Efficiency and innovation in mechanization for highly industrialized countries

by *John K. Schueller* (schuejk@ufl.edu)

U.S.A.

1. Introduction

The world's population continues to increase and will be approximately nine billion by the year 2050. There is a great difficulty in sustainably supplying enough food, feed, fiber, and fuel for the world's population at that point. Not only will there be more people, but much of the world's population will have higher expectations and demands as their homelands become more developed. These higher expectations, such as more fruits and vegetables, more animal proteins, and a higher per-capita fuel consumption, will place great demands upon an agricultural production and distribution system which even now is not adequately supplying all the needs of the world's people. Some estimate that the production of usable agricultural plant material would need to almost double by 2050 to truly meet all the needs.

To achieve anything near this level of agricultural production, there will need to be significant gains in both the developing world and the highly-industrialized world. Examples of situations in the developing world will be dealt with in the two presentations in the next session. This presentation will concentrate on the highly industrialized countries. It builds upon last year's presentation on intensive farming operations in North America (Schueller, 2014).

Agriculture in the high industrialized countries is highly developed and productive. However, there are difficulties. As two examples, Japan only produces forty percent of its caloric consumption and the USA imports eleven billions dollars more fruits and vegetables than it exports. As demands increase in the developing world, the highly industrialized countries need to produce more to meet their own demands as well as to aid the developing world. Since most of the available prime agricultural land is already in use in these countries, most of the increases must be achieved by increasing production on that existing agricultural land rather than converting other land to agricultural uses.

In fact, there are losses of agricultural land due to such processes as urbanization, salinization, desertification, erosion, etc. These losses must be reduced. And the soil, water, and air must be protected so that agricultural production will continue and the health of the inhabitants and the environment are maintained. Consequently, it is important that agricultural production and the rural society remain sustainable.

As we move toward 2050 and beyond, agricultural production in the highly industrialized countries needs to continue to improve in both quantity and quality in a manner that is economically, environmentally, and socially sustainable. Fortunately, innovative agricultural mechanization can aid with that task. Recent mechanization developments have contributed and future developments may be great facilitators of more productive and more efficient agricultural crop production. One way they increase the quantity and quality of agricultural products is by performing the operational processes better. For example, harvesters have less loss and produce less product damage. Another example is planting equipment which places the seed or transplant into the precise location desired and forms an optimum environment around it.

There are many recent and future agricultural mechanization technologies which are promoting agricultural productivity and sustainability in the highly industrialized countries. This presentation will review some of them.

2. Sustainability

2.1. Long-Term Stability

We obviously don't want the highly-industrialized societies to collapse. As Diamond (2005) shows, this requires that the societies be sustainable. As the highly-industrialized countries have already generally expanded and exploited available resources, the concern is keeping the societies economically, environmentally, and socially stable.

2.2. Economic Sustainability

Agricultural producers will only stay in business if there is economic sustainability. The manufacturing and service sectors are highly developed in most highly industrialized countries. Consequently, the available capital and labor in these countries will move away from agriculture if there is insufficient economic opportunity. The high standards of living and the high living costs in these countries means that those who work in the agricultural fields need to have sufficient income in order to justify continuing their efforts. Although the past years have been somewhat favourable, the future is not so bright as, for example, USA farm incomes will decline this year to the lowest level in nine years (Newman, 2015).

As trade increases and trade barriers come down, agricultural commodity prices are becoming more uniform worldwide. Since the per-unit labor costs and some other input costs are high in the highly industrialized countries, agricultural production in the industrialized countries needs to be very productive and efficient in order to be competitive. Efficient and innovative mechanization has done this in the past and needs to continue to do so.

Advanced mechanization of broad-acre production agriculture has allowed the highly-industrialized countries to be competitive in such crops as cereals, oilseeds, animal feeds, and cotton. For example, the top exporters of wheat are the European Union, United States, Russia, Canada, and Australia (USDA, 2015). Many of the high-industrialized countries, even those with ample agricultural land, are net importers of crops, such as fresh fruits and vegetables, where the level of mechanization is not so high. The potential growers of such crops often cannot find suitable labor at an economically sustainable price (Brat, 2015).

2.3. Environmental Sustainability

Agricultural production, if not done in a sustainable manner, can be harmful to the environment. For example, the soil can be salinized, it can lose its nutrients, its tilth can be damaged, or the valuable topsoil can be eroded by water or wind. In addition, there are continued losses of land area to urbanization, transportation systems, and environmental conservation.

