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Agricultural Innovation: Lessons from Medicine

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Abstract

Today, it is widely acknowledged that agriculture is at a crossroads. The need for greater productivity to cope with a growing population and changing consumer demands – coupled with the necessity that this be done sustainably by reducing pollution and greenhouse gas emissions – presents a number of challenges. Inspired by the successes of the Green Revolution in the 20th century, which saw global cereal production double over the course of 30 years or so, greater levels of research-driven innovation have been promoted as offering a solution to these twin crises; yet this method is not without its own problems. A number of publications in recent years have pointed to there being a failure to 'translate' the basic science conducted by agricultural and horticultural scientists into effective technologies 'on the ground'. This paper considers what lessons the agricultural knowledge & innovation system (AKIS) can learn from medical research translation by reviewing recent literature on translational science and implementation. It is hoped that such a synthesis will contribute to agri-innovation policy formation in the UK.

1. Introduction

Global population is expected to peak at some 9 billion during the 21st century [1], although others maintain that population stabilization this century is unlikely [2]. In light of this, it has been claimed that food production must increase by 70% to meet the 'food gap', doing so with less resources and reducing inputs like fertiliser and pesticides [3]. Competition for land, water and energy are increasing [4]. Of the land on Earth that remains uncultivated, most is either marginal and easily degraded [5, p. 672] or under tropical forest and for a reasons of biodiversity conservation, greenhouse gas emissions, regional climate and hydrology, it is undesirable that this be converted to agricultural land [6]. Although agriculture consumes the greatest share of global water withdrawal (70%), competition from the municipal and industrial sectors is growing, along with growing demand for energy crops.

In response to these dilemmas the term 'sustainable intensification' was borrowed from African agro-developmental discourse as a catchall phrase to capture the requirements of 21st century agriculture, i.e. roughly the same area of the globe currently under cultivation must feed more people, with less resources [7]. How

sustainable intensification is to be achieved – and even what constitutes sustainable intensification – is the subject of debate [8]. As such, agriculture is seen to be at 'crossroads' [9] with discussions about its future compounded by competing visions of how it should move forward [10]. A range of voices representing industry [11], government [12] and international organisations [13] are calling for greater levels of innovation to match not only the severity of the challenges for global agriculture mentioned above, but to bolster local competitiveness and quality. Yet, an innovation – be it an improved variety of wheat or better management practice – is not of benefit until it is applied at farm level. While various terms are used to describe the process, certain voices have joined the others in calling for better *translation* of existing research, identifying the failure to translate or transfer knowledge developed in basic science to the farmer as the *key* issue facing agriculture today [14].

This paper reviews the insights developed within the biomedical research environment, primarily in the United States and United Kingdom, over the last 20 years or so and offers an analysis of what the UK *agricultural knowledge and innovation system* (AKIS, sometimes AIS) can learn from a fellow, biology-based industry.

2. Terminology

A plethora of terms are used to describe a host of related phenomena in medicine: research translation is understood as '… improving prevention and treatment strategies for patients and for communities through translating discoveries in basic and clinical research into products and practices in an efficient, cost-effective manner' [15, p. 1]. In biomedical research, *translational science* is itself a new discipline that aims to bridge the gap between basic and clinical research, or from 'bench' to 'bedside' [16]. If translation is the wider aim of moving science from bench to bedside, then *dissemination* and *implementation* are the processes that make that journey possible. Raghavan [17, p. 94] defines dissemination as increasing the use of evidence-based interventions by a target population, and implementation as the putting to use or integration of evidence-based interventions within a particular service setting, respectively. Clinical science - the task of converting basic biomedical discoveries into safe, tested interventions (usually involving human trials) – can be either conceptualised as a prerequisite to translation [18] or a major component of translational science itself [19].

In either case, translational science is often juxtaposed to *basic* science, which is taken to mean *pre-clinical* research. Translation is not only about ensuring that basic science is translated *within* a particular field, but *across* fields. The repurposing of safe drugs for use against other diseases, for instance, has been promoted as an effective way to bypass long (and expensive) drug-development times [20].

Commonly associated with innovation is *diffusion*, a term no doubt made popular by Everett Roger's *Diffusion of Innovations* [21]. Diffusion, dissemination and implementation perhaps represent progressively active steps in the introduction of a certain product or process [22]. Indeed, we see an increasingly *active* role being played by national heath institutions in ensuring effective research translation, as evidenced by the creation of the National Centre for Advancing Translational Sciences (NCATS) in the United States [23]. Alving, Dai & Chan [15, p. 2] note that while many people associate translation (in the US) with a specific programme, it is in fact a philosophy and a culture.

