RESEARCH PAPER

Farmer-driven innovation: lessons from a case study of subterranean clover seed production

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ABSTRACT
Farmers are often overlooked and undervalued as sources of innovation, but can be powerful drivers of ingenuity and development. We evaluate historical developments in the Australian subterranean clover seed-production industry as a case study of farmer-driven innovation. Subterranean clover seed machinery patents (75% of which were patented by farmers) are analysed using conventional innovation frameworks, such as the theory of inventive problem solving (TRIZ), to extract lessons for supporting farmer-driven innovation. The small scale of this industry, compared with mainstream cereal-cropping industries and the isolation of farmers, provides analogous lessons for agriculture in developing countries. Economic drivers are important in enabling farmer innovation and the value proposition for developing new inventions must be clear to justify the time and expense. Farmers are different from firms and their on-farm knowledge and experience can form an essential part of innovation. Drivers of innovation also differ, with farmers less likely to attempt to commercialize inventions. Farmers can also be hesitant to share their inventions, instead holding them as trade secrets in competitive industries. Support and collaboration are needed from government and researchers to assist in commercialization or dissemination of useful innovations and to prevent knowledge from being confined to a localized farmer or region. Advances in agriculture require farmer input in research and development, but the benefits will be greater if farmers are enabled to be drivers of innovation.

Introduction

Farmer-driven innovation

Global agriculture faces the combined challenges of feeding the growing population while reducing its environmental footprint – particularly land use and greenhouse gas emissions (Schmidhuber and Tubiello, 2007; Godfray *et al.*, 2010; FAO, 2018; Sadras *et al.*, 2020). Agricultural innovation is essential to meet these challenges and intensify global agricultural production sustainably (OECD, 2013; MacMillan and Benton, 2014; Läpple *et al.*, 2015; Gaffney *et al.*, 2019). Recognition of these challenges, and of the economic, environmental and social benefits for overcoming them, is driving innovation in agriculture. Approximately US$26 billion was invested into agricultural food and technology (agrifood tech) startup firms in 2020 (AgFunder, 2021). In addition, there is significant

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investment from large, established corporations; for example, Bayer's Crop Science division plans to invest €25 billion (~US$30 billion) in research and development (R&D) over ten years (Bayer, 2019). This increasing investment from private firms and venture capitalists contrasts with stagnating (in real terms) public agricultural R&D investment from high-income countries such as the United States (Heisey and Fuglie, 2018).

However, R&D is not the sole driver of advancement in agriculture and farmers are often key sources of innovation (Biggs and Clay, 1981; Rhoades and Booth, 1982; Hoffmann *et al.*, 2007; Sneddon *et al.*, 2009; Sauer, 2017). On-farm innovation is overlooked (McKenzie, 2013; Bragdon and Smith, 2015; MacMillan and Benton, 2014; Läpple *et al.*, 2015) and farmers are frequently considered only in terms of adoption of knowledge and technology, not its creation (Dolinska, 2017). The US Department of Agriculture estimates US$20 billion in annual private sector agriculture R&D investment, but counts $0 of farmer research in this total (MacMillan and Benton, 2014). This figure underestimates the contribution of on-farm R&D and there is significant untapped potential to harness farmers as sources of agricultural innovation.

As historical context can be a valuable tool for developing new solutions to existing challenges (Guzzomi *et al.*, 2012; Díaz Lankenau and Winter, 2019), we present a history-based perspective of farmer innovation through a case study of subterranean clover (*trifolium subterraneum* L.) seed production in Australia. In particular, we look at the generation of patented machine designs for harvesting subterranean clover (subclover) seed and the factors affecting technology development and success. We posit that understanding the processes driving on-farm innovation and recognizing farmers as valuable sources of ingenuity could provide the tools to enable or empower farmers to contribute novel and grassroots innovation to assist meeting the challenges facing global agriculture.

Subterranean clover seed production

Subclover is Australia's most important and widely sown (over 29 million ha) annual pasture legume (Smith, 2011; Nichols *et al.*, 2013; Ghamkhar *et al.*, 2015). Subclover forms an important part of Australia's farming systems and has contributed to significant agricultural improvements over the last century (Donald and Williams, 1954; Puckridge and French, 1983; Smith, 2000; Peoples and Baldock, 2001). Subclover pastures increase soil fertility for subsequent cropping phases in addition to providing high-quality pasture for stocking phases (Puckridge and French, 1983; Nichols *et al.*, 2012). This legume rotation system is receiving global attention as part of 'sustainable intensification' frameworks, which seek to address food security and climate change issues in global agriculture (Pretty and Bharucha, 2014; Pretty *et al.*, 2018).

One of the strengths of subclover as a pasture plant is its ability to bury its seed, which protects the seed from desiccation and grazing by livestock, and establishes a seed bank for self-regeneration in future years (Loi *et al.*, 2005; Nichols *et al.*, 2012). However, harvesting this small seed (typically 6–10 mg) from below the soil surface presents significant difficulties compared with harvesting aerial-seeding crops. Overcoming this challenge necessitated innovation to develop specialized machinery and techniques, and farmers played a key role in the development of the solutions that advanced this seed-production industry (Moss *et al.*, 2022). This relatively small industry – the size of the Australian subclover seed-production is measured in the thousands of tonnes each year, while Australian wheat production is measured in millions of tonnes (ABARES, 2020, Australian Seeds Authority, 2020) – is analogous to agriculture in developing countries.

To provide context to innovations in the subclover seed industry, a brief historical account of the use of subclover in Australia follows. More detailed accounts are provided in Henzell (2007), Nichols *et al.* (2012) and Moss *et al.* (2022). Subclover seed was first harvested in small quantities around 1900 in Mt Barker, South Australia. From 1907, subclover seed began to be marketed commercially, which necessitated the development of systems to process the seed and overcome the difficulty of harvesting the buried burrs. The sowing of subclover became more widespread in the

1920s and 1930s as the plant became widely used in 'ley farming' systems, a uniquely Australian pasture-crop rotation system where cereal crops utilize the nitrogen fixed by the legume in the previous year (Underwood and Gladstones, 1979; Puckridge and French, 1983).

Rapid expansion in the area sown to subclover occurred from the 1950s to the 1970s. Key drivers included a wool boom, the opening up of new beef markets and government incentives for agricultural investment (Henzell, 2007). This was an era of large-scale pasture improvement, the so-called 'sub and super revolution', based largely on widespread sowing of subclover and the application of superphosphate (Underwood and Gladstones, 1979; Crofts, 1997; Henzell, 2007). The Horwood Bagshaw Clover Harvester was released in 1961, increasing harvest efficiency and becoming the most common subclover seed harvester (Moss *et al.*, 2021b).

In the 1980s, a decline in subclover pasture productivity first became apparent, attributable to a combination of new plant diseases and insect pests, increased soil acidity, reduced fertilizer inputs and increased cropping frequency (Nichols *et al.*, 2013). Increased international demand for synthetic fibres and a reduced demand for wool led to collapse of the wool industry in 1991, instigating a decline in sheep numbers (Henzel, 2007). Subsequent low prices for wool, relative to grains, continued this downturn and contributed to an increase in the area sown to crops at the expense of pastures. Recent trends, however, indicate an increasing domestic and export demand for beef and sheep meat (MLA, 2020) and dairy products (Dairy Australia, 2021) and have the potential to translate into increased demand for subclover seed.

Research design

Innovation frameworks

TRIZ, or the theory of inventive problem solving as it is often referred to in English, is a problem-solving framework developed to support the generation of innovative solutions (Altshuller, 1984). From a study of over 200,000 patents, the TRIZ proponents observed that systems evolve towards 'ideality'. Inventions increase ideality by improving an attribute of the system (Mann, 2001; Dieter and Schmidt, 2013). In its simplest form, TRIZ defines ideality as:

$$ideality = \frac{\text{useful effects of the system}}{\text{harmful effects of the system}}$$

Innovations and improvements progressively increase the ideality of the system over time. Central to TRIZ is the recognition that the strongest inventions emerge from addressing contradictions – trade-offs where improving one aspect of the system has a negative effect on another. Overcoming contradictions leads to high levels of innovation and paradigm shifts in the technology.

