2 Some Brief Examples of Technical Innovation in Agricultural Industries

Thomas Malthus (1798) studied population growth in Europe. He estimated that population was increasing exponentially and resources were only increasing linearly; therefore population was increasing faster than food production. His final conclusion was that global starvation was inevitable.

More recent systematic studies of famine and starvation around the world have revealed that, although famines have occurred ever since the development of agriculture, many of the worst famines in recent history should be attributed to poor distribution of existing food supplies, rather than the ravages of natural disaster and the consequences of population growth outstripping food production (Scrimshaw 1987). Although major innovation was beginning at the time he wrote his essay, Malthus could not foresee how technology would transform food and fibre production. The industrial revolution, green revolution and advent of precision agriculture have forestalled most of Multhus’ most dire predictions.

The transformation in agricultural practices has profoundly affected society. Over the past 200 years, the number of people who are directly involved in agriculture has dramatically declined. In the 1800’s, nearly 80 % of the employed population was involved in agriculture; by the 1900’s those who were directly involved in agriculture had decreased to 35 % (Australian Bureau of Statistics 2000). In the year 2000, it was estimated that 4 to 5 % of the employed population of Australia were directly involved in agriculture (Australian Bureau of Statistics 2000). These employment trends are common across other developed countries. During this same period of about 200 years, the human population has grown from about 790 million in 1750 (Gelbard and Haub 1999) to an estimated 6.4 billion in 2005 (Demeny and McNicoll 2006).

Although agriculture is fundamental to feeding a growing population, the importance of modern agricultural practices to social development is not so clearly understood. Agriculture has two key economic characteristics: first, it produces goods that directly satisfy basic human needs; and second, it combines human effort with natural resources, such as land (Diao, et al. 2007) to deliver these goods. It was believed that, since natural resources were freely available, agriculture could grow independently of other economic activities (Diao, et al. 2007); however, arable land area is a fixed resource so growth is constrained by available technology (Diao, et al. 2007).

Historical evidence suggests that agriculture is the key to economic development. Gollin, et al. (2002) show that once agriculture switches from traditional to modern technology, labour is released to the industrial sector and the economy grows at higher rates. Unfortunately this means that agriculture’s percentage contribution to national productivity declines due to dilution from growth in other sectors of the economy that would not be possible without an efficient agricultural sector.
Agriculture’s declining share in the economy sends a confusing signal to policymakers who conclude that agriculture is relatively unimportant and the falling real prices of agricultural commodities, due to transformational improvements in the supply chain efficiency, sends the signal to investors that returns from agricultural investment are unattractive (Stringer 2001). These confusing signals also reduce the number of researchers and innovators engaging in agriculture (Anonymous 2009), which slows the rate of innovation.

This chapter will outline some historical innovations that have contributed to the transformation of agricultural practices.

2.1 Machines

It has been suggested that this modern era can be described as the machine age; however this is not strictly true (Ubbelohde 1963). Humans have been building and using machines of various types since ancient times. From around 3000 BC, several major achievements appear in the timeline. These include: the development of wedges, wheels and levers; the use of animals to carry and draw loads; and the use of fire to work metals. Other achievements included the digging of irrigation canals, and open-pit mining. Monumental construction programmes such as: the Pyramids in Egypt, China and the Americas (Canadian Council of Professional Engineers 2003); and transport of massive stones (Hazell and Brodie 2005, Hazell and Fitzpatrick 2006, Hazell and Brodie 2012, Brodie and Hazell 2014) were also undertaken.

The Greeks made significant contributions to engineering in the 1000 years that straddled the centuries before and after Christ (Canadian Council of Professional Engineers 2003). They produced the screw, the ratchet, the water wheel and the aeolipile, better known as Hero’s turbine (Figure 2.1).

Figure 2.1: Hero’s aeolipile, about AD 150.
The Persians are credited with harnessing wind power (Ubbelohde 1963). The Romans built fortifications, roads, aqueducts, water distribution systems and public buildings across the territories and cities they controlled. At the other end of the world, the Chinese have been credited with the development of the wheelbarrow, the rotary fan, the stern-post rudder and gunpowder (Canadian Council of Professional Engineers 2003). They also began making paper from vegetable fibres.

Between 1700 and 1850, the Industrial Revolution in Western Europe dominated the development of machinery (Canadian Council of Professional Engineers 2003). It was significantly influenced by the development of steam engines; machinery for the mass production of industrial goods; and the railways developed by Stephenson, Brunel and others (Canadian Council of Professional Engineers 2003). Agricultural machinery, such as seed drills, mechanical harvesters and stump-jump ploughs, and the use of engines rather than horses as a primary power source were the major legacies of this period.