Medicine	**Public Health**
Primary focus on individual	Primary focus on population
Personal service ethic, conditioned by awareness of social responsibility	Public service ethic, tempered by concerns for the individual
Emphasis on diagnosis and treatment	Emphasis on prevention, health promotion for the whole patient and whole community
Medical paradigm places predominant emphasis on medical care	Public health paradigm employs a spectrum of interventions aimed at the environment, human behaviour and lifestyle, and medical care
Well established profession with sharp public image	Multiple professional identities with diffuse public image
Uniform system for certifying specialists	Variable certification of specialists beyond professional public health degree
Biological sciences central, stimulated by needs of patients; move between laboratory and bedside	Biological sciences central, stimulated by major threats to health of populations; move between laboratory and field
Clinical sciences an essential part of professional training	Clinical sciences peripheral to professional training

Table 1 Distinctions between medical and public health, adapted from Gebbie *et al.* (2003) [24]

Health research is also underpinned by the concept of 'evidence-based medicine', or EBM, and more recently with evidence-based public health or EBPH. The distinction between the two arises from how – and for what level of application – the research is consulted; in the case of evidence-based medicine, decisions about the care of an individual patient are made in accordance with the best evidence. In the case of evidence-based public health, the focus is not on an individual but the public at large. Evidence-based medicine draws upon *randomised clinical trials* and reviews (of such trials) to form a broad consensus of medical best practice. Evidence-based public health, on the other hand, involves a series of steps: problem delineation, option development and implementation, each of which rely on different forms of evidence [25, p. 2]. Whilst the two differ in their epistemologies and missions, they retain important similarities (such as the centrality of sound biological science) (see Table 1). The pooling of data through *systematic reviews* and *meta-analyses* is useful to both practices. It is not, however, common in agricultural science (see Discussion). Meta-analysis is a statistical method of combining the results of primary, independent qualitative research to assess clinical effectiveness of a particular healthcare intervention. A systematic – or structured literature – review, is the process of identifying and selecting relevant literature for inclusion in a synthesis or meta-analysis. Evidence-based medicine and public health, are, in an ideal sense, scientifically supported *best practice*s.

Other terms such as knowledge transfer, knowledge exchange, and knowledge mobilisation find use in other industries but less so in medical research. Rabin & Brownson [26] provide an extensive list of key terms used in medical research translation.

3. The drive towards better translation

3.1. History

Over the course of the two decades or so, a concerted effort has been made to understand and improve research translation in medicine and public health for reasons explored below. However, the history of thought on the topic is much broader, the last decade corresponding to what David Chambers (then Associate Director of Dissemination and Implementation Research at the National Institute of Mental Health, USA) dubs the 'action' phase of a longer process that perhaps began with Archibald Cochrane's *Effectiveness and Efficiency* in the UK (1972) [27]. The name Cochrane has particular resonance in medicine today due to its association with the *Cochrane Database on Systematic Reviews*, a collection of databases that include meta-analyses and syntheses to help health care professionals make informed decisions. Cochrane himself was inspired by agricultural science and the use of randomised, controlled field trials to determine efficacy.

Chambers [27] goes on to delineate the stages that implementation science – or rather, what would become implementation science – has gone through since Cochrane's monograph, defined as:

1. **Precontemplation** (1990s): before a field of dissemination or implementation existed, an implicit assumption that clinicians 'digested' what researchers published in academic journals
2. **Contemplation** (1990s – 2000): the 1990s saw a rise in discussions about dissemination and implementation, with evidence-based medicine popularising the notion that scientific findings should be more comprehensively implemented in typical practice; yet, during this period, there was a growing recognition that the path from research to practice was 'messy' and 'frequently futile' with little inquiry into the 'how' and 'why' this was the case
3. **Preparation** (2000 – 2003): by this point, the barriers and facilitators of implementation were known – the question becoming one of how to remedy the situation – spurning a wave of projects targeting the uptake of effective interventions, though, as Chambers notes, these were lacking a universality, focusing on 'what happened' rather than on how to achieve results
4. **Action** (2003 – Present): since 2003, the rigor and ambitiousness of ongoing studies in dissemination and implementation science has significantly advanced; conceptual frameworks have been developed and are being tested and key constructs (such as organisational readiness, fidelity, reach, culture and climate, clinician acceptability of innovations) have been validated, and comparative studies of different implementation strategies are appearing, ushering in what Chambers calls a 'Golden Age' for the science
5. **Maintenance** (the future): whilst gains have been made, Chambers notes, the value of implementation science has not yet been 'proven', nor remains unchallenged; there is a need for a long-term vision, which the next generation of studies will hopefully address

A logical question to ask at this point is: at which stage would we place modern UK agriculture? Recent developments – such as funding for Agri-tech Research Centres in the UK – would suggest that agriculture is entering the 'action' stage of implementation (see Discussion). However, as a large, complex industry with a multitude of actors, there will inevitably be differences between certain sectors. If the impetus for better translation of research in agriculture is 'feeding the world', what prompted Cochrane, and others since, to pay attention to research translation? The most obvious reason may be a Hippocratic one: 20 – 40% of patients receive care that is inconsistent with scientific evidence or is even harmful [28, p. 1].

