof was under the stewardship of a named coordinator. In PiGMaP, however, Roslin's role emerged, in part through its own initiative; it was not stipulated in official plans, and it was never total. Archibald and Haley, and Roslin more broadly, exhibited 'network power' by stimulating and coordinating interaction and shaping their own position within the collaboration rather than fulfilling a pre-established role.[67] The YGSP took the form it did because of the strategic salience of it as a flagship for the EC, the importance of yeast as a model organism, the utility of yeast genomics for biotechnology and human genomics, and the entry of US actors as potential competitors and collaborators.[68] PiGMaP took the form it did in large part because of the nature and agency of the participating institutions, who were facing similar pressures in differing degrees across the continent. The articulation of genomics that resulted was reflected in the control and involvement of the pig genomics community – forged in projects like PiGMaP – in the eventual effort to fully sequence the pig genome.[69]

Rather than trying to produce comprehensive maps and sequences, Roslin and their collaborators targeted and prioritised particular markers, genes and regions that were known to be of interest to members of the community, leading to different kinds of products than those resulting from yeast and human genomics. This community involvement in shaping and conducting genomics even affected how institutions such as the Human And Vertebrate Analysis and Annotation (HAVANA) group at the Sanger Institute saw their role. Their collaboration with the pig genomics community led them to develop a model of "community annotation" in which they facilitated researchers to annotate areas of the genome of interest to them, rather than conducting the annotation themselves.[70] This paper therefore shows how a detailed attention to institutional history can illuminate larger-scale processes and outcomes such as the creation and organisation of projects to map and sequence genomes.

Roslin's strategy represented a re-adjustment of their alignment with the 'working world' problems of livestock breeding.[71] It further shifted their focus away from direct involvement in breed improvement, towards instead providing data on genomic variants and their possible relationship to phenotypic variation, and developing statistical and computational tools and models that could be used by breeding companies. In so adapting itself, Roslin exhibited resilience, defined as 'an organization's ability to anticipate potential threats, to cope effectively with adverse events, and to adapt to changing conditions.'[72] The adoption of *genomics* as one of the ways in which it helped to effect this re-adjustment is significant. In its polyvalence, genomics constitutes a platform; it is something that provides a basis for a multitude of other forms of work, through the provision of data but also in terms of the technologies, techniques, infrastructures and materials that it provides.[73] It can enable and connect forms of work that are not possible in its absence. Developing the means by which to become a centre for genomics research, expertise and infrastructure was therefore an effective way for Roslin to make itself potentially useful to a wider range of potential collaborators – and funders – across the public and private sectors. It therefore enabled it to diversify and become more flexible and adaptive to an ever-changing research environment.

Whether Roslin's re-orientation reflected an existing resilience built through its own institutional history preceding the challenges discussed in this paper, or built resilience as a result of its own response to them, is an open question. One way to address this would be to examine comparator institutions over a similar time period, and to combine this historical research with contemporary studies of how these institutions are responding to new uncertainties and stresses. These might include medical research institutions that were relatively sheltered from some of the issues faced by agricultural research institutions, as well as other agricultural research institutions that responded in different ways.

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[1] Telephone interview with Grahame Bulfield, conducted by author, 7 November 2017.

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[5] Stephen J. Hilgartner, *Reordering Life: Knowledge and Control in the Genomics Revolution*, The MIT Press, 2017, pp. 31 and 38–40; Cook-Deegan, op. cit. (4), pp. 28, 47, 114, 140–1 and 177–80. The polyvalent uses of genome maps and sequences have been frequently touted by promotors of genomics, e.g. for PiGMaP and the later Swine Genome Sequencing Project: 'PiGMaP BRIDGE Proposal', Alan Archibald's personal papers; Gary Rohrer et al., *Porcine Sequencing White Paper: Porcine Genomic Sequencing Initiative*, Iowa State University Animal Science White Papers, 2002: https://core.ac.uk/download/pdf/212813224.pdf, accessed 26 August 2021.