Agricultural production can harm other land, water, and air by pollution or the consumption of resources. Excess erosion sediment and fertilizer nutrients, especially nitrogen and phosphorous, can damage water supplies and ecosystems. For example, this year there is a hypoxia deadzone of about 6500 square miles (17,000 square kilometres) in the Gulf of Mexico from nutrients in the Mississippi river watershed (NOAA, 2015). Pesticides can also be carried from agricultural lands.

Agricultural production, and the environment in general, needs to be protected for the future. Citizens in the industrialized countries demand this for their own health and for that of their offspring. Given that the industrialization and intensification of both agriculture and populations have in many places occurred in the recent past, the practices to sustain the environment have not been as widely developed as applied as they need to be. But efficient and innovative mechanization may help protect the environment.

2.4. Social Sustainability

The perceived relative economic and social advantages of urban and suburban life have led to a migration from the rural areas in many situations. Some rural communities have suffered with population decreases and a lack of economic opportunity. For example, in Japan where "Everything continues to gravitate to Toyko, which takes up only 0.6 percent of Japan's land mass while containing 10 percent of the population and generating 19 percent of the gross domestic product" (Brasor, 2014), there is now a regional revitalization ministry to try to reverse this trend. Even in the U.S.A., which, unlike much of Europe and Japan, is still seeing overall population growth, population in non-metropolitan counties is decreasing (Frey, 2014). This rural-to-urban migration has especially been true for young people with desires for fulfilling careers. New mechanization which utilizes advanced technologies may retain such people in the rural areas and promote more diversity and vitality in them. For example, precision agriculture and other innovative mechanizations provide opportunities for those skilled in computer technologies and electronics.

3. Advances in Agricultural Mechanization in Field Operations

3.1. Changing Field Operations to Improve Productivity and Sustainability

Agricultural crop production can be thought of as involving a series of field operations to preplant prepare, produce, plant, protect, harvest, and, finally, transport the agricultural product. As discussed above, this needs to be done in a productive, efficient, and sustainable manner. Advances in mechanization have helped improve these field operations. Some examples will be given in this section.

3.2. Crop Establishment

Traditionally, agricultural fields were plowed and repeatedly tilled to bury all the existing plant material and to prepare a clean, fine-tilth, and uniform seedbed for the crop being established. Such activities are still needed in some situations. However, in others it is not needed. The unneeded tillage can cause the agricultural fields to be more susceptible to erosion, soil degradation, and water loss. Innovative agricultural equipment has been developed, commercialized, and promoted to allow crop establishment in reduced tillage or no tillage situations. These planters and other machines can establish crops without the fine seedbeds and the preceding field operations to generate them. As the title of a Washington Post article (Plumer, 2013) indicates ("No-till farming is on the rise. That's actually a big deal."), these advances are having a significant effect.

The use of this equipment promotes environmental sustainability by better protecting the soil and water. It also reduces the needed tillage operations, thereby reducing fuel consumption and the production of fuel combustion products. This is advantageous from both economic and environmental sustainability perspectives.

3.3. Crop Promotion and Protection

Growing crops cannot reach their full potential without the necessary nutrients. If the soils cannot natively supply those nutrients, they must be provided supplemental nutrients through fertilization. Granular and liquid fertilizer application equipment has been developed which can provide the nutrients in the proper amounts and proper locations so the crops can grow and produce in an optimal manner. There have been significant advances in nutrient placement which put accurately-controlled amounts of nutrients where the crops can use them and where they are less likely to become pollutants by travelling from the point of application. This promotes both economic and environmental sustainability. Nutrients absorbed by the crop increase the production and don't pollute the environment. For example, nitrogen use efficiency in the USA corn belt has increased 35% in the last 25 years (www.cropnutrition.com, 2015).

Similarly, pesticides are only useful when they kill pests. Better methods of insuring that the pesticides reach their targets cause less pesticides to be used for both economic and environmental benefits. In addition, better irrigation equipment, such as Torre-Neto and Schueller (2000), improves water use efficiency.

Perhaps the most important innovative technology for crop promotion and protection has been the development and adoption of various precision agriculture technologies. These technologies will be discussed in a separate section below.