2.2 Early Innovations in Agriculture

One of the earliest examples of new agricultural technology was the development of the horse drawn seed drill, which is usually attributed to Jethro Tull (1733). Whether Tull was the inventor of the seed drill is doubtful (Sayre 2010); however he did promote its wide spread adoption. What is less well known is that Tull also advocated a new theory of plant nutrition, which promoted an extensive tillage of the soil for improving fertility and maintaining weed control (Sayre 2010). This idea was controversial, because most farmers of the time applied manures and allowed natural decomposition of these manures to improve soil nutrition. Historians are divided over the value of Tull’s ideas about soil nutrition. Some describe him as one of the greatest innovators in agricultural production, while others suggest that, while he was an excellent observer and experimenter, his agronomic theories were incorrect (Sayre 2010). Ultimately, the ability to quickly plant large areas of monoculture crops in relatively straight rows transformed agricultural practice. Modern cropping systems still rely on seed drills.

Eli Whitney’s cotton gin (circa 1793) sped up the post processing of cotton (Peterson 1995). The invention of the cotton gin revolutionised the cotton industry in the United States. Cotton production requires the cotton seed to be removed from the raw cotton fibres. Simple seed-removing devices had been available for centuries before Whitney automated the seed separation process. One of his other important contributions was the idea of standardised interchangeable machine parts, which paved the way for mass production (Peterson 1995). Whitney’s cotton gin had spiked teeth mounted on a revolving cylinder which was turned by a crank. These teeth pulled the cotton fibre through small slotted openings so that the seeds were separated from the fibre.
In 1831, Cyrus McCormick invented the mechanical reaper to help in grain harvesting (Peterson 1995). The adoption of the horse drawn reaper meant that daily harvesting capacity could be increased fivefold, compared to traditional hand methods (Peterson 1995).

The development of the stump jump plough (invented by Richard Bowyer Smith in 1876), the combine harvester and the establishment of large scale irrigation systems transformed the various colonies into significant exporters of agricultural produce (Australian Bureau of Statistics 2000).

2.3 Transportation Technologies

Transportation has played a vital role in society (Short 2010); this is especially true for agriculture. Early transport for agricultural produce was by horse and cart for short distances. For centuries, sailing ships were the fastest means of transportation over longer distances (Short 2010). In 1787, John Fitch demonstrated the first steamboat, which had twelve paddles and was propelled by a steam engine (Poddar n.d.). This allowed steam ships and river boats to become the main methods for transporting agricultural produce (Short 2010).

Of all the advancements of the Transportation Revolution, the construction of railways was the most significant (Poddar n.d.). The first railways carried goods for short distances, but inventors and engineers wanted to be able to carry goods or passengers long distance. Steam locomotion, together with the low rolling friction of iron-flanged wheels on iron rails, enabled George Stephenson (the first of the great railway engineers) to design and superintend the building of the Liverpool and Manchester Railway (1830), which began the railway age in England (Marsh 2009). Railways replaced water ways as the primary means of moving agricultural produce.

The 20th century belonged to road transportation (Short 2010). The development of internal combustion engines, pneumatic tyres, and paved roads allowed for greater trade volumes (Blondé 2010), which lead to economic and cultural development. The breakthrough for agriculture based transportation came with falling relative transformation costs, and rising agricultural prices supported by improving urban economies (Blondé 2010). Even on-farm transportation and mechanisation was transformed.

2.4 The Tractor

Before the advent of traction machines, most heavy pulling was achieved by human effort (Hazell and Brodie 2005, Hazell and Brodie 2012, Brodie and Hazell 2014) or animals (Ubbelohde 1963). Ancient Egyptian drawings illustrate ploughs being pulled by two oxen (Ubbelohde 1963). At the time of the Domesday Book Survey (1086), the
normal plough was pulled by eight oxen (Ubbelohde 1963). It was estimated that eight ox power could plough 120 acres (48.5 hectares) of land in a year (Ubbelohde 1963), which limited the amount of land that could be managed.

Experiments with steam engines can be traced back to Hero’s aeolipile; however James Watt was the first to present a practical steam engine in 1769 (Goering 2008). Fawkes produced a steam tractor that could pull eight ploughs at 4.8 km/h in virgin sod (Goering 2008). Tractors with internal combustion engines first appeared in 1907 (Goering 2008). Competition between the rival technologies climaxed in a series of tractor trials in Winnipeg, Canada between 1908 and 1911, where the limitations of steam tractors became apparent (Goering 2008).

