The role of agronomy in a technical world

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Abstract
The science of agronomy has existed for millennia, but may be viewed as irrelevant by administrators and funding agencies when compared to emerging technological developments in equipment, chemistry and genetics. While new technology provides innovative tools to improve crop productivity and sustainability, the science of agronomy is critical to ensure that those tools are used in an integrated production system. Doing more with less requires that all available technology is used as effectively as possible, which in turn requires an understanding of how that technology interacts with the agroecosystem. Agronomy relies on the continual modification of farming systems based on new technology, challenges and opportunities that arise. For example, the availability of improved herbicides and better equipment paved the way for development of no-till farming systems, which required new agronomic practices for crop rotations and nutrient management. Herbicide tolerant crops led to the development of herbicide-resistant weeds, requiring re-evaluation of weed management systems. The integration of knowledge through agronomic science will be increasingly important to take advantage of the opportunities created by new technology in genetics, chemistry and equipment and to address the risks to a secure and nutritious food supply posed by climate change, soil degradation, decreasing water supplies, increasing population density and the growing disconnect between agriculture and the urban population.

Keywords
Tillage system, 4R nutrient management, genetics.

Agronomy as Ancient History
Agronomy is an ancient science, with many of the crops that we grow today being domesticated as early as 10,000 years ago (http://www.newworldencyclopedia.org/entry/History_of_agriculture, accessed February 26, 2017). By about 7000 to 8000 BCE, the Sumerians in present day Iraq and the Egyptians had organised irrigated wheat- and barley-based cropping systems in the rich soil that was deposited by river flooding between the Tigris and Euphrates and along the Nile River, respectively. Animal drawn ploughs and seeders are shown in bas reliefs from about 2500 to 3000 BCE.

However, although crop production and basic agronomic principles were known millennia ago, in many cases, poor agronomic practices led to land degradation and contributed to the downfall of civilisations (Montgomery 2008). For example, Mesopotamian agriculture was based on irrigation. Irrigation led to salinization and reduced soil productivity. Lower crop production coupled with an expanding population pushed crop production to sensitive hillside soils leading to severe erosion that filled irrigation channels and further degraded the soil. Crop yields declined and the resulting lack of food was a contributing factor to the decline of the civilisation and its subsequent fall to Amorite and Hittite invaders. Egypt was spared from this problem because of the constant regeneration and flushing of salts from the soil by the annual flooding of the Nile until the building of the Aswan dam removed these natural processes, leading to soil degradation.

In ancient Rome, a number of fundamental agronomic principles were laid out by Marcus Porcius Cato (234-149 BCE) (Cato 2016). His recommendations included:

- *Timeliness of operations:* “Get each task finished in good time. If one thing is done late you will do everything late”.
- *Manuring and composting*: “Be sure to have a big compost heap. Store every bit of dung. Sort it and break it down as you shift it”.
- *Crop rotations:* “Legumes can feed cereals while crops that are harvested with the straw deplete the soil”.
- *Select the crop to suit the soil*: “Where the soil is rich and fertile, plant corn. Where the land lies low, plant rape, millet and grass”.
- *Tillage*: “Plough well and in good weather, lest you turn a cloddy furrow”.

- *Seed rate*: "Sow seed plentifully".

In spite of the awareness of good agronomic principles, economic pressures led the Romans to ignore these practices. Clearing of marginal land, excessive tillage, lack of manure return and poor crop rotations led to erosion and nutrient depletion (Montgomery 2008). Declining soil productivity and increasing population in Rome drove a need for military expansion because conquered territory was needed for food production to support the population in the Roman homeland. The Romans pushed into northern Africa and throughout Europe, spreading soil degradation with them as they went. Similar stories were repeated throughout the world, in parts of India, China, Africa, South America and North America.

Population growth in successful civilisations tends to put great pressure on agricultural systems. Two centuries ago Thomas Malthus noted that because population grows geometrically and food production increases arithmetically, population growth will eventually be checked by famine and disease. However, until now, the world has been able to avoid the "Malthusian Catastrophe" through increased crop production. In the past, crop production was largely increased by development of more land but currently new land resources are limited and arable land is being lost due to degradation and industrialisation (Ramankutty and Foley 1999). As a result, crop land per capita is decreasing and is projected to continue to decrease in the future (Ausubel et al. 2013). The current world population of 7.3 billion is expected to increase to over 9.1 billion by 2050 (http://www.un.org/en/development/desa/news/population/2015-report.html). The food for this growing population will have to come from increased production per hectare rather than from the development of new land.