3.4. Harvesting Equipment

After the crop is grown, it must be harvested before it can be used as food, feed, fiber, or fuel. The harvesting operation is often one of the most crucial. Crop losses, that is products which are not successfully gathered and transported out of the field, need to be minimized. Advanced mechanized machines are able to minimize the losses. Harvesting productivity is important because most crops have short time spans within which harvesting must occur for maximum quantity and quality. Recent innovations also help improve quality by reducing the amount of crop damage. Contemporary harvesters are quite sophisticated, even for "minor" crops where the harvester manufacturers cannot expend large equipment development costs. For example, a contemporary turf harvester has eighty analog and digital sensors and one hundred digital outputs (Aposhian, 2015).

Harvesting of many crops, especially certain fruits and vegetables for fresh consumption, has often been resistant to mechanization, despite many good efforts (Sarig, 1993). This is problematic in highly industrialized countries as the cost of labor for harvesting frequently can be even more than half the total production cost. This high labor cost has often led to the importation of those commodities and the resultant transportation energy expenditures. Or they have led to the use of illegal workers. These situations can have economic, environmental, or social sustainability impacts.

4. Advances in Supporting Agricultural Mechanization Technologies

4.1. Underlying Technology Improvements Aid Agricultural Mechanization and Sustainability

As described above, major changes in particular agricultural mechanization equipment have aided agricultural field operations. In addition, there have been significant technological advances which have aided or abetted those changes or improved existing agricultural mechanization and equipment. These changes have made crop production more economically feasible or have reduced the adverse environmental impacts. Some examples are described below.

4.2. Equipment Guidance

Precision agriculture (discussed below) depended upon location technologies. Early technologies (e.g., Searcy, et al., 1990) were eventually replaced with satellite technologies, such as GPS. When the continuing improvements in these technologies achieved sufficient accuracy, they could be used for equipment guidance. Automated equipment guidance has been quickly adopted and has improved crop production agriculture. Light bars which helped the equipment operator steer tractors and other equipment were the first technology to be adopted. Later, automatic steering systems quickly became popular. These systems were economically justifiable because they greatly reduced overlaps and skips. Economic and environmental benefits were seen from the more efficient use of crop production inputs.

A related technology is section control. Section control allows individual sections of large equipment to be controlled. This reduces overlaps in non-rectangular fields and improves performance near grass waterways and other environmental structures.

The economic value of automatic guidance and section control varies greatly with the particular situation. For example, Groover and Grisso (2009) quote a savings of 2% to 7% of input costs with automatic guidance. Luck, et al., (2009) showed spray material savings of 15% in a central Kentucky field with boom section control. Batte and Ehsani (2005) showed a savings of about US$4 to US$8 per hectare for a spraying operation in a field with automatic guidance and boom section control. These savings have both economic and environmental benefits.

4.3. Power Supply Efficiency and Pollution

Existing mobile agricultural equipment is primarily diesel-powered. Significant improvements in diesel engines have resulted in greater levels of fuel efficiency. These improvements reduce fuel consumption and, accordingly, the CO_2 generation.

There has also been great progress in reducing the pollution from such engines. Technologies such as exhaust gas recirculation (EGR), selective catalytic reduction (SCR), and diesel particulate filter (DPT) have reduced the pollutants into the air, such as Cummins (2015). Agricultural equipment has moved to Tier 4/Stage IV compliance, and European equipment will soon have to meet Stage V. For example, this means that nonroad diesel engines with net power between 130 and 560 kW have to meet emissions standards which include less than 0.19 g/kWh of hydrocarbons and 0.4 g/kWh of NO_x (dieselnet, 2015).

4.4. Ground Engagement

Tractors, harvesting machines, materials transporter, and other mobile agricultural equipment travel over the soil in which the crops need to grow. Power needs to be efficiently transmitted to propel the equipment without excessively compacting the soil. This compaction can have detrimental effects on crop production and long-term sustainability of maximum production.

Various technological advances have been achieved to improve the ground engagement. One example is the increasing use of rubber tracks in place of wheels. The use of equipment configurations in which there is a single track on each side of the vehicle (both with and without a complementary wheel) and two tracks on each side of the vehicle (commonly known as “quad tracs”) have become more common. These arrangements can lead to better traction and less compaction, depending upon the local conditions.

The majority of mobile equipment still uses pneumatic tires on wheels.   But there continue to be enhancements to improve traction and reduce compaction. For example, increased flexion (IF) and very high flexion (VHF) tires have lower pressures and higher contact areas than conventional tires.