[6] Skype interview with Martien Groenen, conducted by author, 26 September 2017; Groenen commented that funding had always been short in the Netherlands, encouraging researchers there to seek collaborations, including with the private sector. At INRA, core funding of staff salaries was still provided, but researchers were encouraged to seek more external funding: interview with Louis Ollivier, conducted by author at INRA Jouy-en-Josas, 28 November 2017; personal communication with Claire Rogel-Gaillard, 28 November 2017.

[7] Colin Thirtle, Paolo Palladino, and Jenifer Piesse, 'On the organisation of agricultural research in the United Kingdom, 1945–1994: a quantitative description and appraisal of recent reforms', *Research Policy* (1997) 26(4-5), pp. 557–76.

[8] 'PiGMaP BRIDGE Proposal', op. cit. (5). There was support from breeding companies for PiGMaP, but not substantial.

[9] Yves Gingras, 'Les forms spécifiques de l'internationalité du champ scientifique', *Actes de la Recherche en Sciences Sociales* (2002) 141, pp. 31–45; Marion Maisonabe, Michel Grossetti, Béatrice Milard, Denis Eckert, and Laurent Jégou (tr. Peter Hamilton), 'The global evolution of scientific collaboration networks between cities (1999-2014)', *Revue française de sociologie* (2016) 57, pp. 417–41.

[10] For biotechnology alone, the BRIDGE (Biotechnology Research for Innovation, Development and Growth in Europe; 1990–1993) budget was 100 million ECUs, BIOTECH 1 (1990–94) 186 million, and BIOTECH 2 (1994–98) 595 million. Alfredo Aguilar, Etienne Magnien, and Daniel Thomas, 'Thirty years of European biotechnology programmes: from biomolecular engineering to the bioeconomy', *New Biotechnology* (2013) 30(5), pp. 410–25; Mark F. Cantley and J. Dreux de Nettancourt, 'Biotechnology research and policy in the European Community: the first decade and a half', *FEMS Microbiology Letters* (1992) 100, pp. 25–32. The ECU was the European Currency Unit, the unit of account used in the European Community and Union from 1979 to 1999. On average in 1990 an ECU was equivalent to 0.71385 pounds sterling. Source: 'Euro/ECU exchange rates - annual data': https://ec.europa.eu/eurostat/web/products-datasets/-/ert_bil_eur_a, accessed 26 August 2021.

[11] These included 'laboratories without walls' and 'European Technology Platforms' that Roslin played leading roles in. On laboratories without walls, see: Etienne Magnien, Alfredo Aguilar, Peter Wragg, and Dreux de Nettancourt, 'Les Laboratoires Européens sans Murs: a new tool for biotechnology R&D in the Community', *Biofutur* (1989) 84, pp. 7–30. A

synoptic report of the European Technology Platform that Roslin has been involved in is at: https://cordis.europa.eu/docs/results/44/44228/126625761-6_en.pdf, accessed 26 August 2021.

[12] James D. Adams, Grant C. Black, J. Roger Clemmons, and Paula E. Stephan, 'Scientific teams and institutional collaborations: evidence from U.S. universities, 1981–1999', *Research Policy* (2005) 34, pp. 259–85; Maki Kato and Asao Ando, 'National ties of international scientific collaboration and researcher mobility found in *Nature* and *Science*,' *Scientometrics* (2017) 110, pp. 673–94; Niki Vermeulen, John N. Parker, and Bart Penders, 'Understanding life together: a brief history of collaboration in biology', *Endeavour* (2013) 37, pp. 162–71.

[13] After: Bruno Latour, *Science in Action*, Harvard University Press, 1987, especially pp. 219–32.

[14] David Garwes, *The MAFF/Defra Livestock Science R&D Programme 1991–2006: An overview*, Garwes Associates, 2008.