Figure 1. Wind erosion on the Canadian Prairies (Photo courtesty of Alberta Agriculture, http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex9313/$FILE/photo%202-2-2%20(erosion)_l.jpg)

Agronomy's recent contributions

Technological developments in the twentieth century have allowed food production to keep pace with the growing population. The development of the Haber – Bosch process led to the availability of reasonably priced nitrogen fertiliser, removing one of the major limitations for crop production in soils worldwide. Development of selective herbicides helped in the control of weeds, which were a major limitation for cropping. Semi-dwarf wheat and hybrid corn raised the genetic limits of crop production of higher levels. Each of these technologies provided a critical tool for the improvement of crop yield, but the "Green

Revolution” required the development of an agronomic package of genetics, nutrient management, chemical control of weeds and diseases, and effective water management to take full advantage of the individual technologies.

In the Canadian prairies, development of no-till agriculture followed a similar path (Awada et al. 2014). Prairie soils developed under vegetation ranging from short grass to tall grass prairie, transitioning to a parkland mixture of grass and primarily aspen forest, depending on the available moisture and the frequency of fires. These soils were naturally high in organic matter, and mineralisation provided relatively high amounts of nitrogen for crop production for many years after the land was broken. The settlers who arrived in the prairies brought with them the farming techniques that they used in Europe, including intensive tillage that they viewed as necessary to control diseases, insects and weeds and to provide a uniform, fine seed bed.

For many decades, crop production in the prairies was based on periodic summer fallow, a practice that was introduced in Canada in 1886. Summerfallow on the prairies meant leaving the land unplanted from harvest in September through the next growing season until the spring approximately 20 months later, with the land tilled regularly. Summer fallowing the soils for a year in every two to four year cropping cycle allowed for storage of water, control of weeds through tillage and accumulation of nitrogen from organic matter mineralisation. However, the repeated tillage and nutrient removal with limited return of crop residues led to a large decline in soil organic matter and soil productivity. The intensive tillage and the lack of vegetative cover associated with summer fallow left the soil subject to wind and water erosion and encouraged dryland salinity. While the problem was apparent after the dustbowl years in the 1930’s, prairie farmers had few viable tools to address the problem. The Prairie Farm Rehabilitation Agency (PFRA) was formed in 1935 to work with researchers, farmers, universities and provincial governments to develop and disseminate more sustainable farming practices. Lower disturbance tillage tools such as light duty cultivators, the Nobel Blade plow and Morris rod weeder were developed to replace inversion plowing so that crop residues could be retained on the soil surface to reduce erosion and conserve moisture (Awada et al. 2014). Discs with attached seed boxes to allow one pass tillage, weed control and seeding were developed. However, weed control and nitrogen deficiencies related to declining soil fertility were still major issues.

The introduction of chemical herbicides in the early 1960’s provided alternatives to tillage for weed control. However, the high price and lack of complete effectiveness of chemical weed control and the relatively poor performance of available seeders through the surface residues retained in the absence of tillage meant that no-till systems were not yet agronomically or economically viable in the prairies. Further technological developments during the 1970’s and 80’s improved the practicality of reduced tillage systems. Effective in-crop selective foliar herbicides were developed that could be used in place of the commonly used soil incorporated herbicides Avadex and Treflan. In addition, the introduction of glyphosate contributed greatly to the substitution of herbicides in place of tillage for weed control.

Also of importance was the introduction of canola and pulse crops to allow a diversified cropping system. Canola (**Can**ada **o**il **l**ow **a**cid) refers to rapeseed selections with low glucosinolates and low erucic acid. These cultivars were developed in the1970,s through conventional breeding practices by Keith Downey of Agriculture Canada and Baldur Stefansson of University of Manitoba. The high oil quality for human consumption and increased safety for use of the meal in animal rations greatly increased the international demand for the crop. Pulse crops including lentils and field peas were also developed by prairie plant breeders to be more suited to prairie conditions. Greater cropping options allowed for a more diversified cropping sequence, which also helped in control of weeds, diseases and insects, as well as reducing economic and production risks.

As with any new technology, the adoption of reduced tillage presented both challenges and opportunities. Three major issues still made no-till production problematic in the 1980’s and 90’s: 1) Available equipment was not effective at encouraging consistent crop emergence; 2) Efficient fertiliser application systems were not available for no-till; and 3) The high cost of glyphosate made it economically uncompetitive with tillage for seed-bed preparation.