Due to better guidance capabilities and the proper design possibilities of some equipment, it is now possible to have more controlled traffic in agricultural fields. This has a long tradition in Europe in the form of tram lines for fertilization and pesticide application. But it is now possible to extend traffic controls to more field operations. By restricting traffic to reduced portions and paths, it is possible to increase traction while reducing compaction over most of the field.

4.5. Agricultural Drones

Small unmanned aircraft, often called “drones”, are inspiring great interest and experimentation in agriculture. Estimates of as high as 80% of the future commercial market for drones is for such agricultural uses. Most of the concentration is on the use of drones for scouting purposes to check on soils, crops, and pests. But drones can also be used to perform some field operations, such as pesticide application, and to monitor other field operations. The low cost of drones can make them affordable to farmers. The American Farm Bureau has estimated a return on investment of $12/acre (US$30/hectare) for typical use in corn (Wihbey, 2015).

5. Precision Agriculture Technologies Improve Sustainability

5.1. Precision Agriculture

Agricultural fields are not uniform. So they do not have the same input needs or the same output potential at every point within the field. One of the big advances in agricultural mechanization over the last years is the capability to perform spatially-variable crop production (Schueller, 1992), often known by the popular term of "precision agriculture". Precision agriculture (Auernhammer and Schueller, 1999) seeks to maximize production and minimize environmental degradation by knowing the spatial variability inherent within the field, determining the correct response to that variability, and then performing the strategic and tactical variations in field operations and other crop production activities in order to achieve the economic and environmental sustainability goals. As shown by Bongiovanni and Lowenberg-DeBoer (2015), "most of the papers reviewed indicate that precision agriculture can contribute in many ways to the long-term sustainability of precision agriculture."

The adoption of precision farming technologies varies widely depending upon local farming practices, cropping systems, field soils, field variabilities, economic situations, and other conditions. Although widely-applicable generalizations are impossible, there have been attempts in particular regions and countries to determine the extent of precision agriculture technology usage. For example, a farm practices survey in England found that soil mapping, yield mapping, and variable rate applications were used on 20, 16, and 22% of the farms respectively (DEEFRA, 2013). The Croplife/Purdue survey estimates usage in the USA, concentrating on the corn belt. They estimate higher usage, with about one-third of the market area of the input dealers using yield mapping and boom section control (Holland, et al., 2013).

5.2. Sensing and Mapping Soils, Crops, and Pests

A good farmer knows accurately the conditions and problems of his soils, crops, and pests. This is a difficult task for the farmer, particularly in highly-industrialized countries where large areas must be farmed in order to generate sufficient income. Fortunately, advances in agricultural mechanization are now available to aid the farmer.

Accurate sensing in agricultural environments is difficult due to the fact that the environments are complex systems with interacting biological, chemical, and physical components. In addition, most environments are outdoors with variable weather. Yet information must be gathered with accuracy and at a low cost.

Advances in electronics and computers have led to better sensing systems. There have been very significant recent advances in computer vision systems. These systems can detect and distinguish between crops and weeds. Some can find diseased or pest-damaged portions of the crops. Some systems can identify and evaluate portions of the crops, such as the quantity and quality of fruit or grain kernels.

There have also been corresponding advances in utilizing portions of the electromagnetic spectrum to sense in crop production systems. Again, these systems can identify plants and pests. Both to separate into categories and to quantitatively evaluate situations, such as the health or deficiencies of a crop plant.

Another category of sensing is measuring the amount of crop which is being harvested. Various technologies, some sensing individual items (such as counting the number of fruit) and others sensing volumetric and mass flows (such as the amount of grain passing), have been researched, developed, commercialized, and/or widely adopted.

These and other methods of sensing are widely used to improve the performance of agricultural mechanization equipment conducting field operations. Many times these sensors are mounted directly on the equipment and used to adjust the machines. Some of these automatic control systems improve performance in crop establishment and protection machines. Others insure that the maximum amount of crop is harvested with the minimum amount of damage.

Such automatic control has existed in agriculture since the time of Harry S. Ferguson and Henry Ford. But it is now extended to more aspects of agricultural mechanization and agricultural production. With the computerization of agricultural equipment, it is now possible to store sensor information for subsequent use. Thus, the information can be used to not only improve the current operation, but also subsequent ones.