The drive for greater rates of and gains in translation can, of course, also be seen as part of the wider push for better efficiency in technology transfer for economic reasons [27] confirming Francis Collins' [23, p. 3] claim that the taxpayer should be entitled to "reap the full benefit" of public investment in medicine. There is a concern, too, that – amongst medical scientists and public health policy-makers –

scientific discoveries of the past generation are not being '…translated effectively into tangible human benefit' [29, p. 1278]. Collins [23, pp. 1-2] echoes this point; without effective research translation, he argues, there is a risk of losing these advantages unless the opportunity is taken to 'revolutionise' the science of translation, drawing a parallel between today and debates within the scientific community 25 years ago about whether to fund a large-scale effort to sequence the human genome (the many benefits of which are now being felt). Although the parallels are 'not precise', translational science as a field faces similar challenges to those that genomics once faced. There has been little focused effort to understanding the translation process as a scientific problem linked to innovation, in need of a comprehensive strategy rather than one-off solutions. Sung *et al.* [29, pp. 1278-9] stress the need for the same kind of investment and commitment in creating *translational infrastructure* as spurned the revolutions in stem cell biology, biomedical engineering, molecular biology and immunology over the last 50 years. These concerns appear to be shared on both sides of the Atlantic. In the UK, we have seen the development of NIHR's Office for Clinical Research Infrastructure (NOCRI), designed to facilitate partnership between public, charity and industry research.

The promise of greater quality of life and improved public health therefore relies to a large degree on the effective translation of research, explaining why translational research is the subject of a rapidly growing literature [30, p. 153]. As Jeffrey Lawrence (Editor-in-Chief of *Translational Research*) notes: '… the number of papers in PubMed with 'translational research' in their title or abstract grew exponentially from 1997 to 2004.' [31]. Other relatively new journals such as *Clinical and Translational Science, Science Translational Medicine*, *Journal of Translational Medicine* and *Implementation Science* all seek to 'fill the gap' between bench and bedside that is the cause of so much concern.

3.2. Modelling the 'pipeline'

The medical research environment has been modeled, re-modeled and replaced over time, representing a scientific problematisation of the medical research environment. Here, we examine the attempts to conceptualise the medical research environment and translational 'pipeline', but first detail the key actors in biomedical research.

The main components that make up the medical research environment are: the public body(s) responsible for healthcare and health research (such as the NHS and NIHR in the UK, and NIH in the US), universities/research institutes, and industry (biotechnology, biomedical/pharmaceutical and medical device/diagnostic companies). There is, of course, the potential for technological spillover from any research undertaken, in terms of both unintended uses and users [32], to say nothing of the increasingly globalised research environment in which a multitude of potential innovation pathways exist. Yet, the translation of basic biomedical research into clinical applications "… remains a slow, expensive and failure-prone

endeavour" [23, p. 1]. As noted earlier, there is a concern that investments in heath research are not reaching the public, policy makers or practitioners in the form of evidence-based practice; this lack of ability to apply research findings has been compared to a 'leaky or broken pipeline' [33], reminiscent of the modern rhetoric surrounding agricultural research translation in the UK that also seeks to invoke the idea of a 'broken pipeline' [14]. This is the first and perhaps most simplistic conceptualisation of the environment through which medical innovations move: a pipeline with inputs at one end and outputs at the other. The validity of such a simplistic, uni-directional model is now being questioned by many of those reckoning with the modern complexity of knowledge and innovation, especially given the number of actors involved. Yet, the image of a simple input-output system or pipeline endures [34, p. 14]. In 2011, Francis Collins called for the identification of 'bottlenecks' in the therapeutic research pipeline and their subsequent 're-engineering' [23].

Balas & Boren [35] developed an early model of the medical research pipeline, synthesizing data from various sources to provide an account of how much, and at which point, research is lost, as well as timescales. In a later imagining of the research environment, Sung *et al.* [29] identified 'blockages' along the pipeline that prevented the effective translation of research, occurring between basic science and improved health outcomes. These included *individual* issues (career disincentives) and *structural* issues (regulatory burdens, fragmented infrastructures and research costs), or what former NIH Director Elias Zerhouni dubbed 'cultural' and 'administrative' barriers [18]. It is most commonly the 'middle ground', between basic science and health outcomes, where problems – be they structural or individual – lie [23]. A number of other potential barriers to research translation were delineated by Greenhalgh *et al.* [36] in a complex but informative model that took account of concepts only recently finding their way into the mainstream of translational science such as the values, goals and social networks of receiving organisations.

In another attempt to codify the medical research environment, Westfall *et al.* [19] developed a simplistic yet powerful model to depict the process of translating basic medical research into public health benefit (see Figure 1). In this conceptualisation, there are three 'stages' of translation, the first two outlined in NIH 'roadmaps' as being T1 (translation of basic biological science into human testing, corresponding to the first 'laboratory' of medical research: the 'bench') and T2 (translation of testing in humans to clinical practice, corresponding to the second 'laboratory' of medical research: the 'bedside'). Westfall *et al.* add a third 'laboratory' (practice-based research) and translational stage (T3, improving the translation of research discoveries into day-to-day care) that nests between human trials and clinical practice. The reconfigured role of T2 places more emphasis on guideline development and meta-analyses, leaving dissemination and implementation activity to T3, with 'feedback loops' (flows of information) up and down the 'chain'. The power of this model as an explanatory tool lies in its simplicity, acknowledgement of feedback loops – translational research is a 'two-way road'

with flows from ‘bench to bedside’ and from ‘bedside to bench’ [37] - and the equal weight given to all three ‘laboratories’ and translational stages, the arrival of the third representing the realisation that research does not apply itself and capitalisation on past research requires asserted effort today.