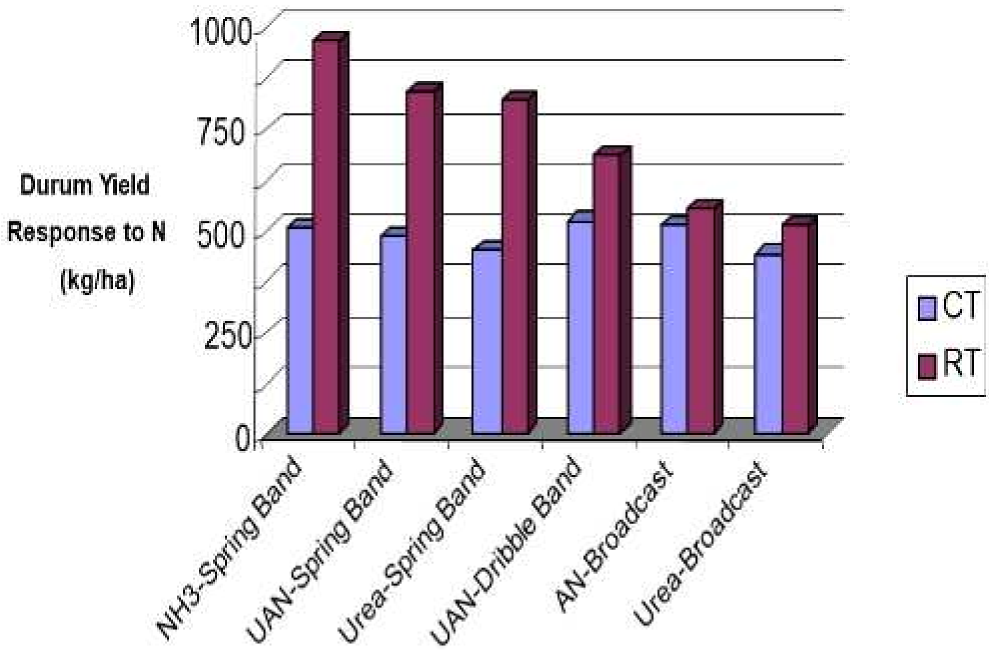

Figure 2. Increase in yield of durum wheat in response to source and placement of application of 40 kg per ha of actual nitrogen under conventional tillage (CT) and reduced tillage (RT) management, averaged over 8 site-years (Grant et al. 2001).

Initially, fertiliser placement was a major initial issue in no-till. Early no-till systems used broadcast fertiliser application when rates of application were greater than the amount that could be safely placed with the seed. Many early no-till systems showed lower yield, protein concentration and nitrogen use efficiency as compared to conventional tillage. While part of the issue was related to lower mineralisation of organic matter, efficiency of surface applications of nitrogen fertiliser was also reduced because placing them in close contact with surface residues enhanced the risk of immobilisation and volatilisation. Agronomic studies showed that the advantage of banding nitrogen fertilisers below the crop residue layer as compared to broadcast application was much greater under no-till than conventional tillage systems (Figure 2; Malhi et al. 2001; Grant et al. 2001). In the 1980's and 90's, innovative farmers and equipment manufacturers on the prairies worked to develop a number of seeding systems, primarily air-seeders, that could more accurately place seed and fertiliser in the ground in a one-pass system under high residue condition while maintaining seed-bed integrity. In addition, improved methods of spreading straw and chaff during harvest were developed to reduce the residue issue. Adoption of effective residue distribution during harvest and one-pass seeding and fertilising systems that included some form of in-soil banding led to better crop emergence and greater fertiliser use efficiency under no-till systems.

In the early 1990's the expiry of the initial glyphosate patent allowed competition from generic products that lowered the cost from over $30 per liter to below $10 per liter. Meanwhile, rising oil prices dramatically increased the cost of tillage operations, increasing the economic advantage of chemical weed control relative to tillage. Development of herbicide tolerant crops in the mid to late 1990's provided more tools for no-till. With the technology in place to allow efficient no-till production, work on development of optimal agronomic practices for no-till intensified. In comparisons of no-till and conventional tillage systems, a number of differences were apparent. Removing tillage reduced mineralisation of nitrogen and led to a slow accumulation of organic matter, resulting in tie-up of nitrogen. This meant that, at least in the initial years of no-till, additional nitrogen was required to optimise crop yield and protein. Also, if higher yields were produced under no-till, higher fertiliser rates would be needed to optimise production (Grant et al. 2002b). No-till also encouraged mycorrhizal colonisation, leading to better performance of mycorrhizae-dependant crops such as flax under no-till as compared to conventional tillage (Lafond et al. 1992; Gao et al. 2010).

Some legume crops, such as field peas, also seemed to do better under no-till (Lafond et al. 1992) . Soil compaction and nutrient stratification were concerns, but ultimately did not appear to be a serious problem under prairie conditions, possibly due to frost action during the winter months.