[15] On the contestations surrounding the genesis and early decades of the ARC, see: Timothy DeJager, 'Pure science and practical interests: the origins of the Agricultural Research Council, 1930-1937', *Minerva* (1993) 31(2), pp. 129–50. For a general account of the Rothschild report and its impact on the organisation and funding of research, see: Miles Parker, 'The Rothschild report (1971) and the purpose of government-funded R&D—a personal account', *Palgrave Communications* (2016) 2, 16053. The effects of the Rothschild reforms and other measures on ABRO is further detailed in: Myelnikov, op. cit. (2). The customer-contractor principle was reversed in 1981 for the Medical Research Council in the case of the latter: Stephen M. Davies, 'Rothschild reversed: explaining the exceptionalism of biomedical research, 1971–1981', *The British Journal for the History of Science* (2019) 52(1), pp. 143–63.

[16] Jon Agar, *Science Policy Under Thatcher*, UCL Press, 2019, pp. 24–25 and chapter 3. The UK government's expenditure on agricultural and food research declined 1980–96; there was an increase in research council funding over this period, but a considerable decline in MAFF research commissions. Institutions like Roslin relied more on the latter, and faced competition from universities for the former; see the following Hansard entries: https://www.publications.parliament.uk/pa/cm199697/cmhansrd/vo970305/text/70305w05.htm and https://www.publications.parliament.uk/pa/cm199697/cmhansrd/vo970227/text/70227w10.htm for UK-wide figures; for Scottish figures: https://www.publications.parliament.uk/pa/cm199697/cmhansrd/vo970305/text/70305w14.htm. Unsurprisingly, staffing levels declined from 1980 to 1991; see: https://www.publications.parliament.uk/pa/cm199091/cmhansrd/1990-12-04/Writtens-1.html and https://www.publications.parliament.uk/pa/cm199091/cmhansrd/1991-06-17/Writtens-1.html all accessed 26 August 2021.

[17] Soraya de Chadarevian, 'The making of an entrepreneurial science: biotechnology in Britain, 1975–1995', *Isis* (2011) 102, pp. 601–33; Geoffrey Owen and Michael M. Hopkins, *Science, the State and the City: Britain's Struggle to Succeed in Biotechnology*, Oxford University Press, 2016.

[18] Roslin adopted recombinant DNA technology to produce transgenic farm animals for animal breeding and the production of therapeutic proteins, the exigencies of the latter leading to research that culminated in the birth of Dolly; see García-Sancho, op. cit. (2); Myelnikov, op. cit. (2); Miguel García-Sancho and Dmitriy Myelnikov, 'Between mice and sheep: biotechnology, agricultural science and animal models in late-twentieth century Edinburgh', *Studies in History and Philosophy of Biological and Biomedical Sciences* (2019) 75, pp. 24–33.

[19] Agar, op. cit. (16), chap. 3.

[20] For example, as a consequence of the 'Next Steps' programme enacted following an initial report in March 1987; Agar, op. cit. (16), pp. 48–9.

[21] New Public Management was applied more generally to the public sector, not just research; Rebecca Boden, Deborah Cox, Maria Nedeva and Katharine Barker, *Scrutinising Science: The Changing UK Government of Science*, Palgrave Macmillan, 2004, esp. pp. 49–50.

[22] Niki Vermeulen, 'From virus to vaccine: projectification of science in the VIRGO consortium', in Bart Penders, Niki Vermeulen, and John Parker (eds.), *Collaboration across Health Research and Medical Care: Healthy Collaboration*, Routledge, 2016, pp. 31–58.

[23] On this retooling see: Robert Bud, *The Uses of Life: A History of Biotechnology*, Cambridge University Press, 1993, pp. 189–206; de Chadarevian, op. cit. (17); Myelnikov, op. cit. (2)

[24] The creation of an order requiring 'perpetual adjustment' from individuals, institutions and states was a key aim of the 'Geneva School' of neo-liberalism, promulgated by figures such as Hayek; Quinn Slobodian, *Globalists: The End of Empire and the Birth of Neoliberalism*, Harvard University Press, 2018.