All modern tractors use internal combustion engines, with most of them using Diesel engines because of their inherent efficiency and high torque compared with petrol engines. Rudolf Diesel developed the idea for the diesel engine and obtained the German patent for it in 1892. His goal was to create an engine with high efficiency. Spark ignition engines were invented in 1876 and were not very efficient.

The transition from oxen or horses to tractors began in Australia after 1920 (Davidson 1981); however this transformation was initially slow. Based on a detailed survey of 115 farms, Perkins (Perkins 1929) demonstrated that one 24 H.P. (18.75 kW) tractor could replace 11.4 horses on an average South Australian farm; thus freeing additional cropping land that was previously used to grow feed for work animals. By 1930, only about 40 % of Australian farmers were equipped with tractors (Davidson 1981). One of the contributing factors to this relatively slow adoption rate was revealed by Perkins (1929). He demonstrated that for an average farm size of 300 acres (121.4 ha) the replacement of horses with a tractor led to a reduction in annual profit of £114. Australian grain growers had realised that mechanisation was only viable if it was applied to large scale production (Davidson 1981). It was the interaction between agricultural production and other factors in modern economies that ultimately promoted the transition to full mechanisation.

Most modern tractors are truly all purpose. They can operate a vast array of: mounted implements; trailed implements; and machines running from the power take off (PTO). They have hydraulic devices, which give the operator easy and accurate control from the driver’s seat. Tractors are normally rated using two criteria: the draw bar power - a measure of how much the tractor can physically pull; and the PTO rating (Culpin 1976). Experimental PTO’s were tried as early as 1878 (Goering 2008). The American Society of Agricultural Engineers adopted the first PTO standard for defining the direction of rotation, speed, size, shape, and location (Goering 2008). The inclusion of PTO’s on tractors transformed agricultural practice allowing many functions to be performed on the go in the field rather than requiring a multi-pass approach.

The most recent inclusion in modern tractors is the GPS and auto steer. This has facilitated the development of high resolution farming (or precision farming).
2.5 The Green Revolution

Massive investment in agricultural research during the 20th century lead to dramatic crop yield increases in most industrialised countries. For example, it took nearly 1,000 years to increase wheat yields from 0.5 to 2 tonnes per hectare; however it took only 40 years during the 20th century to increase yields from 2 to 6 tonnes per hectare (International Food Policy Research Institute 2002). These astonishing improvements in yield can be attributed to better plant breeding, improved agronomy, the development of inorganic fertilisers, the development of chemical pesticides and herbicides, large scale irrigation schemes, and the mechanisation of farming systems (International Food Policy Research Institute 2002). Unfortunately, these advances in technology did not reach developing countries as quickly, due to various influences including lack of political will, which lead to significant famines in many places (Scrimshaw 1987).

The Green Revolution originally focused on developing high-yielding varieties for rice and wheat; however high-yielding varieties have since been developed for other major food crops, including: sorghum, millet, maize, cassava, and beans (International Food Policy Research Institute 2002). The green revolution led to substantial increases in on-farm income, which on the international scale raised rural demand for goods and services. This has given rise to new rural service industries in many countries (International Food Policy Research Institute 2002). This has profoundly affected the standard of living for many rural communities. For example, the percentage of the Indian rural population living below the poverty line fluctuated between 50 and 65 percent before the mid-1960s; however this has declined steadily to about one-third of the rural population by 1993 (International Food Policy Research Institute 2002).

The Green Revolution has also given rise to no-till agricultural practices, in which grain seed is directly planted into uncultivated soil using a planter (called a drill) that drops the seed into a very shallow furrow, which is immediately filled with soil using a press wheel. Reduced tillage reduces soil erosion, improves soil physical and chemical properties, conserves soil moisture, and saves fuel costs. No-till systems rely on extensive use of herbicides to manage weed infestations (Chauhan 2006). One of the earliest herbicides to be developed was 2,4-dichlorophenoxyacetic acid (2,4-D), which was discovered in the 1940’s. It was effective at killing di-cotyledons, but not mono-cotyledons. Many other chemicals have been developed to control weeds, including chemicals such as Atrazine and Glyphosate. Chemical weed control was initially very effective; however more recently herbicide resistance (Heap 2008) and health concerns due to long term exposure (Troudi, et al. 2012) have arisen.