Standing stubble under no–till trapped snow and retained it in the field. The extra snow-cover over the winter reduced wind erosion and also led to higher winter soil temperatures. The higher soil temperatures allowed for successful production of winter wheat in areas of the prairies where extreme cold had prevented its production under conventional tillage, providing an additional cropping option (Grant et al. 1984). Notably, with the extra snow cover and the reduction or elimination of tillage, the amount of moisture retained in the soil increased (Table 1). This meant that in the drier parts of the prairies, there was often sufficient moisture available to move to continuous cropping rather than having a season of summer fallow in the rotation. The extended, intensified rotations substantially improved productivity in the drier areas of the prairies and provided more incentive for adoption of reduced tillage systems.

Table 1. Soil moisture and penetration resistance (PR) at different depths on a Black Solodized Solonetz (Glossic Udic Natriboroll) loam soil under zero tillage, minimum tillage and conventional tillage in spring in east-central Alberta (Malhi and Nyborg 1992).

Tillage	Soil moisture (%) at 0-15 cm			Soil moisture (%) at 15-30 cm			Penetration Resistance (MPa) in 1989	
	1985	1986	1987	1985	1986	1987	0-10 cm	10-20cm
Zero Till	32.4 a	32.0 a	17.9	26.1	25.7	19.2	1.34 a	1.33
Minimum Till	30.1 a	28.5 ab	17.7	27.8	22.5	18.8	1.13 a	1.40
Conventional Till	27.1 b	25.1 b	16.4	24.7	20.5	16.5	0.65 b	1.10

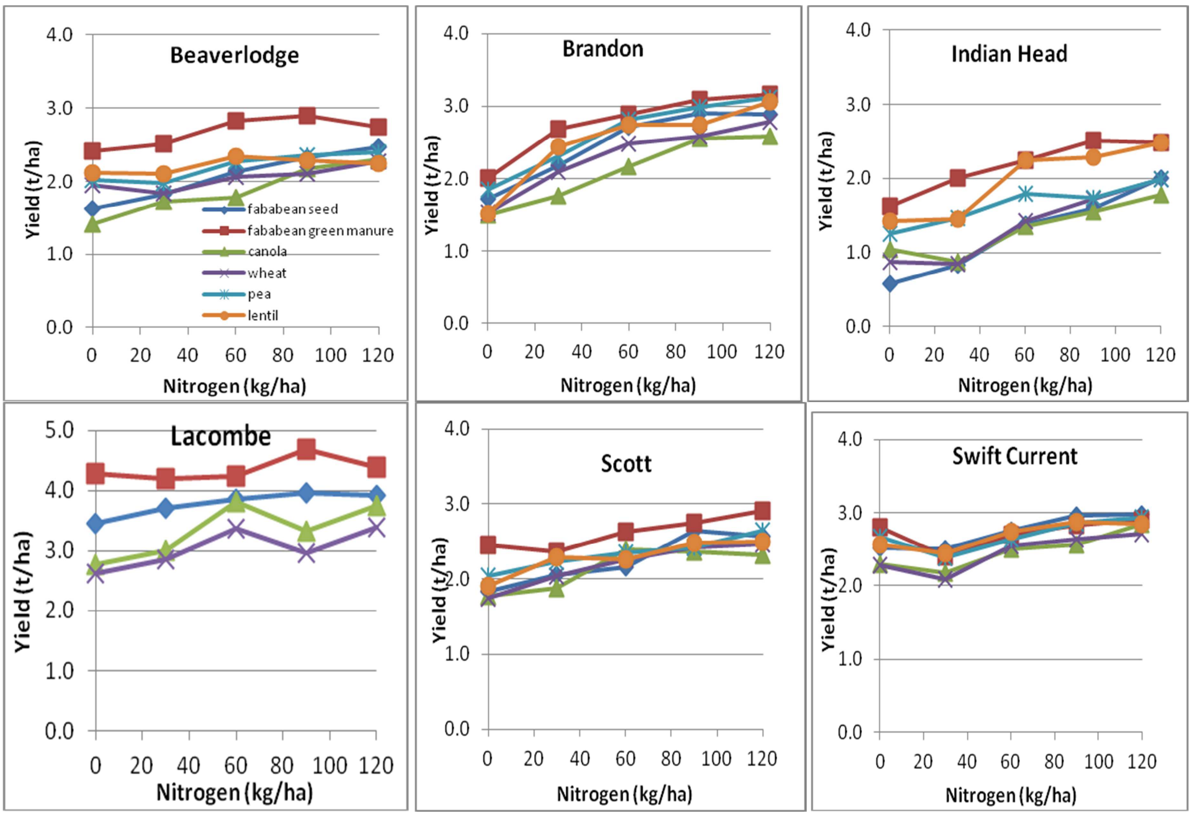

Figure 3. Yield response of canola as a function of nitrogen fertilisation and preceding crop at six locations in western Canada adapted from (O’Donovan et al. 2014).