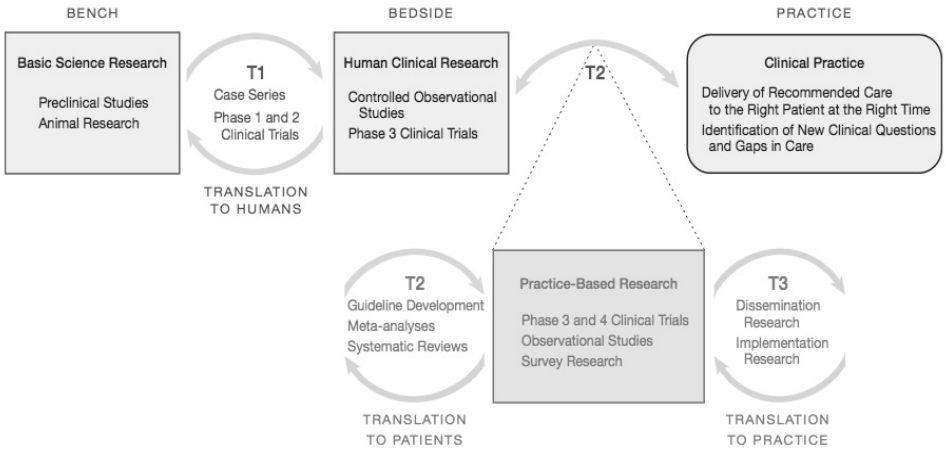

Figure 1 Westfall *et al.*'s model of the biomedical research pipeline with the inclusion of a ‘T3’ translational stage involving dissemination and implementation research [19]

Khoury *et al.* [38] add yet another translational stage (T4) in their model, which divides medical research translation into: gene discovery to health application (T1), health application to evidence-based guideline (T2), guidelines to health practice (T3) and health practice to (public health) impact (T4). Interestingly, this shifts the ‘balance of power’ towards the middle, *translational* end of the pipeline, since the whole process of gene discovery, clinical research and trialing takes place in the first stage, followed by three successive stages of dissemination, implementation and impact assessment. In one sense, we might see Khoury *et al.*’s as a normative model, a suggestion of an ideal rather than reality. It also lacks any representation of feedback loops. Feedback is accounted for by Trochim *et al.* [30, p. 157] who conceive of the medical research landscape a ‘continuum’, with movement in both directions of the continuum, and maintain that directional shifts occur at each juncture in the ‘normal course of things’. In addition, Trochim *et al.* synthesise a number of models (including those cited here), finding that there are five major themes, including: 1) basic research, 2) clinical research, 3) research synthesis (meta-analysis, systematic reviews and guidelines), 4) practice-based research and 5) health impacts. An important commonality between the models is the distinction between research that takes place before and after the development of synthesised clinical trial knowledge [30, p. 156].

Interestingly, later models have rejected the linearity of prior models; this re-thinking of the 'pipeline' is mirrored in evolving conceptions of extension science in farming, first challenged by the 'Farmer First' approach in the 1980s [39] and more recently by systems approaches and social network analysis [40].

3.3. Towards a Science of Translation

It is no surprise that modeling the medical research environment takes a low-resolution approach designed to inform policy makes and identify 'weak points' in the pipeline; the political emphasis on translation, the emergence of journals dedicated to various aspects of translational science, as well as new funding mechanisms for translational research, has each contributed to a wealth of higher-resolution literature examining clinical translation, dissemination and implementation, at a range of conceptual levels. The sheer scope of medical research makes it difficult for practitioners to be kept up to date with current best practice; some two million articles on medical issues are published annually (bear in mind that this is a figure from the early 2000s, so is now likely to be much higher) [41, p. 1].

Cochrane Reviews are one way of consolidating much of this research, but ensuring that best practice is effectively spread and up-taken remains a challenge: Glanville, Haines & Auston [42, p. 19] noted over ten years ago that the drive for more efficient use of evidence-based medicine would require good access to this sizable store of information. Today, the practice of dissemination is handled on a number of levels, from a particular medical field (such as oncology [43]), to university-based schemes (such as the University of York Centre for Reviews and Dissemination (CRD, run by the UK National Institute of Health Research (NIHR)), to national programs (UK NIHR Dissemination Centre). Indeed, effective dissemination has also been espoused for *global* health programmes [44], [45].

With regards to implementation, numerous barriers have been identified that can hinder or enhance uptake of evidence-based medicine (or public health interventions) (see Table 2). Zardo and Collie [46, p. 5], found that the factor most strongly predicting use of research in a public health setting was *research relevance,* suggesting that if research can be made more relevant, the task implementation would be made easier (the question becomes: how can this be achieved?). Green *et al.* [33] and Glasgow & Emmons [47] have also provided thorough analyses of barriers to dissemination and implementation of research, both stressing the importance of context. Other significant factors determining uptake include *skills*, *intention*, and *prompts* [46], meaning that there is responsibility at the organisational level for effective translation. Indeed, the idea of organisational responsibility is embodied in the Promoting Action on Research Implementation in Health Services (PARIHS) framework, which contends that implementing research into practice is as much an organisational issue as an issue of the individual. The framework considers successful implementation (SI) a function (f) of the nature of the evidence (E) being implemented, the context (C) in

which implementation takes place, and the way in which that process is facilitated (F): SI = f(E,C,F) [28, p. 2].