The evolutionary trajectory of technology is often represented schematically through use of the S-curve, as depicted in Figure 1 (Christensen, 1992, Sunding and Zilberman, 2001). The S-curve comprises a period of slow development in the technology's infancy, followed by a growth phase, which slows at maturity and eventually plateaus in the decline stage. This is not necessarily a permanent decline for the product and performance can continue to increase with innovation and new technology. In this scenario, a new period of growth is produced by new technology improving or replacing the previous system.

The investigation by Coccia (2017, p.1050) into sources of technological innovation has the central hypothesis that 'relevant and consequential problems/needs of consumers induce problem solving activities of firms (by learning processes and acts of insight) that generate incremental and radical innovations in markets, *ceteris paribus*'. His framework is in line with S-curve theory; an initial technological paradigm or radical innovation occurs in response to a relevant problem or need and subsequent problems/needs result in further incremental innovations over time until there is a new radical innovation that results in a paradigm shift and substantial progress. Here we expand Coccia's hypothesis to the agricultural context where farmers, rather than firms, drive innovation.

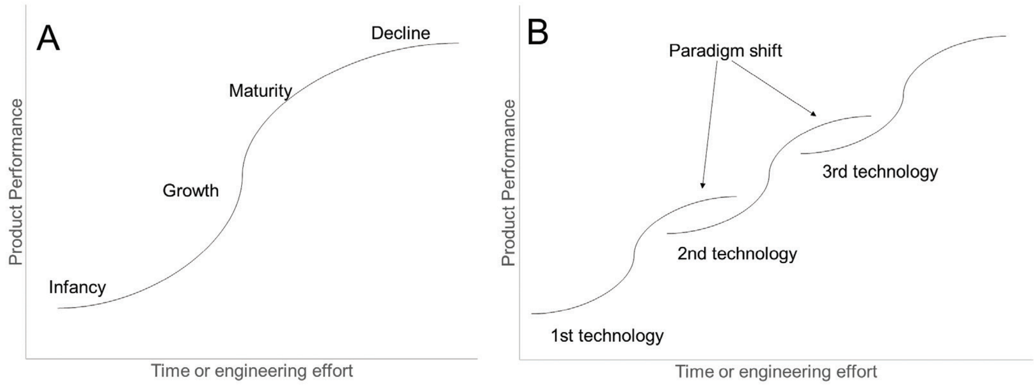

Figure 1. Evolutionary trajectory of technology

Note: A) Technology S-curve stages and B) progression with multiple technologies. Technology progresses incrementally from infancy through to decline, but performance can be increased further with the advent of new technology, causing a paradigm shift.

However, farmers also act as consumers having to solve problems that affect themselves, in addition to addressing problems of outside consumers.

Singh and Fleming (2010) examine whether lone inventors are more or less likely to invent breakthroughs. The Australian subclover seed case study provides an opportunity to examine this question in an on-farm context, where seed producers were often geographically isolated from each other with limited communication between them (until recent advances in communication technology and especially the advent of social media).

Data analysis

We apply these innovation frameworks to analyse technological development in subclover seed production and identify the key innovations that drove the industry forward. This is primarily achieved through analysis of the 48 Australian patents related to subclover seed harvesting technology, which span 1924 to 1992 when the last patent was granted. To classify the technological type represented by each patent, we adapt the standard five-tier TRIZ innovation ratings (Dieter and Schmidt, 2013) into three levels to offer greater clarity:

Level 1: Minor corrections made to an existing system by well-known methods.

Level 2: Substantial improvement in an existing system that resolves a basic behaviour compromise by using knowledge from the same technology area; the improvement typically involves adding a component or subsystem.

Level 3: Paradigm shift solutions based on application of a new principle to eliminate basic performance compromises.

Patent data are classified into these innovation levels. Patents are also classified by inventor profession and locations, recorded from information specified in the patent filing. Where these details are not available in patent records, primarily after 1955, inventor information is sought through other literature – mainly Moss *et al.* (2022) and Smith (2000). Professions are classified as: farmer, engineer (including related trades such as blacksmith), firm (patents filed by corporations) and researcher. Patents are classified by invention type on the basis of method or purpose: thresher or huller, rake, seed cleaner, pneumatic harvester, brush harvester and sheepskin roller.

The cumulative number of patents over time is plotted in frequency charts to display trends in patent activity to analyse technology development and reveal S-curve patterns (Daim *et al.*, 2006, Park *et al.*, 2013) based on inventor occupation (where noted), invention type and TRIZ innovation level. A stacked column chart is used to present the relative proportions of inventor professions and innovation levels across the patent data. Adapting the recent methods of Díaz Lankenau and Winter (2019), who use a flow diagram to represent the contextual factors shaping technological development in tractors in the United States, a flow diagram is used to depict the contextual factors driving the evolution of subclover seed-production technology.

Results and discussion

Farmers have been very powerful sources of innovation and have driven progress in the subclover seed industry. Some 75% of identified subclover patents were patented by farmers (Figure 2B). With the exception of threshing technology, all of the paradigm-shifting advancements in seed production were the result of farmer innovation. In contrast, over a similar time period (1900–1950s), major developments in tractor technology in the US were dominated by firms rather than farmers; for example, International Harvester and Ford (Díaz Lankenau and Winter, 2019). Figure 2 depicts the cumulative number of Australian subclover production patents by inventor profession, invention type and innovation classification level in panels A, C and D respectively. A full list of Australian subclover seed-production patents, with their innovation classifications and inventor details, is provided in Tables 1 and 2 of the Appendix.

Drivers of innovation

The factors driving innovation in the subclover seed industry meet the Coccia (2017) framework for problem-driven innovation: relevant and consequential problems induce problem-solving activities and generate incremental and radical innovation. However, in the case of technology development for subclover harvesting, it was primarily farmers and not researchers or firms that developed the new solutions. The economic and social context of this industry is important in the progression of innovation. Although driven by a consequential problem, the value proposition of undertaking innovation must be readily apparent to farmers because they are less able than firms to invest time and capital into research activities. The contextual factors driving the evolution of subclover seed-production technology are depicted in Figure 3.

Innovation occurred from farmers' desire to overcome a problem and recognition of the benefit from doing so. However, these farmers were not full-time inventors and their approach likely differed significantly from that of research entities or firms. Many inventions were the result of over ten years of work and significant personal investment (Moss *et al.*, 2022). As opposed to a systematic research effort to overcome a problem, most innovations stemmed from on-farm observations and experience. For example, in subclover harvesting seed burrs sticking to wool inspired the sheepskin roller method (i.e., wool-covered drums rolled over a paddock to collect seed burrs) and the observation of seed blowing in the wind led to the development of a suction harvester (Moss *et al.*, 2022). These farmer insights, born from years of experience and trial and error, were key drivers of innovation. The innovative nature of the sheepskin roller is noteworthy considering it was first patented in 1933, nearly a decade before Swiss engineer George de Mestral's similar insight about burdock seeds clinging to fabric in 1941, leading to the paradigm-shifting development of the Velcro hook and loop fastening system (Holyoak *et al.*, 1995).

All Level 3 inventions were patented prior to 1934 (Figure 2). These innovations introduced a new principle to subclover production technology, but were often adapted from other industries. Threshers and brush systems in particular were well known in similar agricultural sectors and it is unsurprising that subclover-specific adaptions were devised early on. Sheepskin and suction harvesters were derived from elements of existing systems, but were applied in much more novel ways that stemmed from farmer experience. Subsequent advancements in technology came from Level 2 inventions that combined different systems to overcome problems and increase performance.