More continuous cropping combined with retained residue also increased the risk of crop diseases, particularly some of the leaf diseases of cereal crops. Plant breeders responded, placing even more emphasis on genetic disease resistance in new cultivars than they had in the past. However, diversification of the rotation, alternating cereal with broadleaf oilseed or pulse crops was of particular importance under no-till.

Numerous studies have shown that diversifying the crop rotation, particularly with pulse crops, can increase economic and environmental performance of the cropping system, especially under no-till (
Figure 3) (Gan et al. 2015; St. Luce et al. 2015; O'Donovan et al. 2014).

The 2011 farm census of Canada showed that nearly 85% of land in western Canada was farmed using conservation tillage practices, with only 15 % prepared with incorporation of most of the crop residue (Table 2). Across Canada, conservation tillage and no-till practices have increased from just over 30% of the land area in 1991 to over 80% of the land area in 2011, with conventional tillage practices declining correspondingly (Figure 4). This widespread adoption of reduced farming system on the prairies required not only the development of suitable technology in the form of equipment, chemistry and crop genetics, but also the formulation and evaluation agronomic packages to optimise production and reduce economic and environmental risks.

Table 2. Area (million hectares) under various tillage practices for crop production in the Canadian Prairie Provinces in 2011 (Adapted from Statistics Canada 2011 Census of Agriculture, http://www5.statcan.gc.ca/cansim/a26?lang=eng&id=0040205&p2=33, accessed February 23, 2017).

Province	Total Land Prepared for Seeding	No-till or Zero-till	Retains most residues	Incorporates most residues
Manitoba	3.7	0.8	1.4	1.4
Saskatchewan	13.3	9.3	2.7	1.3
Alberta	8.1	5.2	1.8	1.0
Total	25.1	15.3	5.9	4.2

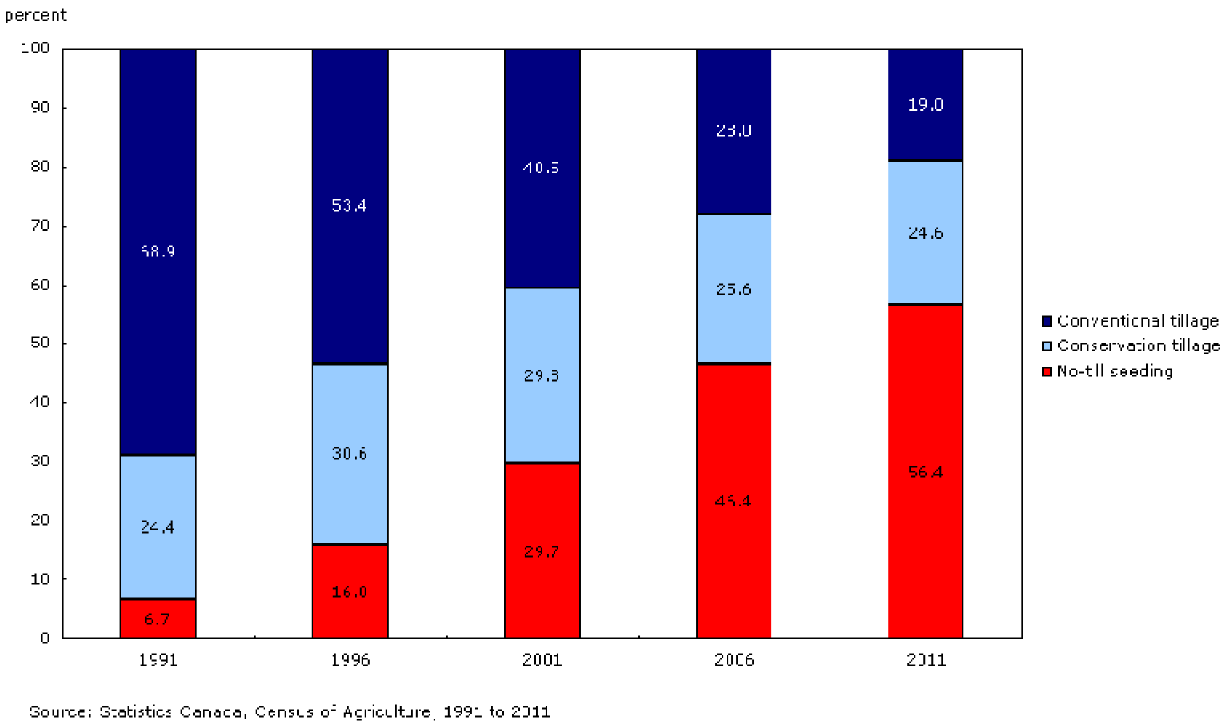

Figure 4. Change in tillage practices in Canada from 1991 to 2011 (Statistics Canada, 2016. http://www.statcan.gc.ca/pub/95-640-x/2011001/p1/figs/figure24-eng.htm)