Factor	Potential Barrier
Practice environment	Limitations of time Practice organisation (e.g. lack of disease registers
Educational environment	Inappropriate continuing education/failure to link with programmes promoting quality of care Lack of incentives to participate in effective educational activities
Healthcare environment	Lack of financial resources Lack of defined practice populations Health policies promoting ineffective or unproven activities Failure to provide practitioners with access to appropriate information
Social environment	Influence of media on patients' demands/beliefs Impact of patients' access to care
Patient factors	Demands for care Perceptual/cultural beliefs about care

Table 2 Potential Barriers to Change (adapted from Haines & Donald, 2002) [41]

However, when it comes to changing provider behaviour – that is, the behavior of medical practitioners towards new or improved evidence-based practice – no one method is effective in all circumstances [48]. In fact, there is "… currently no single theory or set of theories that offer testable hypotheses about when and why specific constructs will predict specific outcomes within implementation science" [49, p. 2]. In public health, the use of research in decision-making is highly context dependent [46] and there is little reliable evidence of its use in general [25]. It is therefore difficult to generalise about what translational activities work in public health interventions; *process evaluation*, a framework for assessing why intervention efforts are effective or ineffective, for whom, and under what conditions, has risen in prominence in response to these difficulties [50]. First espoused by Paswon & Tilley in 1997[51], *Realist evaluation* has emerged as a theoretical framework of process evaluation [52], [53] for public health intervention, and has notable parallels with some recent analyses in rural sociology [54].

In this way, process evaluation seeks to correct for a weakness in medical research that has been noted by others; namely, that attempts to preserve the *internal validity* of research through randomised, academic trials with strict inclusion and exclusion criteria can distort *external validity*, or generalisability, to the population as a whole, whom receive care in an entirely different setting [19, p. 403], [33, p. 156].

3.4. Policy to Support Translation

The development of dissemination and implementation science – which have only been superficially outlined here – and particularly clinical science, has been enhanced in the biomedical research environment through pro-active, systemic appraisal and policy measures designed to support these 'critical arenas of research' [18, p. 1621].

The last two directors of the National Institutes of Health (NIH) have made it their mission to improve research translation in US medical research. In 2006, under Elias Zerhouni, NIH launched the CTSA award scheme, which supports investigators translating basic science into health outcomes, as well as Centres of Translational Research at participating institutions (with 62 such centres as of 2015). His successor, Francis Collins, unveiled the National Centre for the Advancement of Translational Science (NCATS) in 2011, with the purpose of transforming the translational science process so that new treatments for illnesses can be delivered to patients more quickly. In Europe, too, translational research has been bolstered: Woolf [55] notes that some consider translational research the cornerstone of the European Commission's €6 billion budget for health-related research, and that the UK is also investing in translational research.

A key message of the push for improved translational science has been on the transformative potential of certain technologies and responsibility to ensure that those innovations translate into health impacts [18], [23]. For instance, Collins, a key leader of the Human Genome Project, cites recent developments in genetics as having exposed many new potential 'avenues' for clinical intervention {Collins:2011wm}. The championing of certain approaches is an influential way to push those technologies further up the political agenda, and offers a lesson in political leadership to agriculturalists.

This isn't to say that the politicization of translational research has been uncontroversial: some have levelled criticism at the 'political pressure' to demonstrate tangible benefit of investments in biomedical research and 'impatience' with the pace of commercialisation of basic science [56], while others take issue with the shift in focus away from basic science [57]. Some suggest that clinical studies should remain the domain of pharmaceutical/private interests [58]. Indeed, pre-market clinical trials – the 'downstream end' of the pipeline - are the strong suit of the private sector [23, p. 1]. Gerald Weissmann (Editor-in-chief of the *FASEB* journal) expressed concern that (renewed) emphasis on translational

science might dampen the childlike curiosity of those whose passion is basic science [57]; it's not difficult to imagine a similar response from scientists within the realm of agricultural research in response to the arrival of translational science discourse. As Fang & Casadevall [56] explain, basic science provides the 'raw material' for translation in biomedical research (and this is no less true for agriculture). They call for robust investment in basic science to match support for translational research. The links between investment in agricultural research and productivity are well known [59], but changes in the rationale, structure and delivery of R&D funding for agricultural research since the 1980s [60]-[62] has caused a re-examination of the agricultural research environment at a number of conceptual levels.