One set of technologies which demonstrates this capability is mapping of soils, crops, and pests. The most significant of these is yield mapping. Yield mapping while harvesting, or even now before harvesting, allows better management decisions to be made. Yield mapping tells the farmer what is happening within the farmer's fields and indicates where problems exist. Yield mapping technologies have been developed for such crops as grains (e.g., Searcy, et al., 1989), fruits and vegetables (e.g., Schueller, et al., 1999), and animal feeds (e.g., Lee, et al., 2005).

Similarly, maps of soils and fertilities can be very useful. As can maps of pests, such as weeds and disease infestations. Maps of crop conditions can also be useful. For example, maps of the reflectivity of certain electromagnetic spectrum components can indicate deficiencies of nutrients or water. Or the presence of a pest at the locations of anomalies on the map.

These maps can be gathered in different manners. Many times they can be generated during other field operations. For example, yield maps can be gathered during harvesting. Or pest or crop condition maps during pesticide or fertilizer application operations. Another example is gathering information while center-pivot irrigation systems are operating.

At other times, they can be gathered during specific scouting operations. This scouting can be done by a human. There has also been a significate interest in small robotic ground vehicles. And, of course, it can be done with aerial views. These can be manned aircraft, such as airplanes, or unmanned such as drones or satellites. In any event, these remote sensing operations can gather valuable information that can be used as maps in precision agriculture systems.

5.3. Determining Management Actions

Precision agriculture maps of yields and other spatially-variable characteristics are only useful if something is done with the information. Strategic or tactical decisions need to be made (Schueller, 1992). Strategic decisions tend to be large-scale, one-time decisions such as removing areas from production, changing field boundaries, landforming, or adding drainage. Modern equipment can be programmed to perform the landforming or drainage installation in a proper manner.

Tactical decisions are generally on smaller spatial scales and generally involve items which will be repeated in subsequent cropping cycles. For example, this could be scheduling a spatially-variable fertilizer, pesticide, or irrigation application in which different portions of the field would receive different amounts of the crop input. These decision-makings would need to be repeated again at some times in the future. The management actions would integrate all the appropriate information, perhaps including multiple maps, into a determination of the best action to take. The mechanization aspects of this part of precision agriculture involves sophisticated software which can process all the information and the algorithms that determine the desired actions.

5.4. Actuating Accurate Spatially-Variable Control

The final step of precision agriculture technology is to actuate the determined actions in an accurate manner. This is possible due to the improved performance of modern agricultural equipment. The equipment is able to apply the right amount of the agricultural input for that particular location at the right time in a manner that will maximum crop production while minimizing adverse environmental impacts.

The modern equipment available for contemporary agricultural mechanization is able to perform accurately in both static and dynamic situations. The dynamic accuracy of the equipment means that it can respond automatically to localized changes in conditions and crops (Chan, et al., 2004) despite being very productive. This is achieve by improvements in computers, mechanical design, and electronic controls.

6. Impact of Efficient and Innovative Mechanization

6.1. Efficient Mechanization

Contemporary mechanization increases the productivity and efficiency of crop production. It insures that field operations are performed in a timely manner and in such a manner such that the maximum amount of quality agricultural products are produced. The contemporary equipment minimizes the use of water, fertilizers, pesticides, and fuel, thereby minimizing the environmental impacts of those usages.

6.2. Innovative Mechanization

As the examples above indicate, innovations in agricultural mechanization are helping supply the needed quality agricultural production in a sustainable manner. Further innovations are needed to insure that production increases and sustainability is enhanced. These innovations need to occur along the innovation spectrum from research to development to commercialization to adoption.

7. Conclusions

The production and quality of the food, feed, fiber, and fuel produced by crop production in the highly-industrialized countries must increase to meet the needs of expanding world populations and increasing expectations. This must be done primarily on existing agricultural land while promoting economic, environmental, and social sustainability. Present and future advances in agricultural mechanization are necessary to aid this process.

References

Aposhian, S. 2015. Wheels: LabVIEW helps smart turf-harvesting machine boost productivity, reduce cost. *Design Fax*. 8 September.

Auernhammer, H., and J.K. Schueller. 1999. 3. 2. Precision farming. In B.A. Stout and B. Cheze, eds., *CIGR Handbook of Agricultural Engineering*, Vol. III, Plant Production Engineering. American Society of Agricultural Engineers. pp. 598-616.

Batte, M.T., and M.R. Ehsani. 2006. The economics of precision guidance with auto-boom control for farmer-owned agricultural sprayers. *Computers and Electronics in Agriculture*. 53(1):28-44.