There are still agronomic questions related to no-till copping systems in the prairies. Economic shifts, climate change, and increasing farm size are among the pressures that are influencing producers' management decisions. For example, as farm sizes increase, the need to cover more land area during the narrow seeding window has led some producers to move away from in-soil placement of fertilisers at seeding towards broadcast nitrogen, sometimes as an in-crop application, raising questions on the effects that this will have on nutrient use efficiency. Recently, prairie farmers have been moving to less diversified rotations, mainly in response to crop prices, and relying more on chemical disease control mechanisms. In particular, the availability of a range of herbicide-tolerant canola cultivars, improved genetic disease resistance, the availability of relatively effective chemicals for disease control and the high revenues from canola in comparison to alternative crops led production of canola more frequently in the crop rotation. However, rotating both crop type and herbicide control mechanism is critical to slow the development of herbicide resistant weeds. Crop production in the prairies, whether no-till or conventional till, relies on judicious use of herbicides. Herbicide tolerant weeds are not a new issue, but still pose a major risk, particularly if glyphosate resistant weeds reduce the effectiveness of glyphosate in no-till systems. Excessive reliance on limited herbicide chemistry increases the risk of tolerance, and glyphosate resistant weeds have been identified world-wide, including common and giant ragweed, horseweed and kochia in Canada (Beckie et al. 2014). With the slow development of novel herbicide chemistries, integrated weed management incorporating a range of agronomic practices such as herbicide and crop rotation, field sanitation, clean seed, use of competitive cultivars and perennial crops, as well as innovative mechanical weed control must be used to combat development of herbicide tolerance.

New technology is providing innovative agronomic tools to include in farming systems. Genetically modified (GM) crops have been widely adopted in many parts of the world, in spite of consumer opposition. New breeding techniques such as CRISPR/Cas9 allow much more targeted manipulation of genes already found within the species, eliminating the need for insertion of genetic material from foreign species (Bortesi and Fischer 2015). This will avoid the concern of cross-species manipulation most commonly raised by GM opponents. The highly controlled techniques allow for tightly targeted gene editing and may allow for the removal of allergens or increase in nutrient concentration in the crop products. From a production viewpoint, there is potential for improvements in water- or nutrient-use efficiency, harvest index or nutrient harvest index, photosynthetic efficiency, vigor, and tolerance to salinity, drought, heat, water-logging, insects, diseases, weeds or other biotic or abiotic stresses. Shifting genetic technology to address not only herbicide tolerance but also environmental and nutritional issues might improve public perceptions and hasten acceptance of genetic modification by consumers. Agronomic studies will be needed to develop practices to capture the yield potential of new cultivars and avoid the buildup of resistance in pest populations. The impact on factors such as salinity remediation, nutrient depletion from the soil, water availability for following crops, or crop competitiveness will need to be evaluated for the overall effect on the environment and the cropping systems.

New technology is also emerging for nutrient management. The “4R” nutrient management system describes a platform for nutrient management that promotes using the right source, right rate, right time and right place for fertiliser applications to enhance the economic, environmental, and social performance of farming systems (http://www.ipni.net/4r, accessed August 17, 2017). Developing technology provides new options to fit into 4R systems. For example, enhanced efficiency fertilisers, including inhibitors, controlled release products and novel formulations have been on the market for a number of years and can be effective within a 4R system in improving nutrient use efficiency in some environmental conditions. This may provide methods of improving nutrient use efficiency for no-till farmers shifting away from in-soil applications to surface applications to save time during the seeding operation. However, enhanced efficiency products often may not provide a benefit, depending on the magnitude and pathways of loss that are present (Grant et al. 2012). For example, in studies conducted across Canada, controlled release urea provided a benefit greater than uncoated urea under wet conditions (
Figure 5) but not under drier conditions where potential nitrogen losses were lower (Grant et al. 2012). There is strong interest in use of microbial products such as mycorrhizal or bacterial inoculants to increase the ability of crops to extract phosphorus from the soil, but the effectiveness of these products under field conditions has often been limited (Figure 6). As new products are developed, agronomic studies are essential to evaluate the conditions under which they can be beneficial and their potential effects on other economic or environmental characteristics of the system.