4. Discussion

Today, the aims of agricultural research are as numerous as the challenges it faces. The post-war, 'productivist' research agenda largely achieved its aims, eliminating food shortages in the developed world [14]. Emphasis shifted towards a 'post-productivist' paradigm [63] in which measurements of success were determined not only by yield and productivity, but environmental impact. The waning of the dominant, productivist paradigm also saw changes in the practice and theory of agricultural *extension* [64], a term we might wish to compare to 'translation'. However, in recent years 'translation' – as well as knowledge transfer, exchange and mobilization – has entered the agricultural lexicon (particularly at the level of policy), exemplified by the rhetoric of 'fixing' broken 'pipelines' (of research) [14], ensuring 'effective translation' or 'effective flows' of scientific evidence [12], [65], [66] and 'bridging gaps' between lab and marketplace [67].

What might have once been called extension – and one can debate to what extent the terms extension and translation are equivalent – has gained the language of the biomedical research environment in the US and UK. The Thatcher-era privatisation of England's formerly public extension service, ADAS, may have led to this 're-branding' of extension as a problem of scientific translation. As a term, extension is primarily agricultural, whereas 'translation' can work for, and across, different industries or fields (i.e. life science as a whole). As Pollock [14] notes with regards to the successes of the post-war era agri-research:
'In most cases, these successes were based upon a solid foundation of innovative basic science that linked effectively both into directed strategic and applied research and into effective deployment of new knowledge and practice by producers.' (p. 1)
Some have bemoaned the loss of this service, which undertook the dissemination of research through a network of agronomists and close links with universities, industry and research institutes as well as policy-makers. Others have argued that the practice and theory of extension – and not only in England and Wales - is rooted in the older, top-down, productivist model of knowledge transfer that can no longer solve agricultural problems given their scale and complexity [40] p. e105203. Interestingly, we have seen both a push from 'above' for better

translation (at least in the UK) in response to lower-than-expected agricultural productivity and simultaneous push in academia towards the 'negotiated knowledge' of human and international development approaches in response to interest in multi-functional land management, environmental problems and challenges to 'scientific superiority' [64]. This has led to, firstly, a systems approach to the study of agricultural change [68], and secondly, a recognition that with the right conditions, information and interactions, land managers will use their own knowledge to develop solutions to their problems. Here we see several analogies between the biomedical research environment and the agricultural; both have experienced or are experiencing a top-down push for improved research translation in response to a perceived lack of research impact (and slow lead-times and high failure-rates in medical research) and concurrent, academia-led challenges to certain scientific methodologies within the respective fields (process evaluation supported by realist theory in the case of medical research and systems approaches supported by international and human development theory in agricultural research). There are also have similar sets of actors operating within the wider system; researchers supported by public and private partners; medical practitioners and public health policy-makers, farmers and agronomists, to whom information must flow; and those involved in determining how this best be done.

A fundamental difference between the two industries does limit what comparisons we can make, however: commercial farmers are under no direct obligation to adopt 'best practice'. As long as a profit is made (and sometimes, even if it isn't) a farmer or grower may continue his or her operations, and certain designations have been used to describe the attitude of farmers and growers towards the use of new technologies ('traditionalists' vs. 'pioneers' in the horticultural industry, for instance [69]). Farmers are not (necessarily) researchers, whereas medical practitioners will have been exposed to evidence-based medicine from early on in their careers. It is worth noting, however, that since the introduction of *Farmer First* [39] in 1989, there has been a move in some spheres to place farmers at the centre of research endeavours (rather than excluding them entirely or seeing them as passive recipients of 'new' knowledge). The development of the Farmer First approach came with recognition that farmers are not only the initiators of agricultural innovation themselves, but modify and adapt new products and processes to suit their specific needs through tacit, experiential knowledge. In a way, this mirrors the concerns in public health research that what works in one setting may not in another, and that context is key. It is certainly true that tacit, experiential knowledge plays a key role in the medical profession [70], with un-codified 'good judgment' determining the application of evidence-based medicine. However, there is a condition that medical practitioners be kept up-to-date with the latest science and best practice (litigation, whilst not absent in farming, is an important consideration in healthcare delivery). There is no Hippocratic oath in farming, despite its importance. In this sense, implementation – the most 'active' form of translation – is more pronounced in healthcare than in agriculture. This is perhaps best exemplified by the differences in funding between the two: while some £800 million

was made available for UK biomedical research in 2011 (including two translational research partnerships) [71] £70 million was invested in the Agri-Tech Catalyst fund in 2013, the goal of which is to help develop and introduce agricultural technologies. What funding has been made available, though, does suggest a commitment to the idea of translation, placing UK agriculture at an early stage of 'action' on translational issues (see Chambers' 'stages of implementation science' above).

With these similarities and differences in mind, what lessons can the agricultural research environment draw from biomedical research, given the attention paid to translation in medicine over the last few decades and the recent attention it has been given in agriculture?

4.1. The Agricultural Research Environment

Like the biomedical research environment, the key actors in the agricultural research environment in the UK include public bodies (be it the Department for Environment, Food and Rural Affairs (Defra), agricultural levy bodies such as the Agriculture and Horticulture Development Board (AHDB) or a specific Research Council (like the BBSRC), universities and research institutes (such as Rothamsted Research and Warwick Crop Centre) and industry (seed and agri-technology companies for example). Whereas the medical research environment has most commonly been conceptualised as a pipeline, the dominant framework for assessing the agricultural research environment has become the *agricultural knowledge and innovation systems* (AKIS) approach, used to analyse technological, economical and institutional change in agriculture [72]. This framework has been used by the European Union [73], OECD [60] and in developmental research policy [62].