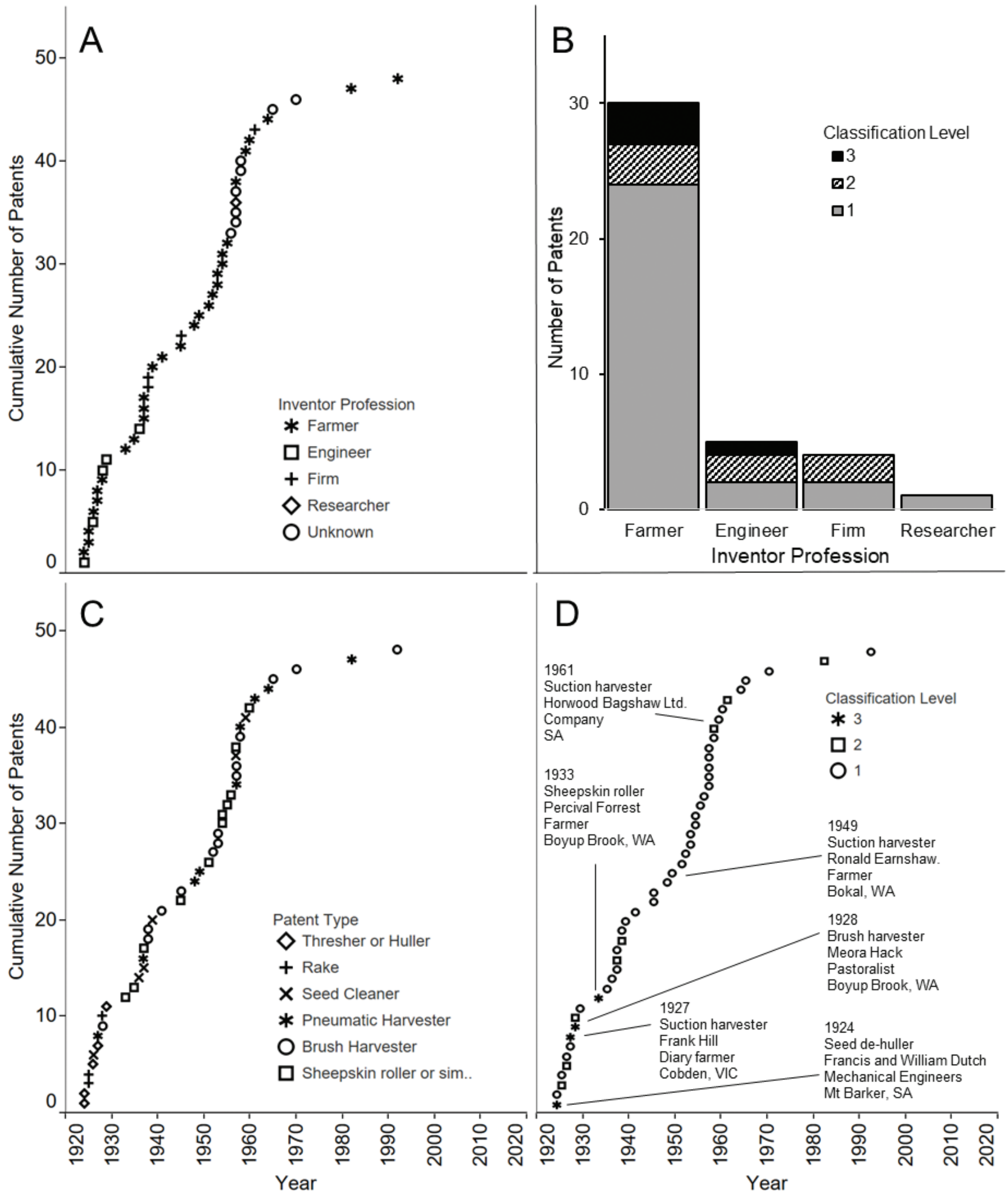

Figure 2. Subclover seed-production patents

Note: A) Inventor profession denoted.

B) Number of patents at each innovation classification level and profession, with 8 patents by unknown professions omitted.

C) Type of subclover invention denoted.

D) Level of innovation denoted, where 1, 2 and 3 represent minor corrections, substantial improvements and paradigm shift innovation, respectively.

Details are provided for Level 3 patents and patents related to the Horwood Bagshaw Clover Harvester. No relevant patent activity has occurred since 1992.

The Horwood Bagshaw (HB) clover harvester has been the most significant of these inventions in the industry. This suction style harvester, manufactured by Horwood Bagshaw Ltd, but based on a farmer's design, remains the most common subclover seed harvester used today (Moss *et al.*, 2021b). Suction harvester designs prior to the HB were limited in their adoption by lack of commercial support. The original patent, filed by farmer Ronald Earnshaw, had little effect on the industry until commercialized by Horwood Bagshaw Ltd. However, commercial manufacturers were hesitant to be involved in the subclover seed industry in this period. Earnshaw's original

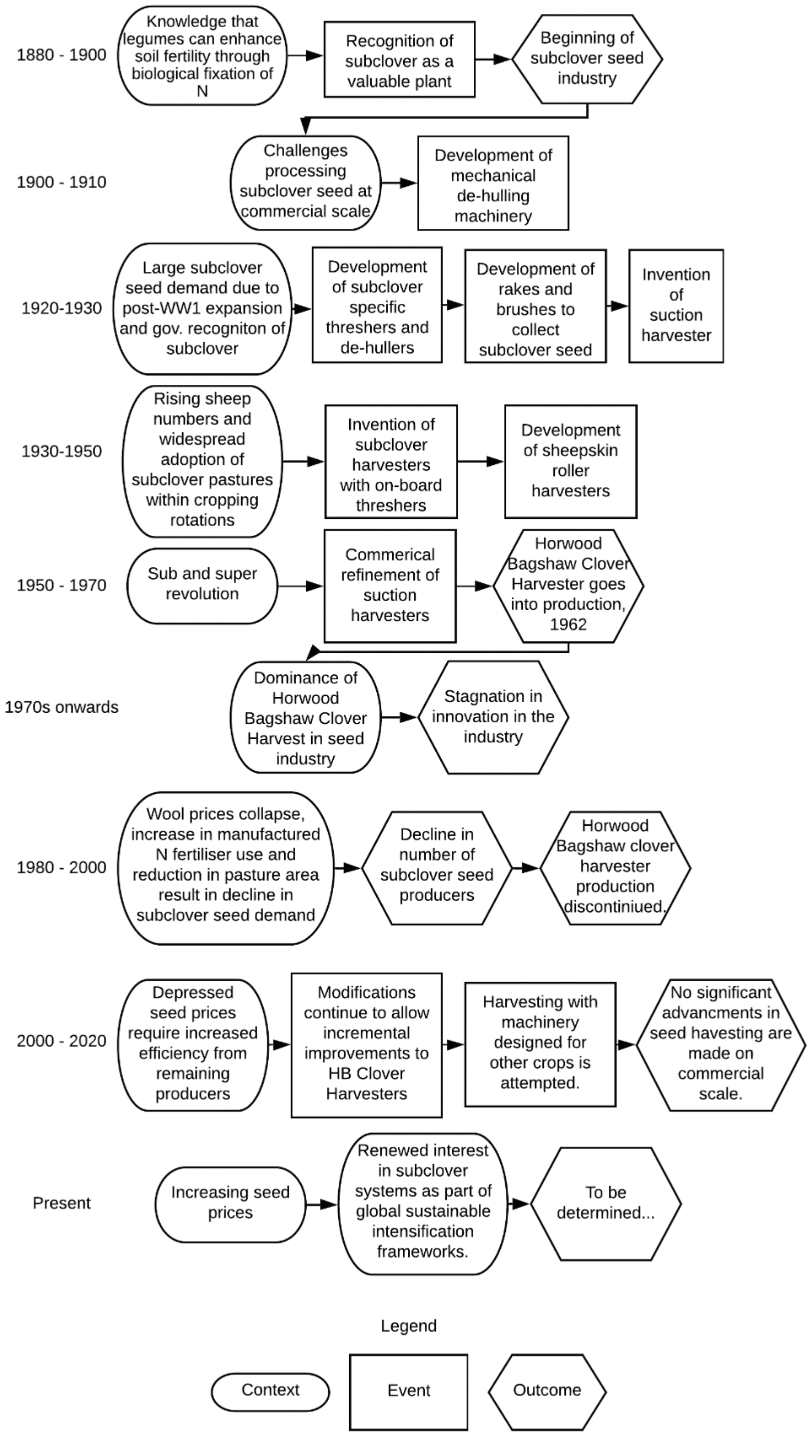

Figure 3. Progression of subclover seed-production technology and key economic or historical events that influenced innovation