Genetic engineering of crops (GMC’s) has the potential to double or even triple world food, feed and fibre production by the year 2050 (James and Krattiger 1996); however there has been concern about the development of GMC’s (or transgenic crops) since 1971 (James and Krattiger 1996). The first field trials featured herbicide...
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resistance. These crops have become commercially available and widely adopted to improve production and better manage weed by allowing the use of broad spectrum herbicides, such as Glyphosate. Resistance to pests and improvement in production and nutrition have also been introduced.

More than 50 transgenic crops have been trialled worldwide. Commercialised transgenic crops include: cotton, maize, melon, canola, potato, soybean, tobacco, tomato, alfalfa, cantaloupe, carnations, flax, rice, squash, sugar-beet, and sunflower (James and Krattiger 1996). In some cases, genes have been introduced to enhance production, enhance nutrition, resist pests or introduce resistance to chemicals that are used to manage other pests.

Green revolution technologies are well suited to larger farms. In some cases, this has displaced smaller farm operators from the industry as more successful farmers acquire more land for their operations. This may have contributed to increases in urbanisation across the globe. Another consequence is that high yields are now only sustained in high input farming systems. These input expenses are only economically viable because their costs are diluted by the increased availability of saleable commodities. Attempts at better understanding and managing high inputs have prompted further innovation in the form of high resolution production systems.

2.6 High Resolution Production Systems

The objective of high resolution, precision agricultural systems is to avoid over application of inputs while maintaining optimal growing conditions for the crop (Cao, et al. 2012). High resolution agricultural systems are based on a network of sensors and actuators for real time monitoring and control of agricultural production. These are often combined with existing information technologies (Schuh, et al. 2007) such as Radio Frequency Identification (RFID), Programmable Logic Controllers (PLC), Personal Digital Assistants (PDA) and Smart Phones that can interface with these sensor networks to monitor and control some activities remotely.

These systems depend on automatic acquisition of both spatial (position-based) and temporal (time-based) data, which allows the operator, or the automated operating system, to make finer adjustments to inputs than would normally be considered in conventional farming systems.

2.7 Spatial Data

Spatial data acquisition often involves using various aerial or ground based canopy sensors. The spectral reflectance of plants is much higher in the infra-red part of the electromagnetic spectrum than in the visible part of the spectrum. Plant stresses due to water or nutrient deficiencies have a greater effect on infra-red reflectance than on
the visible light reflectance (Figure 2.2); therefore sensors that can detect infra-red light can be used to quickly identify stressed plants. For example, the GreenSeeker canopy sensor (NTech Industries, Inc., Ukiah, California, USA) is a commercially available optical sensor that captures both a red (650 ± 10 nm) and a Near Infra-red (NIR @ 770 ± 15 nm) images of the crop canopy (Cao, et al. 2012). These images can be analysed to determine the health of the crop.

![Figure 2.2: Reflectance data for wheat plants under different levels of phosphorous stress.](image)

A common analysis option for assessing the health of plants is the Normalised Difference Vegetation Index (NDVI). NDVI values are calculated on a pixel by pixel basis using the following equation:

\[
NDVI = \frac{R_{\text{NIR}} - R_{\text{R}}}{R_{\text{NIR}} + R_{\text{R}}}
\]

(2.1)

where \(R_{\text{NIR}}\) is the crop reflectance at the NIR wavelength and \(R_{\text{R}}\) is the crop reflectance at the red wavelength. The resulting analysis can resemble an image; however the individual pixels within the image are calculated rather than captured as in the case of a photograph.

As an example, the NDVI for the blue sample in Figure 2.2 is approximately 0.78; however the NDVI value for the red sample in Figure 2.2 is:

\[
NDVI = \frac{R_{\text{NIR}} - R_{\text{R}}}{R_{\text{NIR}} + R_{\text{R}}} = \frac{0.405 - 0.07}{0.405 + 0.07} = 0.7
\]

(2.2)
Figure 2.3 shows an example of an NDVI image.