Despite the move away from a pipeline approach, we can identify a formal, structured environment – that one might argue resembles a pipeline – in agricultural research, consisting of granting bodies (like the BBSRC and levy-bodies), universities and research institutes who receive funding to undertake either basic plant, animal or applied science, and independent agronomists, growers and farmers. Private firms, such as large seed companies, either invest in research 'in-house' via their own organisational pipeline (and disseminate their product by way of marketing and their agronomists) or enter the formal pipeline outlined above by funding or co-funding research projects. What we have in the recent focus on so-called 'bottlenecks' in the US biomedical research pipeline and translation in general, is a case study in the problematisation of a research environment. The challenge for agriculture will be blending the valuable insights from systems approaches to the narrower – but more focused – appraisal of agricultural pipelines.

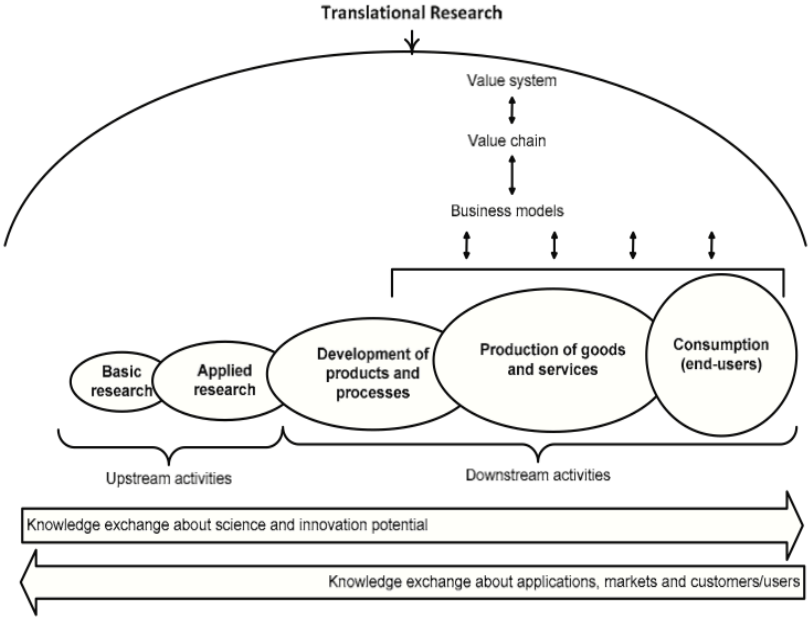

Figure 2 RAND & INNOGEN's conceptual framework for translational research and knowledge exchange in agriculture and food [66]

What might a model of the agri-research environment look like? Where do blockages exist? In 2011 Defra and BBSRC commissioned RAND Europe to examine the issue of translational research in UK agriculture. Focussing specifically on the wheat value chain, researchers at RAND were able to offer both a model and an analysis of the communication system comprising the actors in the wheat industry (see Figure 2). The model lacks Sung *et al.*'s [29] focus on personal and structural barriers to translation, and lacks detail of translational activity between crucial stages (such as basic research and applied research), as is developed in the biomedical models of Khoury *et al.* [38], for example. Instead, 'translational research' acts as an umbrella term for the continuum of agricultural research and its end-uses. In this sense, the model is normative and not in itself a problematisation of the research environment. A useful addition to this model would be the NIH's delineation of 'laboratories' of translation; for example, if basic science is considered the first laboratory or stage (T1), then applied research using field trials form the second such laboratory (T2), followed by disseminatory activities (T3) and finally on-farm experimentation and impact-assessment (T4).

The extent to which information can go 'both ways' through the model is unclear. Although the authors have specified a multi-directional flow of information – knowledge and innovation potential one way, and applications, markets and customer information the other – the model does not include the barriers that might exist to these flows of information, though many were delineated in the report.

Pollock [14] notes that the decreased role of research institutes – typically involved in more 'applied' research – and increased role of the university – typically involved in more 'basic' science – coupled with declining funding for strategic research has meant a focus away from industry needs. Add to this a lack of UK-wide, comprehensive extension service, and the social 'distance' of scientists from their 'customers' (farmers and agronomists), which is a problem even in countries with an extension service [39], we see several challenges to translation in UK agri-research.