design was rejected by firms prior to being developed by Horwood Bagshaw Ltd. Firms believed there was insufficient demand by seed producers to justify the research, development and manufacture of complex harvesting equipment (Avery *et al.*, 2001; Hassall & Associates, 2001: Moss *et al.*, 2022). This lack of commercial support inhibited innovation and highlights the importance of industry support and collaboration with farm innovators in creating widespread benefit, as farmers often lack the resources to commercialize inventions themselves.

Innovation plateau

As shown in Figure 2, there are clear successive S-curve trends in subclover patents with periods of initial high activity decreasing over time before the next upswing. From the 1960s there was a shift in the level of innovation and a significant decrease in patent activity through the subsequent decades. This coincided with the patent and commercial release of the HB (see Figure 2D). Although this harvester represented a paradigm shift in the industry, its release also began a period of reduced innovation.

The release of the HB harvester was perfectly timed at the heart of the 'sub and super revolution' (a period of widespread subclover pasture expansion) and it became very popular with seed producers. This period of rapid adoption of subclover by graziers created a need and tangible incentives to improve seed production. However, instead of leading to increased innovation, there was a marked reduction in patent activity in this period. There are several explanations for this decrease. First, seed producers were interested in increasing seed production and a great deal of effort went into improving the HB. Numerous HB modifications, representing incremental improvements, were developed by farmers (Boyle, 1995; Moss *et al.*, 2021a). These modifications were not patented (they lacked the 'novel' step required for a patent) and therefore are not reflected in patent data. The most significant of these modifications was the tandem drive, which allowed multiple HBs to run behind a single tractor, but the majority of modifications were only minor improvements (Moss *et al.*, 2021a).

Second, the HB's patent provided it with protection and restricted other inventions. This conforms with the theory that intellectual monopolies act to stifle innovation by providing too much power to existing patent holders (Boldrin *et al.;* 2008, Chu *et al.*, 2012). The HB would also have acted as a commercial monopoly, being the only suction harvester on the market produced by an established manufacturer. To be commercialized, other inventions would have needed to compete with the incumbent HB, something manufacturers were reluctant to do. Third, complacency is likely another factor in the decline of innovation in the subclover seed industry. While high demand for seed during the 'sub and super revolution' would have provided incentives to innovate, the marginal benefits might not have outweighed the capital costs necessary to develop the new technologies. The HB was effective and subclover seed harvesting could be highly profitable, with anecdotes of farmers paying off their farm mortgages after just a single harvesting season (Moss *et al.*, 2022). Farmers continued to work on new equipment and techniques, but with harvesting activities already so financially lucrative, there was less incentive to invest time, money and effort in developing new innovations. This, in particular, would have reduced the likelihood of paradigm-shifting innovations, which require higher development costs and longer timeframes for farmers to develop.

Innovation stagnated until the 1980s and then declined further as economic conditions deteriorated and subclover seed demand dropped. Farmers still had an interest in improving seed production, but this focused on utilizing modern technology already on farm (e.g., cereal combines) and on guarding trade secrets rather than commercialization (Moss *et al.*, 2021b). Financial incentives were not great enough to support high levels of innovation and consequently there was to be no significant advance in subclover seed-production systems since the 1960s. This contrasts with earlier periods of subclover seed production, where strong economic incentives supported high levels of innovation. However, stagnating conditions inhibited innovation in the last several decades, highlighting the need for collaboration to support farmer invention.

Isolation and collaboration

A continuous feature of technological development in the subclover case study has been the isolation of farm inventors, which both encouraged and impeded innovation. The vast majority of patents were filed by a single inventor (Figure 4). Single inventor patents are well represented in paradigm-shifting Level 3 innovations as well as in lower level incremental improvements, and there is no evidence that multiple-inventor patents were more likely to result in a technological breakthrough. This illustrates that lone inventors can be powerful sources of agricultural innovation.

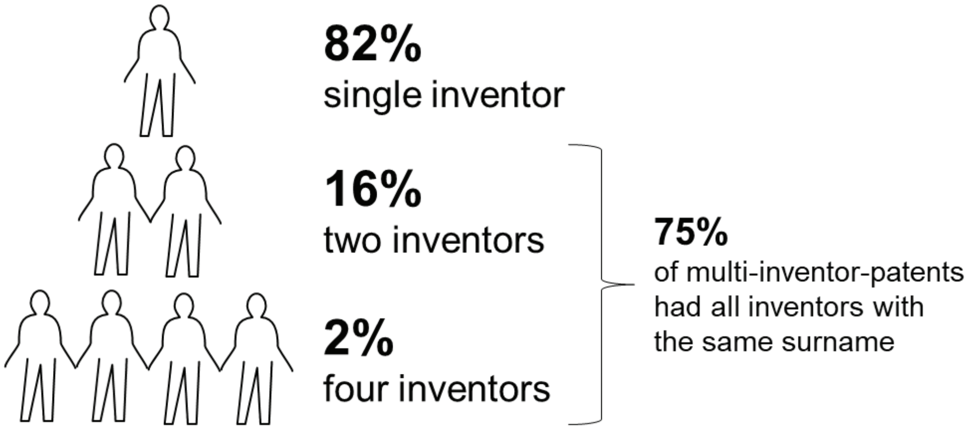

Figure 4. Proportion of non-firm subclover-related patents (n=44) invented by single and multiple inventors

The predominance of single inventors may have been out of circumstance rather than choice. In 75% of patents with multiple inventors, all listed inventors on the patent had the same surname, suggesting they were related (Moss *et al.*, 2022). If this is the case, then <5% of non-firm patents were the result of collaboration among non-family inventors. This suggests significant barriers to collaboration exist for farmers, probably resulting from geographical isolation, lack of communication technology and a highly competitive industry that disincentivizes farmers from sharing ideas.

There does not appear to be notable collaboration among inventors of subclover seed harvesting techniques, even in similar locations. The location and year of each identified patent is shown in Figure 5. While groupings of patents appear in similar locations and timeframes, we found no evidence to indicate this was the result of inventors working together or sharing ideas. Instead, these clusters of activity are likely to be attributable to high subclover seed production in these regions, creating conditions favourable to invention and patent protection. For example, Western Australian farmers Earnshaw and Moore both patented suction harvest systems in 1949. Despite their properties being located <100 km from each other (Appendix, Table 1, Bokal and Benjinup) and working on similar systems for years in close proximity, they did not have knowledge of each other's inventions and developed their harvesters independently (Moss *et al.*, 2022). At this time, there were limited means for farmers to share information and there would also have been reluctance to do so in order to obtain a competitive advantage. These factors resulted in reduced knowledge transfer in the industry.