[25] The AFRC Institute of Grassland and Animal Production encompassed multiple sites. These were in Wales, southern England, south-west England, and the former PRC buildings near Roslin.

[26] The CRS had considerable problems of its own, such as inadequate buildings. The built environment of the CRS was one of the subjects of W.V. Shaw's 1992 Review.

[27] 'REPORT OF THE EDINBURGH RESEARCH STATION', ahead of Visiting Group visit in 1992, IN23/3/2/6/ part 2 of 2; Edinburgh University Library Special Collections.

[28] Document by P. Shaw, dated 24.06.91: 'Confidential Institute Administration Restructuring Discussion Paper', IN23/3/1/2/9; Edinburgh University Library Special Collections.

[29] Interview with Sir Brian Heap, conducted by author, Cambridge, 3 October 2017.

[30] Letter from Grahame Bulfield, 28 June 1991, to Philip Shaw, IAPGR Institute Secretary. IN23/3/1/2/9; Edinburgh University Library Special Collections.

[31] Interview with Sir Thomas Blundell, conducted by author, Cambridge, 8 March 2017.

[32] Though the Barnes Review identified £11.7 million of 'near-market' research concerning livestock to cut (from a total of £32.4 million agricultural research funding), it was unclear how 'near-market' research was to be identified. Also, little consultation preceded the announcement of this new category and the related cuts; Nicholas Read, 'The "near market" concept applied to UK agricultural research', *Science and Public Policy* (1989) 16(4), pp. 233–8. On the genesis of this policy shift, see: Agar, op. cit. (16), especially pp. 88–99.

[33] Op. cit. (27).

[34] Source: 'RESTRICTED AGRICULTURAL AND FOOD RESEARCH COUNCIL REPORT OF THE REVIEW OF THE ROLE OF IAPGR IN AFRC ANIMAL SCIENCE RESEARCH (SHAW REVIEW) SEPTEMBER 1992'. IN23/3/2/6/ part 1 of 2 (Visiting Group report 1992); Edinburgh University Library Special Collections.

[35] Document entitled: 'MANAGEMENT AUDIT UNIT TERMS OF REFERENCE FOR STAFF INSPECTION', attached to a letter from GMP Myers of AFRC to 'Secretaries, New Institutes of Research', dated 17 June 1986, subject: 'STAFF INSPECTION: TERMS OF REFERENCE', in EUA IN23/3/1/2/1 (AFRC Staff inspections 1986-93); Edinburgh University Library Special Collections.

[36] Boden et al., op. cit. (21); Christopher Pollitt, Xavier Girre, Jeremy Lonsdale, Robert Mul, Hilkka Summa, and Marit Waerness, *Performance or Compliance? Performance Audit and Public Management in Five Countries*, Oxford University Press, 1999.

[37] Letter from John Withers to Philip Shaw, dated 15 May 1990, subject: 'MAU ANNUAL REPORT', and enclosed document by Grahame Bulfield, entitled 'STAFF INSPECTION OF SCIENCE POST'. EUA IN23/3/1/2/1
(AFRC Staff inspections 1986-93); Edinburgh University Library Special Collections.

[38] Cm 2991, 'PUBLIC SECTOR RESEARCH ESTABLISHMENTS. Government response to the Multi-Departmental Scrutiny of Public Sector Research Establishments. Presented to Parliament by the President of the Board of Trade by Command of Her Majesty, September 1995', HMSO.

[39] Quotes from the 1993 government white paper 'Realising our potential: A Strategy for Science, Engineering and Technology' and a 'Review of allocation, management and use of Government expenditure on science and technology' authored by the Cabinet Office Efficiency Unit and the Office of Science and Technology, quoted by: William Lea, 'Prior options review of public sector research establishments', Research Paper 96/69, 10 June 1996. House of Commons Library. On this 1990s review process, see Boden et al., op. cit. (21), pp. 59–74.