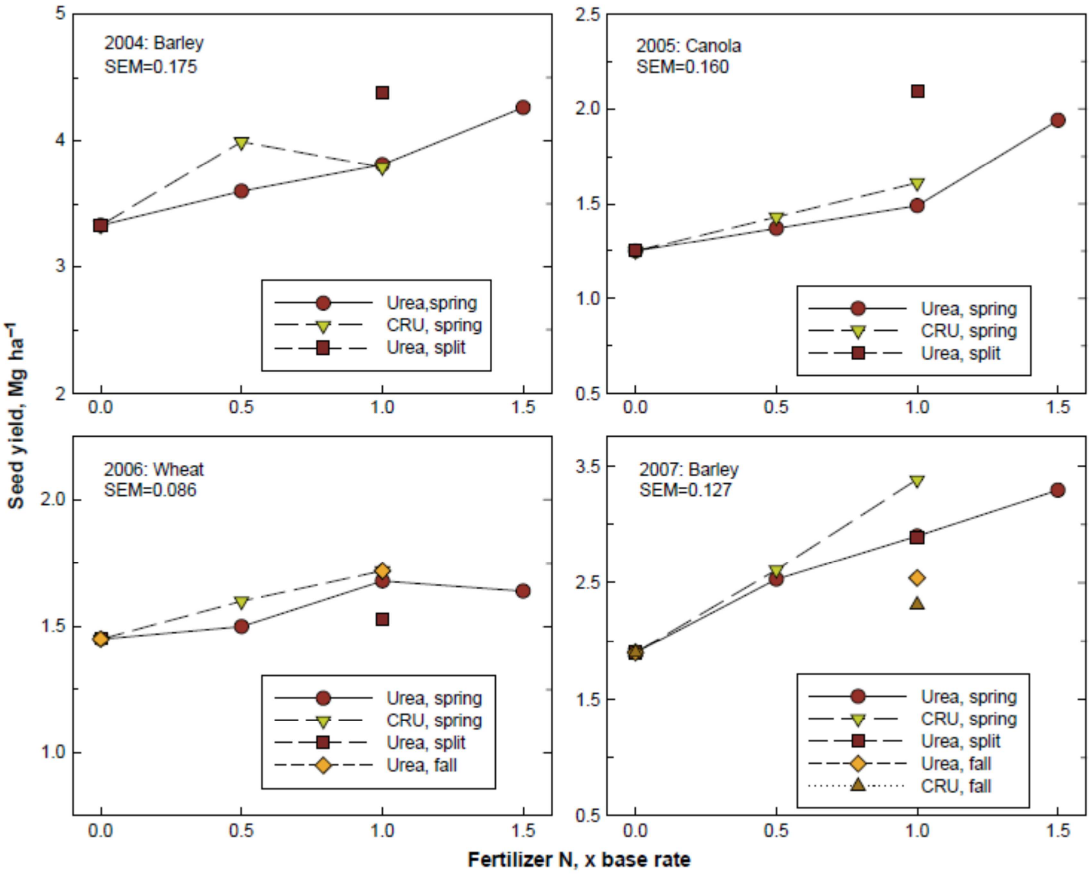

Figure 5. Seed yields of (a) barley in 2004, (b) canola in 2005, (c) wheat in 2006, and (d) barley in 2007 at Beaverlodge, Alberta, as influenced by the form, rate and method of application of urea fertiliser. Although not all data points are shown to reduce cluttering, the range is displayed in the data shown. A base rate of 1.0x is: 60 kg N ha^{-1} for 2004 and 2007, 50 kg N ha^{-1} for 2005, and 55 kg N ha^{-1} for 2006. (Malhi et al. 2010).

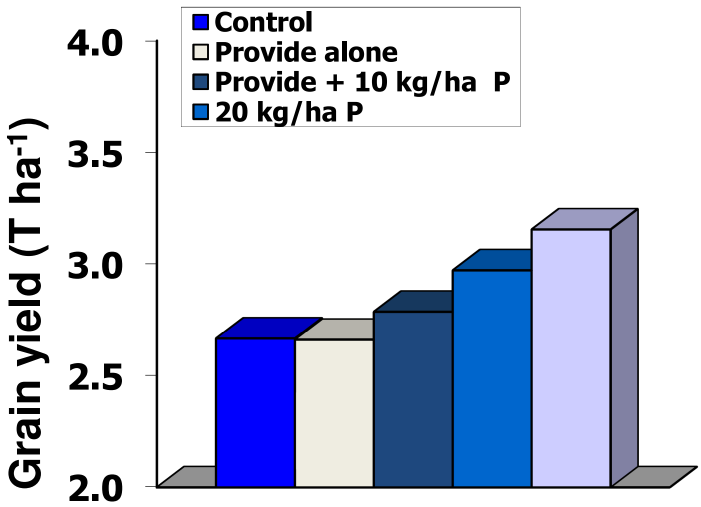

Figure 6. Impact of phosphorus fertilisation with or without use of Provide (*Penicillium bilaii*) on yield of durum wheat (Mean of three sites over three years) (Grant et al. 2002a).