There are several variants of the NDVI calculation. These provide better separation of healthy from unhealthy plants. For example, the Enhanced Vegetation Index (EVI) uses either two or three bands of an image (NIR, red and blue) to calculate the index:

\[
EVI = G \frac{R_{\text{NIR}} - R_{\text{R}}}{R_{\text{NIR}} + C_1 R_{\text{R}} - C_2 R_{\text{B}} + L}
\]  

where G, C1, C2 and L are constants. The coefficients adopted in the MODIS-EVI algorithm are; L=1, C1 = 6, C2 = 7.5, and G (gain factor) = 2.5. In the case where only two spectral bands are available (NIR and red), the EVI can be calculated using C1 = 2.4:

\[
EVI2 = G \frac{R_{\text{NIR}} - R_{\text{R}}}{R_{\text{NIR}} + C_1 R_{\text{R}} + L}
\]

Using the earlier examples from Figure 2.2, the EVI2 for the blue sample is approximately 0.91 while the EVI2 for the grey sample is approximately 0.55. The NDVI is chlorophyll sensitive; however the EVI is more responsive to canopy structural, including leaf area index (LAI), canopy type, plant physiognomy, and canopy architecture.
These vegetation indexes can differentiate stresses in different parts of a crop, allowing spatially specific management of the crop inputs to optimise production. The sensors can be mounted on machinery, on aircraft or drones, on satellite platforms, or even on small airships (Figure 2.4).

Although there is usually good success with spatially specific input management during the early stages of technology adoption, it is clear that longer term influences, such as system inertia, can mitigate potential improvements in agricultural systems. Achieving better system responses requires high resolution temporal (time based) data as well as high resolution spatial data.

![Figure 2.4: (left) Dual camera system with IR and true colour cameras (right) mounted on a transportable airship (Photographs of the system in operation over the vineyard at Dookie campus of the University of Melbourne).](image)

### 2.8 Temporal Data

Understanding how a system changes over time is critical to better system management. Data acquisition is simply the gathering of information about a system or process over an extended period of time. It is a core tool to the understanding, control and management of complex systems or processes. As with most systems, complexity becomes more apparent as monitoring frequency increases; therefore high resolution temporal data usually depends on automatic data acquisition (Vandoren 1982).

Information such as temperature, pressure or flow is gathered by sensors that convert measurements into electrical signals. Sometimes only one sensor is needed, such as when recording local rainfall. Sometimes hundreds or even thousands of sensors are needed, such as when monitoring a complex industrial process. The signals from sensors are transferred by wire, optical fibre or wireless links to an instrument which conditions, amplifies, scales, processes, displays and stores the sensor signals (Brodie 2009).
In the past data acquisition equipment was largely mechanical, using clock work and chart recorders. Later, electrically powered chart recorders and magnetic tape recorders were used. Today, powerful microprocessors and computers perform data acquisition faster, more accurately, more flexibly, with more sensors, more complex data processing, and elaborate presentation of the final information.

Data acquisition can be divided into two broad classifications – real time data acquisition and data logging. Real time data acquisition is when data acquired from sensors is used either immediately or within a short period of time, such as when controlling a process (Frey and Williams 1994). An example of this kind of data acquisition and control system is an automatic irrigation system that responds to output from a soil moisture sensor. Data logging on the other hand is when data acquired from sensors is stored for later use (Frey and Williams 1994). In reality, there is a continuum of devices between real time data acquisition and data logging that share the attributes of both of these classifications.

All data acquisition requires proper sampling of the system. In terms of time based sampling, the Nyquist-Shannon sampling theorem states that reconstruction of a continuous signal from its samples is only possible if the sampling frequency is greater than twice the bandwidth of the monitored system (Nyquist 2002). A similar principle applies to spatial sampling. Therefore appropriate sampling rates depend on how quickly the phenomenon of interest is changing with respect to both time and location.

2.9 Conclusions

Transformational innovations have allowed agricultural production to increase as rapidly as population, forestalling the dire predictions of Malthus; however this sustained innovation has meant that developed societies have become dependent on a small portion of the population for its food security. Adoption of high resolution agriculture has allowed agricultural production to increase while reducing or maintaining system inputs; however this can only be sustained by ongoing research and investment into novel technologies that may allow greater agricultural productivity or improvements in the quality of what is currently being produced. Although they have not been mentioned in this chapter, microwave and radio frequency technologies that can contribute to agricultural production are currently being explored. The next chapter will highlight some of the potential developments in this domain.
References


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Stringer, R. 2001. *How important are the ‘non-traditional’ economic roles of agriculture in development?* Centre for International Economic Studies


Tull, J. 1733, *The Horse-Hoing Husbandry: Or, an Essay on the Principles of Tillage and Vegetation. Wherein is Shewn a Method of Introducing a Sort of Vineyard-culture into the Corn-fields, in Order to Increase their Product, and Diminish the Common Expence; by the use of Instruments Described in Cuts*, London: Self Published.