Success in the subclover seed harvesting industry necessitated a high level of inventiveness from farmers. However, there has also been a clear duplication of effort, with farmers devoting time and resources to overcoming the same problem, without sharing knowledge gained or lessons learned. Limited communication and reduced knowledge sharing created barriers to commercializing useful inventions, incentivizing farmers to focus on developing and retaining a competitive advantage rather than a commercial product. So, while isolated farmers may have been driven to invent, the lack of communication and collaboration has had negative consequences for the overall seed-production industry.

Singh and Fleming (2010) hypothesize that diversity of experience across team members increases inventive outcomes. As a result of their isolation, subclover seed harvesting inventors have utilized their own diversity of experience as skilled fabricators, mechanics and trouble shooters, in addition to being farmers. There is a business imperative for farmers to be knowledgeable about their machinery repair, fabrication and servicing (especially in isolated and sparsely populated rural locations of Australia), as elucidated by recent 'right to repair' arguments (Fitzgerald,

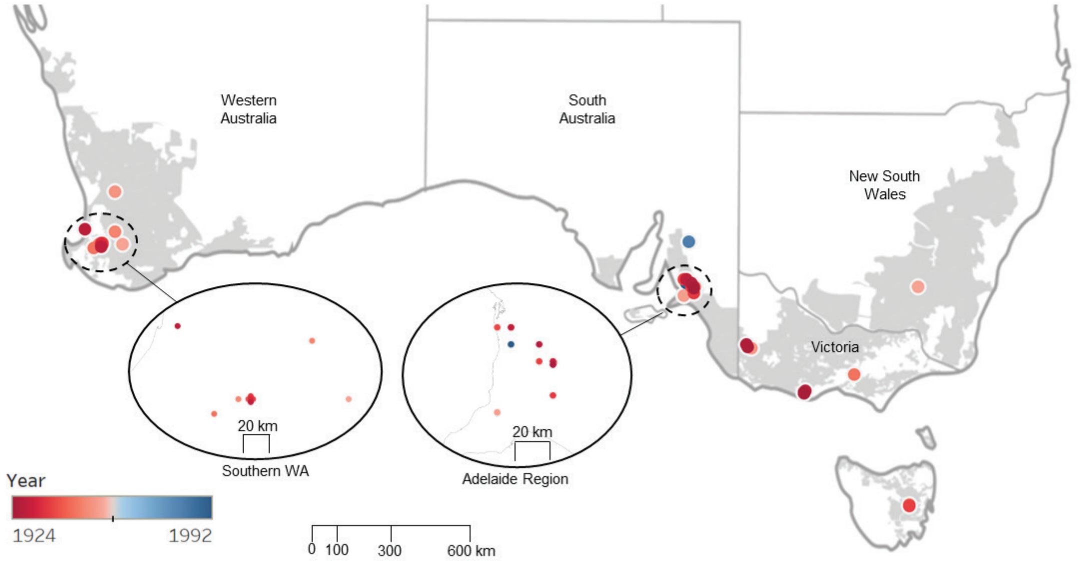

Figure 5. Location of each identified subclover seed-production patent

Note: The year an invention was patented is indicated by the colour scale. There are distinct groupings of patents, notably in the Adelaide region and southern Western Australia. All inventors were located in either seed-producing regions or capital cities. The area of contemporary subclover pastures is shaded (adapted from Donald, 2012). The land used to grow subclover as a seed crop is significantly smaller. The pasture area reflects current figures and would have been smaller at the time inventions were patented.

2008; Shah, 2018; Sirois-Leclerc, 2018). This encourages farmers to tinker with equipment and is also a driver of innovation (Hatta, 2020). Overall, this diversity of experience and the mechanical aptitude common among farmers has had a positive effect on inventive outcomes.

The success of the subclover seed-production inventors occurred prior to modern advances in communication technology. Singh and Fleming (2010) acknowledge that heroic lone inventors may have been common in the 19th and early 20th centuries, but changes in technology and organization have increased the advantages of collaboration. Social media in particular have increased farmers' ability to communicate and share knowledge. While it is clear that some level of isolation is beneficial for driving on-farm innovation, collaboration and shared knowledge are also important factors for maximizing the benefits of innovation across an industry. Particularly in remote agricultural settings and non-industrialized regions, communication and collaboration are important in supporting commercialization and wide adoption of farmer inventions.

Commercialization

As inventions became more complex in the subclover seed industry, it became increasingly important to have commercial support for the innovation to have widespread positive impact. Lack of commercial support inhibited innovation and contributed to the decline in the industry. Therefore, collaboration with industry, government and research is a key component to support innovation in agriculture. Sadras *et al.* (2020) advocate multidisciplinary research to improve return on agricultural R&D investment. Multidisciplinary approaches also increase the ability to translate scientific discoveries into realized productivity improvements (Passioura, 2020). This 'translational research' approach is a core TRIZ principle for achieving high levels of innovation (Altshuller, 1984). Although collaboration between research and industry can support high levels of innovation, on-farm stakeholders must still be a key part of this process to maximize benefits (McKenzie, 2013). The Rhoades and Booth (1982) 'farmer-back-to-farmer' model for generating agricultural technology stresses that applied research must begin and end with the farmer. This includes farmer participation in setting priorities (Sadras *et al.*, 2020). The subclover case study has shown just how innovative farmers can be, and why farmers should be utilized in generating agricultural innovation.

Farmers cannot afford to conduct large research projects themselves, but frameworks exist to involve farmers directly in funding R&D. Australia, Canada, the US and the UK have created R&D organizations funded by levies on agricultural output and controlled, at least partially, by farmer representatives (Sadras *et al.*, 2020). These organizations collectively invest hundreds of millions in R&D annually. In Australia, the Grains Research and Development Corporation (GRDC) is the largest of these organizations, with annual revenue of A$200 million (Sadras *et al.*, 2020). The high farmer involvement in these organizations and collaboration with research and industry allow them to create and leverage new innovations. These rural development and research corporations were key in supporting innovative farmers in developing conservation agriculture systems in Australia (Bellotti and Rochecouste, 2014). Recent examples of GRDC-funded innovations are the Harrington seed destructor and the weed chipper. The Harrington seed destructor (Walsh *et al.*, 2012), which devitalizes weed seeds that exit grain harvesters in the chaff fraction, has had a significant impact on global grain production. The evolved technology is now commercially available in an integrated version compatible with many combine harvester makes and models and is demonstrating weed control success internationally. The weed chipper is the first fallow mechanical weeder compatible with large-scale cropping systems (Walsh *et al.*, 2020). The success of the weed chipper is attributed to collaboration with stakeholders in farming, research (agronomy and engineering), manufacturing and industry.

Farmer-funded organizations like these could be valuable in accelerating agricultural innovation in small industries and developing countries. There are relevant and significant agricultural problems that need to be addressed, but solutions may not have sufficient market size to attract investment from firms. Farmer-funded organizations can fill the gap left by firms, and align those who pay for R&D with those who benefit from it. However, collecting agricultural tax or levies in developing countries can be challenging because of the absence of standard account-keeping and are often effective only in large-holdings (Rajaraman, 2004). While a levy approach may not work in all contexts, systems are needed to support on-farm innovation and enable the commercialization or dissemination of useful inventions.

It is likely that farmers generally have less motivation to commercialize their ideas than firms. In previous decades, the high price of subclover seed provided financial incentive to innovate, but there are several instances of subclover harvesting inventions, both patented and unpatented, where commercialization was not attempted (Moss *et al.*, 2022). The prospect of developing techniques to provide a competitive advantage in seed production would have been sufficient in some cases, particularly in a highly competitive and protected industry (Avery *et al.*, 2001; Moss *et al.*, 2021b). Farmers tend to be less likely than firms to document or patent their inventions (Rhoades, 1989) and can be reluctant to bear the cost of patent protection, relying instead on secrecy to prevent others from seeing and copying their ideas. Many unpatented and unadvertised subclover seed harvester inventions developed from the desire of farmers to make their own jobs easier (and the urge to tinker and improve practices/equipment) rather than to pursue commercialization. A drawback of this approach is that the benefits of the innovation can become restricted to its inventor or region. Frameworks are needed to support farmers to share or commercialize useful inventions.