More work needs to be done, as has been done in the biomedical research environment, to determine where research 'leaks' from the pipeline (as Balas & Boren [35] undertook for medical research), how long research takes to 'pass through' the pipeline and how much it costs for a particular product or process to go from 'bench' to 'bedside', or perhaps more accurately: 'lab' to 'field'. This process may not capture the relationships between actors as does a systems approach, but may serve to highlight areas in which the formal agricultural research pipeline can be improved. Likewise, there is a need to assess how formalised agri-research fits into the overall agricultural knowledge and innovation system; abandoning the systems approach for a solely uni-linear model of knowledge development would represent a major step-backward and would fail to acknowledge the many sources of agricultural knowledge that exist in the wider system [54], [64]. Indeed, a multitude of actors now exist that provide advice to farmers, such as commercial organisations, private consultancy, government, non-government organisations (NGOs), farmer-funded organisations and research institutes, using a variety of mechanisms to send a range of messages [54]. Farmers respond differently to these various actors, and there is already a long history in extension science, and in the burgeoning systems-focussed literature, on examining the relationships between farmers, agronomists and researchers, for example. The shift towards human development theory in farming should be welcomed; the farmer is not patronised (Wood *et al.* note that in the linear model of agricultural learning, new knowledge was construed as something farmers did not posses and that must be transferred, somehow, to them), it being assumed that land managers use their own knowledge to develop solutions to their problems given adequate information and interactions within the system. With this in mind, we see a need for adequate dissemination to ensure land managers are making the best possible decisions (and a raft of research related to farmer decision-making and decision-making support has appeared in recent years [74]-[76]). One could argue this need is most similar to disseminating information on the latest evidence-based *medicine* to medical practitioners, and is a central concern of levy-bodies in today's agriculture.

When it comes to wider agro-environmental schemes, however, we see analogies with evidence-based *public health*. In the academic literature we see a particular focus – using approaches not dissimilar from process evaluation and the ethos of realist evaluation – on implementation of agri-environmental schemes, the 'public-health' domain of agriculture [54]. Here, we are focussing on the success of

national or regional level initiatives, rather than individual farms. Yet whether we are concerned with medicine or public health and what analogies there may be to farming, both are underpinned by the idea of systematic review. In agriculture we see only limited use of this process; it has been used to assess the effects of particular farming systems, such as organic agriculture on biodiversity [77] or crop responses to conservation agriculture [78], and less so to determine best practice in the same way it used in biomedical research. Syntheses can provide a valuable analysis of factors affecting research-use in agricultural policy-making, for instance. In a study of this kind, Garforth & Usher [32] note that context is key and, like medicine, *research relevance* is the most significant factor determining research uptake (see Seers *et al.* (2012) and Zardo & Collie (2014)). How can research be made more relevant? It has been suggested that the entire farming industry have a greater stake in R&D strategy by improving communication between industry and those who set the basic science agenda [14]. If the role of the agricultural scientist is to provide farmers and industry at large with solutions – in the same way biomedical scientists provide clinicians and medical practitioners with interventions to improve health – then a consequence of the post-productivist era may have been to repurpose agricultural research to serve environmental and not (necessarily) industry needs. Indeed, by refocussing agri-research on industry needs the relevance of research for farmers will inevitably be enhanced. While industry and policy-makers may speak a similar language, it has been noted that *scientists* and policy-makers do not [79]. We can turn, again, to the medical field for solutions; the concept of knowledge brokers, individuals who find, assess, and interpret evidence, facilitate interaction and identify pressing research questions, has been used primarily in public health settings to get evidence into practice [80]. Agronomists have been at the interface between industry, farming, research and policy for decades, and are often amongst the most trusted sources of knowledge for farmers. Likewise, the biomedical research environment has actively supported clinical translation and researchers at the interface between basic and applied science.

However, as we have seen in US biomedical research, there is a need to actively support these types of career; noting that recruitment and retention of translational scientists was being hampered by increasing financial burdens and time restrictions, investment in human capital and the provision of ‘well-defined’ career paths in translational science were ensured through the creation of the CTSAs [18]. Entry-rates into UK farming are low, and the exit-rate is growing, as is the average age of British farmers [81]. There has also been no ‘clear picture’ of how to make agriculture more attractive to new entrants in research or technology development, or farming in general [12]. By better supporting intermediary roles such as agronomists and applied - or even translational - scientists, UK agriculture could enhance the translation of research from laboratory to field.

Just as the focus on translation in the biomedical research environment was seen as jeopardising basic science, being seen as less about *good* science and more about politics, the same might be argued for agricultural research; diminishing

returns on agricultural research may not be down to a failure in translation, but down to reduced funding for basic biological research and, notably, applied agricultural research. Empty political rhetoric about reaping the rewards of research, or perhaps impatience with the pace of commercialisation due to unrealistic expectations of science, may lead us to believe that the 'system' is broken, as opposed to merely lacking investment.

5. Conclusion

In this paper we have reviewed recent literature on biomedical research translation and have sought to draw comparisons with recent emphasis on translational research in UK agriculture. Both fields are complex and not easily described in a limited fashion, but there are a number of similarities – and differences – that can be drawn between them. Although extension science has been present within the wider agricultural research environment since at least the early post-war years, the biomedical research environment began 're-engineering' its own translational infrastructure earlier than did agriculture. In this way, we have a case study of a fellow, biology-based industry to learn from; many insights gleaned from the medical sphere reflect things already know in agriculture (such as the centrality of context in implementation). Other concepts, such as the problematisation of research pipelines and investment in intermediary actors (through specific granting mechanisms) offer valuable lessons for agricultural researchers to learn from.

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