[40] García-Sancho, op. cit. (2); Myelnikov, op. cit. (2).

[41] Clare Button, 'James Cossar Ewart and the origins of the Animal Breeding Research Department in Edinburgh, 1895–1920', *Journal of the History of Biology* (2017) 51, pp. 445–77.

[42] Edinburgh is and was an important centre for quantitative genetics: Douglas Falconer, 'Quantitative genetics in Edinburgh: 1947-1980', *Genetics* (1993) 133(2), pp. 137–42.

[43] Myelnikov, op. cit. (2)

[44] Alan L. Archibald and Pat Imlah (eds.), ‘The halothane sensitivity locus and its linkage relationships’, *Animal Blood Groups and Biochemical Genetics* (1985) 4, pp. 253–335.

[45] ‘Conclusions and Recommendations from Working Party Reports by Heads of Departments: May 3rd 1989’, IN23/3/2/6/ part 1 of 2; Edinburgh University Library Special Collections.

[46] Letter from Alan Archibald to Louis Ollivier, 16 August 1989; Alan Archibald’s personal papers.

[47] Letter from Joel Gellin to Alan Archibald, 11 September 1989; Alan Archibald’s personal papers.

[48] I thank Alan Archibald for clarifying some of the details concerning this meeting, 26 August 2019.

[49] Interview with Alan Archibald, conducted by author, Roslin Institute, 17 November 2016.

[50] ‘N’ projects were ‘Network’ projects that aimed ‘at stimulating basic research in the Community and give rise to the organisation of highly integrated European Laboratories Without Walls (ELWWs) devoted to the removal, through transnational efforts, of specific bottlenecks in knowledge and know-how’: Cantley and de Nettancourt, op. cit. (10). Source for the conversion of ECUs to pounds sterling, op. cit. (10).

[51] Roslin here performed a similar function to the *C. elegans* databases and mapping software developed at the Laboratory of Molecular Biology in Cambridge in the 1980s, with a similar legacy of being at the heart of a new international network: Soraya de Chadarevian, ‘Mapping the worm’s genome. Tools, networks, patronage,’ in Jean-Paul Gaudillière and Hans-Jörg Rheinberger (eds.), *From Molecular Genetics to Genomics: The mapping cultures of twentieth-century genetics*, Routledge, 2004, pp. 95–110; Miguel García-Sancho, ‘From the genetic to the computer program: the historicity of “data” and “computation” in the

investigations on the nematode worm *C. elegans* (1963–1998)', *Studies in History and Philosophy of Biological and Biomedical Sciences* (2012) 43(1), pp. 16–28.

[52] Andrew H. Paterson et al., 'Resolution of quantitative traits into Mendelian factors by using a complete linkage map of restriction fragment length polymorphisms', *Nature* (1988) 335, pp. 721–6.

[53] Interview with Chris Haley, conducted by author, Edinburgh, 1 February 2017. The different options for constructing populations that are available to scientists researching humans and plants are explored in: Staffan Müller-Wille, 'Making and Unmaking Populations', *Historical Studies in the Natural Sciences* (2018) 48, pp. 604–15.

[54] EUA IN23/3/3/1/10; Edinburgh University Library Special Collections.

[55] https://cordis.europa.eu/project/rcn/5323_en.html, accessed 26 August 2021.

[56] Wei Zhang, Chris Haley, and Chris Moran, 'Alignment of the PiGMaP and USDA linkage maps of porcine chromosomes 2 and 5', *Animal Genetics*, (1995) 26, pp. 361–4.

[57] Alan Archibald, personal communication, 2017; Alan Archibald personal papers.

[58] On moral economies in science, see: Lorraine Daston, 'The moral economy of science', *Osiris* (1995) 10, pp. 2–24; Robert E. Kohler, *Lords of the Fly: Drosophila Genetics and the Experimental Life*, The University of Chicago Press, 1994; Bruno J. Strasser, 'The experimenter's museum: GenBank, natural history, and the moral economies of biomedicine', *Isis* (2011) 102(1), pp. 60–96.