Promoting knowledge sharing among farmers can be challenging, as farmers are competitors in the same industry. However, collaboration does not have to rely on altruism. Knowledge sharing can result in net positive benefits for the industry, which will benefit individual farmers as members of that industry. Innovation is likely to proceed more efficiently when networks of informal know-how sharing are encouraged. Networks of knowledge sharing among competitors have enabled important discoveries in industries from steam engines to semiconductors (Pedraza-Fariña, 2016). These networks should be supported; shared knowledge can still be protected. Research collaboration is becoming increasingly common among firms, universities and institutes, but is navigated with intellectual property protection (Slowinski *et al.*, 2006). Governments and research and development corporations can provide financial and logistical support to farmers to protect or commercialize their inventions. This will secure farmers' intellectual property, allowing valuable innovations to have widespread benefit.

Lessons and recommendations to support future agricultural innovation

The subclover seed-production industry offers a number of lessons for agricultural innovation in the future. The high proportion of farmer invention reflects the innovativeness of farmers in this industry, but also highlights the reluctance of larger firms to invest unless there is significant market size. These lessons are particularly applicable to small-scale farms and the developing world. Constraints in the developing world often lead to radically different solutions from those found in resource-rich countries (Mattson and Wood, 2014; Mattson and Winter, 2016). Farms in the US, where a significant amount of R&D takes place, are 100 times larger than 80% of all farms globally (Díaz Lankenau and Winter, 2019) and Australian farms are significantly larger than US farms (Australian Bureau of Statistics, 2016; USDA, 2021). However, half the world's food is produced by 1.5 billion small-scale farmers and in non-industrialized nations, 80% of food is produced by small-scale farmers (Bragdon and Smith, 2015). Significant positive impacts in global agriculture can be realized if innovation from these farmers is supported and focused.

To maximize farmer innovation, the drivers must be understood. There must be a relevant problem and perceived benefit in overcoming it. This aligns with current economic and management technology theory (Coccia, 2017), but the approach of farmers is different from that of firms. Favourable economic conditions will encourage farmers to invest in innovation. However, the costs and time of developing an invention can be an obstacle to farmers, which can be overcome with research and industry collaboration. The absence of this support can inhibit farmer innovation, particularly in small markets.

Farmers are also less likely than firms to develop inventions for commercialization, instead aiming to improve their own production and competitive advantage. Industry engagement is crucial to increase commercialization of useful inventions and enable maximum benefit. However, farmers can be hesitant to share ideas and knowledge, and keep inventions as closely guarded trade secrets. Knowledge sharing amongst farmers, industry and research can contribute positively to innovation. Therefore, frameworks and incentives are needed to encourage farmers to communicate and collaborate. External support for intellectual property protection can encourage farmers to share or commercialize inventions while still maintaining ownership.

Farmer-funded research and development corporations are one avenue of support for farmers to enable innovation and reduce the amount of useful knowledge confined to an individual or a region. While isolation was a key driver of innovation in subclover seed harvesting, collaboration will be key to creating new advances in a more complex and connected future. Harnessing the creative power of farmers has the potential to accelerate agricultural innovation and contribute to solving the considerable challenges facing global agriculture.

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Appendix

Table 1. Full list of Australian subclover seed-production patents and classifications used in this study

Year	Innovation classification	Patent type	Inventor/s	No. of inventors	Inventor profession	Location	State
1924	3	Thresher or Huller	Dutch	2	Engineer	Mt Barker	SA
1924	1	Thresher or Huller	Hill	1	Farmer	Cobden	Vic
1925	2	Rake	Schnickel	1	Farmer	Kybybolite	SA
1925	1	Rake	Shepherd	1	Farmer	Kybybolite	SA
1926	1	Seed Cleaner	Hill	1	Farmer	Cobden	Vic
1926	2	Thresher or Huller	Kaesler	2	Engineer	Hahndorf	SA
1927	1	Thresher or Huller	Ford	1	Farmer	Burekup	WA
1927	3	Pneumatic Harvester	Hill	1	Farmer	Cobden	Vic
1928	2	Rake	Campbell	1	Engineer	Adelaide	SA
1928	3	Brush harvester	Hack	1	Farmer	Boyup Brook	WA
1929	1	Thresher or huller	Daniel	1	Engineer	Mt Barker	SA
1933	3	Sheepskin roller or similar	Forrest	1	Farmer	Boyup Brook	WA
1935	1	Sheepskin roller or similar	Nix and Kohlman	2	Farmer	Boyup Brook	WA
1936	1	Seed cleaner	Virgo	1	Engineer	Strathalbyn	SA
1937	1	Sheepskin roller or similar	Doust	2	Farmer	Boyup Brook	WA
1937	2	Pneumatic harvester	Lowe	1	Farmer	Echunga	SA
1937	1	Seed cleaner	Williams-Ellis	1	Farmer	Longford	Tas
1938	1	Brush harvester	Kretsmer	N/A	Company	Adelaide	SA
1938	2	Brush harvester	Hannford	N/A	Company	Woodville	SA
1939	1	Seed cleaner	Henderson	1	Farmer	Boyup Brook	WA
1941	1	Brush harvester	Paterson	1	Farmer	Longford	Tas
1945	1	Sheepskin roller or similar	Moore	1	Farmer	Bridgetown	WA
1945	1	Brush harvester	Wright and Stephenson	N/A	Company	Melbourne	Vic
1948	1	Pneumatic harvester	Earnshaw	1	Farmer	Bokal	WA
1949	1	Pneumatic harvester	Moore	1	Farmer	Benjinup	WA
1951	1	Sheepskin roller or similar	Bailey	1	Farmer	Beverley	WA
1952	1	Brush harvester	Thomas	1	Farmer	Apsley	Vic
1953	1	Brush harvester	Stephenson	1	Farmer	Mt Barker	SA
1953	1	Brush harvester	Rowley	1	Farmer	Myponga	SA
1954	1	Sheepskin roller or similar	Ellis	1	Farmer	Kojonup	WA
1954	1	Sheepskin roller or similar	Hepburn and Lovett	2	Farmer	Wagga Wagga	NSW
1955	1	Sheepskin roller or similar	Barrow Linton	1	Farmer	Unknown	WA
1956	1	Sheepskin roller or similar	Matson	2	Unknown	Unknown	Unknown
1957	1	Pneumatic harvester	Adams	2	Unknown	Unknown	Unknown
1957	1	Brush harvester	Presser	1	Unknown	Unknown	Unknown
1957	1	Brush harvester	Millington	1	Researcher	Unknown	WA

(Continued)

Table 1. (Continued)

Year	Innovation classification	Patent type	Inventor/s	No. of inventors	Inventor profession	Location	State
1957	1	Seed cleaner	Clugston	1	Unknown	Unknown	Unknown
1957	1	Sheepskin roller or similar	Bell	1	Farmer	Unknown	Unknown
1958	2	Pneumatic harvester	Garrett	1	Unknown	Unknown	Unknown
1958	1	Brush harvester	Thomas	1	Unknown	Unknown	Unknown
1959	1	Seed cleaner	Dickerson	1	Farmer	Unknown	WA
1960	1	Sheepskin roller or similar	Dunn	1	Farmer	Unknown	Unknown
1961	2	Pneumatic harvester	Horwood Bagshaw	N/A	Company	Adelaide	SA
1964	1	Pneumatic harvester	Barrow Linton	1	Farmer	Unknown	WA
1965	1	Brush harvester	Wren	1	Unknown	Unknown	Unknown
1970	1	Brush harvester	Oswald	4	Unknown	Unknown	Unknown
1982	2	Pneumatic harvester	Dutschke	1	Farmer	Brinkworth	SA
1992	1	Brush harvester	Moore	1	Farmer	Novar Gardens	SA

Note: No relevant patent activity has occurred since 1992.