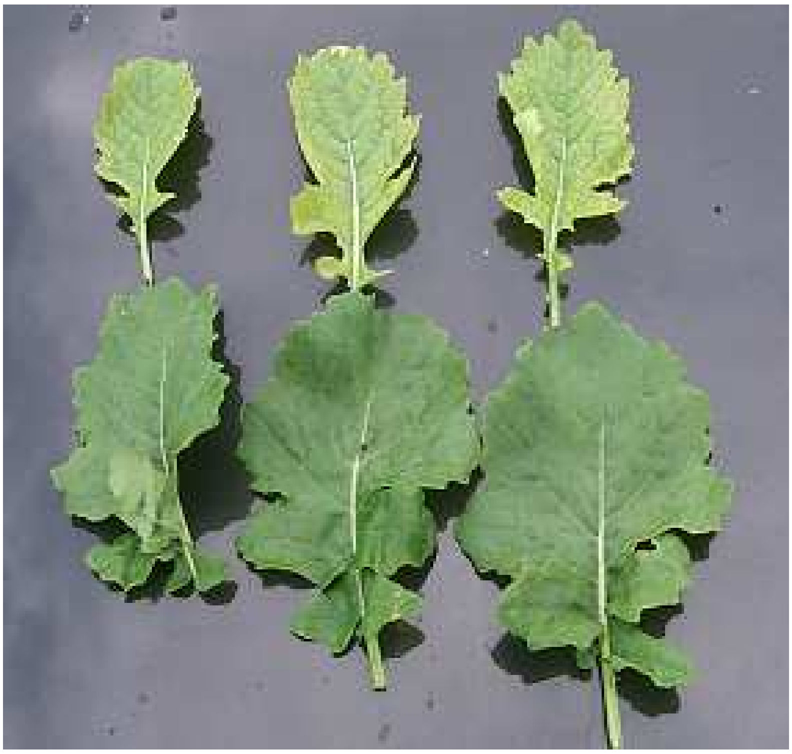

Figure 7. Influence of increasing N applications on sulphur-deficient (upper) and sufficient (lower) conditions.

Mechanical technology can help to improve management practices, not only for nutrients but for a range of issues such as diseases, weed, insects, and drainage. Low cost drones are becoming readily available and can be used to more easily supply images to identify areas of the crop that are under stress and fine-tune both pest management and nutrient applications. On-the-go sensors can be used for in-crop site specific nutrient management. Crop monitors can provide maps of final crop yield and protein concentration to address yield constraints or capture yield potential on a site-specific basis. The ability to capture and store data is continually increasing, but there is the risk of drowning in data while starving for information. The ability to take collected data and translate it into usable information requires an understanding of the agronomic platform where the crop is growing to determine what is causing the crop stress to effectively remediate the problem. For example, applying extra nitrogen to a chlorotic crop will only exacerbate the problem if the crop is actually sulphur deficient (**Error! Reference source not found.**). Similarly, if crop yields are being limited by poor drainage, input of extra nutrients will be both economically and environmentally harmful. It is critical to be able to pull data together and interpret it correctly to understand the system and identify both constraints and opportunities. Effective use of both mechanical and the chemical nutrient management tools into an integrated system is critical to develop practices to overcome constraints and take advantage of opportunities in an economic manner.

Conclusions

Changing global conditions and advances in technology continue to provide agronomic problems and opportunities in the prairies and around the world. Ultimately, crop yield is determined by the environmental limitations, such as light, temperature, length of growing season, carbon dioxide and, in a rain-fed situation, water. If these factors are changed either positively or negatively by climate change, production practices must be fine-tuned to complement the new situation. As the world's population increases, there is a greater and greater demand placed on the diminishing arable land area. The considerable yield gap between potential crop yields and actual yields attained in farmer fields must be reduced in order to meet the projected food demand for the growing world population (Ittersum et al. 2013). This will require improved agronomics of production to increase crop yields in a sustainable fashion. Advances in technology will provide new tools for agriculture. The science of agronomy is essential to ensure that the new technology is used effectively to improve the economics and sustainability of our faming systems.

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