[59] Jian Hu et al., 'The ARKdb: genome databases for farmed and other animals', *Nucleic Acids Research* (2001) 29(1), pp. 106–10.

[60] E.g., the later production of radiation hybrid panels by INRA institutes and their collaborators in the US: Martine Yerle et al., 'Construction of a whole-genome radiation hybrid panel for high-resolution gene mapping in pigs', *Cytogenetics and Cell Genetics* (1998) 82, pp. 182–8.

[61] Michel Callon and Fabian Muniesa, 'Economic markets as calculative collective devices', *Organization Studies* (2005) 26(8), pp. 1229–50; Latour, op. cit. (13), chapter 6; Heike Jöns, 'Centre of calculation', in John A. Agnew and David N. Livingstone (eds.) *The SAGE Handbook of Geographical Knowledge*, SAGE, pp. 158–70.

[62] The importance of the identification and mapping of different kinds of genetic markers is assessed in: James W.E. Lowe and Ann Bruce, 'Genetics without genes? The centrality of genetic markers in livestock genetics and genomics', *History and Philosophy of the Life Sciences* (2019) 41, 50.

[63] On the swine genome sequencing project: James W.E. Lowe, 'Sequencing through thick and thin: historiographical and philosophical implications', *Studies in History and Philosophy of Biological and Biomedical Sciences* (2018) 72, pp. 10–27.

[64] Examples of these different forms of research are: Greger Larson et al., 'Worldwide phylogeography of wild boar reveals multiple centers of pig domestication', *Science* (2005) 307(5715), pp. 1618–21; Zhaoqiang Cui et al., 'Molecular cloning, characterization, and chromosomal assignment of porcine cationic amino acid transporter-1', *Genomics*, (2005) 85(3), pp. 352–9.

[65] Telephone interview with Grahame Bulfield, conducted by author, 7 November 2017.

[66] These include the Farm Animal Industry Platform (FAIP; 1995–2004), its successor, the European Forum of Farm Animal Breeders (EFFAB; 2004–present), and the UK-based 'Genesis Faraday' partnership.

[67] Markku Sotarauta and Nina Mustikkamäki, 'Institutional entrepreneurship, power, and knowledge in innovation systems: institutionalization of regenerative medicine in Tampere, Finland', *Environment and Planning C: Government and Policy* (2015) 33, 342–57.

[68] Giuditta Parolini, 'Building human and industrial capacity in European biotechnology: the Yeast Genome Sequencing Project (1989–1996)', Technische Universität Berlin preprint (2018): http://dx.doi.org/10.14279/depositonce-6693, accessed 26 August 2021.

[69] Lowe, op. cit. (63).

[70] Jane E. Loveland, James G.R. Gilbert, Ed Griffiths, Jennifer L. Harrow, 'Community gene annotation in practice', *Database* (2012), bas009; Harry D. Dawson et al., 'Structural and functional annotation of the porcine immunome', *BMC Genomics* (2013) 14, 332.

[71] Working worlds are domains that pose particular problems, which scientists can approach by constructing abstract representatives; Jon Agar, *Science in the Twentieth Century and Beyond*. Polity, 2012; Jon Agar, 'What is science for? The Lighthill report on artificial intelligence reinterpreted', *The British Journal for the History of Science* (2020) 53(2), pp. 289–310.

[72] Stephanie Duchek, 'Organizational resilience: a capability-based conceptualization', *Business Research* (2020) 13, pp. 215–46.

[73] It has indeed been labelled as such, e.g., in: The *C. elegans* Sequencing Consortium, 'Genome sequence of the nematode *C. elegans*: A platform for investigating biology', *Science* (1998) 282(5396), pp. 2012–18; https://cordis.europa.eu/programme/id/H2020-EU.2.1.4., accessed 26 August 2021.