Table 2. Number of Australian patents related to subclover seed production classified by inventor profession (specified in patent) and TRIZ level of innovation demonstrated by the patent

		Inventor profession					
		Farmer	Engineer	Firm	Researcher	Unknown	Total
Innovation classification	Level 1	24	2	2	1	7	**36** (75%)
	Level 2	3	2	2	0	1	**8** (17%)
	Level 3	3	1	0	0	0	**4** (8%)
	Total	**30** (63%)	**5** (10%)	**4** (8%)	**1** (2%)	**8** (17%)	48

References

ABARES (2020) ‘Agricultural commodities: December quarter 2020’, Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra.

AgFunder (2021) *AgFunder AgriFoodTech Investment Report*, available at https://agfunder.com/research/2021-AgFunder-agrifoodtech-investment-report/ (accessed December 2021).

Altshuller, G. (1984) *Creativity as an Exact Science: The Theory of the Solution of Inventive Problems*, Gordon & Breach, London.

Australian Bureau of Statistics (2016) *Agricultural Commodities, Australia, 2015–16,* ABS, Canberra.

Australian Seeds Authority (2020) *Certified Seed Produced under OECD, AOSCA and Australian Seed Certification Schemes in Australia in the 12 Months to 30 September 2019*, Australian Seeds Authority, Lindfield NSW.

Avery, A., Ronnfeldt, G., Virgona, J. and Owen, O. (2001) *Improved Sub-clover Seed Production*, Rural Industries Research and Development Corporation, Wagga Wagga NSW.

Bayer (2019) *Annual Report,* Bayer AG, Leverkusen, Germany.

Bellotti, B. and Rochecouste, J. (2014) ‘The development of conservation agriculture in Australia – farmers as innovators’, *International Soil and Water Conservation Research,* 2, 1, pp.21–34.

Biggs, S. and Clay, E. (1981) ‘Sources of innovation in agricultural technology’, *World Development,* 9, 4, pp.321–6.

Boldrin, M., Levine, D. and Nuvolari, A. (2008) ‘Do patents encourage or hinder innovation? The case of the steam engine’, *The Freeman: Ideas on Liberty,* 58, 10, pp.14–17.

Boyle, S. (1995) ‘Horwood Bagshaw vacuum seeds harvesters’ in Boyle, S., *Pasture Plus: The Complete Guide to Pastures,* Kondinin Group, Belmont WA, pp.406–9.

Bragdon, S. and Smith, C. (2015) *Small-Scale Farmer Innovation*, Quaker United Nations Office, Geneva.

Christensen, C. (1992) ’Exploring the limits of the technology S-curve. Part I: component technologies’, *Production and Operations Management,* 1, 4, pp.334–57.

Chu, A., Cozzi, G. and Galli, S. (2012) ‘Does intellectual monopoly stimulate or stifle innovation?’, *European Economic Review,* 56, 4, pp.727–46.

Coccia, M. (2017) ‘Sources of technological innovation: radical and incremental innovation problem-driven to support competitive advantage of firms’, *Technology Analysis & Strategic Management,* 29, 9, pp.1048–61.

Crofts, F. (1997) ‘Australian pasture production: the last 50 years’ in Lovett, J. and Scott, J. (eds) *Pasture Production and Management,* Inkata Press, Melbourne, pp.1–16.

Daim, T., Rueda, G., Martin, H. and Gerdsri, P. (2006) ‘Forecasting emerging technologies: use of bibliometrics and patent analysis’, *Technological Forecasting and Social Change,* 73, 8, pp.981–1012.

Dairy Australia (2021) Dairy Situation Report and Outlook 2021, September, Dairy Australia, available at https://www.dairyaustralia.com.au/resource-repository/2021/03/16/situation-and-outlook-report-march-2021#.YF7fiK8zaUk (accessed December 2021).

Díaz Lankenau, G. and Winter, A. (2019) ‘An engineering review of the farm tractor’s evolution to a dominant design’, *Journal of Mechanical Design,* 141, 3, 031107.

Dieter, G. and Schmidt, L. (2013) *Engineering Design,* McGraw-Hill, New York.

Dolinska, A. (2017) ‘Bringing farmers into the game. Strengthening farmers’ role in the innovation process through a simulation game, a case from Tunisia’, *Agricultural Systems,* 157, pp.129–39.

Donald, C. and Williams, C. (1954) ‘Fertility and productivity of a podzolic soil as influenced by subterranean clover (*Trifolium subterraneum* L.) and superphosphate’, *Australian Journal of Agricultural Research,* 5, 4, pp.664–87.

Donald, G. (2012) *Analysis of Feedbase Audit, Final Report*, Meat and Livestock Australia, March, North Sydney NSW, available at https://www.mla.com.au/contentassets/be0d5cf52e7949fc9b97f9ef3e9af4aa/b.pas.0297_final_report.pdf (accessed December 2021).

FAO (2018) *The State of Food Security and Nutrition in the World 2018: Building Climate Resilience for Food Security and Nutrition*, Food and Agriculture Organization, Rome, available at https://www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1152267/ (accessed December 2021).

Fitzgerald, D. (2008) *Every Farm a Factory: The Industrial Ideal in American Agriculture*, Yale University Press, New Haven CT.

Gaffney, J., Challender, M., Califf, K. and Harden, K. (2019) 'Building bridges between agribusiness innovation and smallholder farmers: a review', *Global Food Security,* 20, pp.60–5.

Ghamkhar, K., Nichols, P., Erskine, W., Snowball, R., Murillo, M., Appels, R. and Ryan, M. (2015) 'Hotspots and gaps in the world collection of subterranean clover (*trifolium subterraneum* L.)', *Journal of Agricultural Science,* 153, 6, pp.1069–83.

Godfray, H., Beddington, J., Crute, I., Haddad, L., Lawrence, D., Muir, J., Pretty, J., Robinson, S., Thomas, S. and Toulmin, C. (2010) 'Food security: the challenge of feeding 9 billion people', *Science,* 327, 5967, pp.812–18.

Guzzomi, A., Maraldi, M. and Molari, P. (2012) 'A historical review of the modulus concept and its relevance to mechanical engineering design today', *Mechanism and Machine Theory,* 50, April, pp.1–14.

Hassall & Associates (2001) *A Study of the Costs of Production of Lucerne, Medic and Clover Seeds in Australia*, Rural Industries Research and Development Corporation, Barton ACT.

Hatta, M. (2020) 'The right to repair, the right to tinker, and the right to innovate', *Annals of Business Administrative Science,* 19, 4, pp.143–57.

Heisey, P. and Fuglie, K. (2018) *Agricultural Research Investment and Policy Reform in High-Income Countries*, Economic Research Report 249, Economic Research Service, US Department of Agriculture, Washington DC.

Henzell, T. (2007) *Australian Agriculture: its History and Challenges,* CSIRO, Melbourne.

Hoffmann, V., Probst, K. and Christinck, A. (2007) 'Farmers and researchers: how can collaborative advantages be created in participatory research and technology development?', *Agriculture and Human Values,* 24, 3, pp.355–68.

Holyoak, K., Holyoak, K. and Thagard, P. (1995) *Mental Leaps: Analogy in Creative Thought*, MIT Press, Cambridge MA.

Läpple, D., Renwick, A. and Thorne, F. (2015) 'Measuring and understanding the drivers of agricultural innovation: evidence from Ireland', *Food Policy,* 51, C, pp.1–8.

Loi, A., Howieson, J., Nutt, B. and Carr, S. (2005) 'A second generation of annual pasture legumes and their potential for inclusion in Mediterranean-type farming systems', *Australian Journal of Experimental Agriculture,* 45, 3, pp.289–99.