Bongiovanni, R., and J. Lowenberg-DeBoer. 2004. Precision agriculture and sustainability. *Precision Agriculture*. 5:359-387.

Brasor, P. 2014. Tokyo continues to pull people in, which pulls the rest of Japan down. *The Japan Times*. 15 November.

Brat, I. 2015. Even at $17 an hour, farms can’t fill jobs. *The Wall Street Journal*. 13 August.

Chan, C.W., J.K. Schueller, W.M. Miller, J.D. Whitney, and J.A. Cornell. 2004. Error sources affecting variable rate application of nitrogen fertilizer. *Precision Agriculture*. 5(6):601-616.

cropnutrition.com. 2015. Understanding Fertilizer and Its Essential Role in High-Yielding Crops. http://www.cropnutrition.com/understanding-fertilizer-and-its-essential-role-in-high-yielding-crops. accessed 13 September 2015.

Cummins. 2015. Cummins looks ahead with new component technology. articles.sae.org/14097/ . 21 August. accessed 13 September 2015.

DEFRA. 2013. Farm practices survey Autumn 2012—England. U.K. Department for Environment, Food, & Rural Affairs. 28 March.

Diamond, J. 2005. *Collapse: How Societies Choose to Fail or Succeed.* Viking Press. ISBN: 0-14-303655-6.

dieselnet. 2015. Nonroad engines. https://www.dieselnet.com/standards/eu/nonroad.php . accessed 14 September 2015.

Frey, W.H. 2014. A Population Slowdown for Small Town America. www.brookings.edu . 31 March. accessed 14 September 2015.

Groover, G., and R. Grisso. 2009. Investing in GPS guidance systems? Virginia Cooperative Extension Service Publication 448-076.

Holland, J.K., B. Erikson, and D.A. Widmar. 2013. 2013 Precision Agricultural Services Dealership Survey Results. Department of Agricultural Economics, Purdue University. Staff paper.

Lee, W.S., J.K. Schueller, and T.F. Burks. 2005. Wagon-based silage yield mapping system. *Agricultural Engineering International*. CIGR. Vol. VII. Manuscript IT 05 003.

Luck, J.D., S.K. Pitla, S.A. Shearer, T.G. Mueller, C.R. Dillon, J.P. Fulton, and S.F. Higgins. 2010. Potential for pesticide and nutrient savings via map-based automatic boom section control of spray nozzles. *Computers and Electronics in Agriculture*. 70(1):19-26.

Newman, J. 2015. Steep farm-income decline forecast. *The Wall Street Journal*. 26 August.

NOAA. 2015. Gulf of Mexico dead zone above average. (USA) National Oceanic and Atmospheric Administration. www.noaanews.noaa.gov. August 4. accessed 14 September 2015.

Plumer, B. 2013. “No-till farming on the rise. That’s actually a big deal.” *The Washington Post*. www.washingtonpost.com. 3 November.

Schueller, J.K. 1992. A review and integrating analysis of spatially-variable control of crop production. *Fertilizer Research*. 33:1-34.

Schueller, J.K. 2014. Intensive farming systems: Efficiency and innovation for sustainability—The case of North America. Club of Bologna. http://www.clubofbologna.org/.

Schueller, J.K., J.D. Whitney, T.A. Wheaton, W.M. Miller, and A. E. Turner. 1999. Low-cost automatic yield mapping in hand-harvested citrus. *Computers and Electronics in Agriculture*. 23(2):145-153.

Searcy, S.W., J.K. Schueller, Y.H. Bae, and B.A. Stout. 1990. Measurement of field location using microwave frequency triangulation. *Computers and Electronics in Agriculture*. 4(3):209-223.

Searcy, S.W., J.K. Schueller, Y.H. Bae, S.C. Borgelt, and B.A. Stout. 1989. Mapping of spatially-variable yield during grain combining. *Transactions of the ASAE*. 32(3):826-829.

Torre-Neto, A., and J.K. Schueller. 2000. Networked sensing and valve actuation for spatially-variable microsprinkler irrigation. ASAE Paper No. 00-1158. ASAE Annual International Meeting. Milwaukee. July 8-12.

U.S. Department of Agriculture. 2015. Grain: World Markets and Trade. September. www.usda.gov . accessed 11 September 2015.

Wihbey, J. 2015. Agricultural drones may change the way we farm. *The Boston Globe*. 22 August.