McKenzie, F. (2013) 'Farmer-driven innovation in New South Wales, Australia', *Australian Geographer,* 44, 1, pp.81–95.

MacMillan, T. and Benton, T. (2014) 'Agriculture: engage farmers in research', *Nature News,* 509, 7498, p.25.

Mann, D. (2001) 'An introduction to TRIZ: the theory of inventive problem solving', *Creativity and Innovation Management,* 10, 2, pp.123–5.

Mattson, C. and Winter, A. (2016) 'Why the developing world needs mechanical design', *Journal of Mechanical Design,* 138, 7, 070301.

Mattson, C. and Wood, A. (2014) 'Nine principles for design for the developing world as derived from the engineering literature', *Journal of Mechanical Design,* 136, 12, 121403.

MLA (2020) *State of the Industry Report 2020,* Meat and Livestock Australia, North Sydney NSW.

Moss, W., Guzzomi, A., Foster, K., Ryan, M., Erskine, W. and Nichols, P. (2021a) 'Vacuum harvesting sucks: improving the Horwood Bagshaw Clover Harvester', paper delivered to Australian Grassland Association Symposium.

Moss, W., Guzzomi, A., Foster, K., Ryan, M. and Nichols, P. (2021b) 'Harvesting subterranean clover seed – current practices, technology and issues', *Crop and Pasture Science,* 72, 3, pp.223–35.

Moss, W., Nichols, P., Foster, K., Ryan, M., Erskine, W. and Guzzomi, A. (2022) 'A century of subclover: lessons for sustainable intensification from a historical review of innovations in subterranean clover seed production' in Sparks, D. (ed.) *Advances in Agronomy,* 171, Academic Press, London, pp.305–39.

Nichols, P., Foster, K., Piano, E., Pecetti, L., Kaur, P., Ghamkhar, K. and Collins, W. (2013) 'Genetic improvement of subterranean clover (*trifolium subterraneum* L.). 1. Germplasm, traits and future prospects', *Crop and Pasture Science,* 64, pp.312–46.

Nichols, P., Revell, C., Humphries, A., Howie, J., Hall, E., Sandral, G., Ghamkhar, K. and Harris, C. (2012) 'Temperate pasture legumes in Australia – their history, current use, and future prospects', *Crop and Pasture Science,* 63, 9, pp.691–725.

OECD (2013) *Agricultural Innovation Systems: A Framework for Analysing the Role of the Government,* OECD Publishing, Paris.

Park, H., Ree, J. and Kim, K. (2013) 'Identification of promising patents for technology transfers using TRIZ evolution trends', *Expert Systems with Applications,* 40, 2, pp.736–43.

Passioura, J. (2020) 'Translational research in agriculture. Can we do it better?', *Crop and Pasture Science,* 71, 6, pp.517–28.

Pedraza-Fariña, L. (2016) 'Spill your (trade) secrets: knowledge networks as innovation drivers', *Notre Dame Law Review,* 92, 4, pp.1561–1610.

Peoples, M. and Baldock, J. (2001) 'Nitrogen dynamics of pastures: nitrogen fixation inputs, the impact of legumes on soil nitrogen fertility, and the contributions of fixed nitrogen to Australian farming systems', *Australian Journal of Experimental Agriculture,* 41, 3, pp.327–46.

Pretty, J. and Bharucha, Z. (2014) 'Sustainable intensification in agricultural systems', *Annals of Botany,* 114, 8, pp.1571–96.

Pretty, J., Benton, T., Bharucha, Z., Dicks, L., Flora, C., Godfray, H., Goulson, D., Hartley, S., Lampkin, N. and Morris, C. (2018) 'Global assessment of agricultural system redesign for sustainable intensification', *Nature Sustainability,* 1, 8, pp.441–6.

Puckridge, D. and French, R. (1983) 'The annual legume pasture in cereal-ley farming systems of southern Australia: a review', *Agriculture, Ecosystems and Environment,* 9, 3, pp.229–67.

Rajaraman, I. (2004) 'Taxing agriculture in a developing country: a possible approach', *Contributions to Economic Analysis,* 268, pp.245–68.

Rhoades, R. (1989) 'The role of farmers in the creation of agricultural technology' in Chambers, R., Pacey, A. and Thrupp, L. (eds) *Farmer First: Farmer Innovation and Agricultural Research,* Intermediate Technology Development Group, London, pp.3–9.

Rhoades, R. and Booth, R. (1982) 'Farmer-back-to-farmer: a model for generating acceptable agricultural technology', *Agricultural Administration,* 11, 2, pp.127–37.

Sadras, V., Alston, J., Aphalo, P., Connor, D., Denison, R. F., Fischer, T., Gray, R., Hayman, P., Kirkegaard, J., Kirchmann, H., Kropff, M., Lafitte, H. R., Langridge, P., Lenne, J., Mínguez, M. I., Passioura, J., Porter, J. R., Reeves, T., Rodriguez, D., Ryan, M., Villalobos, F. J. and Wood, D. (2020) 'Making science more effective for agriculture' in Sparks, D. (ed.) *Advances in Agronomy*, 163, Academic Press, London, pp.153–77.

Sauer, J. (2017) 'Estimating the link between farm productivity and innovation in the Netherlands', *OECD Food, Agriculture and Fisheries Papers*, OECD, Paris.

Schmidhuber, J. and Tubiello, F. (2007) 'Global food security under climate change', *Proceedings of the National Academy of Sciences,* 104, 50, pp.19703–8.

Shah, A. (2018) 'Can you repair what you own?', *Mechanical Engineering,* 140, 9, pp.37–41.

Singh, J. and Fleming, L. (2010) 'Lone inventors as sources of breakthroughs: myth or reality?', *Management Science,* 56, 1, pp.41–56.

Sirois-Leclerc, A. (2018) 'Ag and bio ethics winner: fighting the right to repair: the perpetuity of a monopoly', *Resource Magazine.* 25, 1, pp.18–19.

Slowinski, G., Hummel, E. and Kumpf, R. (2006) 'Protecting know-how and trade secrets in collaborative Rand D relationships', *Research Technology Management,* 49, 4, pp.30–8.

Smith, D. (2000) *Natural Gain in the Grazing Lands of Southern Australia,* UNSW Press, Sydney.

Smith, D. (2011) 'The greening of the arid boundary', *Quadrant,* 55, 7–8, pp.94–103.

Sneddon, J., Soutar, G. and Mazzarol, T. (2009) 'On-farm innovation in the Australian wool industry: a sensemaking perspective', *Experimental Agriculture,* 45, 3, pp.295–312.

Sunding, D. and Zilberman, D. (2001) 'The agricultural innovation process: research and technology adoption in a changing agricultural sector' in Gardner, B. and Rausser, G., *Handbook of Agricultural Economics*, Elsevier, Amsterdam, volume 1, part A, pp.207–61.

Underwood, E. and Gladstones, J. (1979) 'Subterranean clover and other legumes' in Burvill, G. (ed.) *Agriculture in Western Australia 1829–1979,* University of Western Australia Press, Perth.

USDA (2021) *Farms and Land in Farm 2020 Summary*, United States Department of Agriculture, Washington DC, available at https://downloads.usda.library.cornell.edu/usda-esmis/files/5712m6524/tq57pj927/rx914h75j/fnlo0221.pdf (accessed December 2021).

Walsh, M., Harrington, R. and Powles, S. (2012) 'Harrington Seed Destructor: a new nonchemical weed control tool for global grain crops', *Crop Science,* 52, 3, pp.1343–7.

Walsh, M., Squires, C., Coleman, G., Widderick, M., McKiernan, A., Chauhan, B., Peressini, C. and Guzzomi, A. (2020) 'Tillage based, site-specific weed control for conservation cropping systems', *Weed Technology*, 34, 5, pp.704–10.