Techno-economic analysis of future precision field robots

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Abstract. *Precision agriculture (PA) technology provides a means to increase equipment productivity and field efficiency, and input efficiency; however, the potential of PA technologies to enable smaller, autonomous machines has yet not been realized in the market place. In developed countries, the size of tractors and implements continue to increase. Such trend cannot continue indefinitely because of size, technical and cost constraints. A long operating life for agricultural equipment enables a greater benefit relative to the high initial cost and investment. However, long equipment life can lead to technologically obsolete machines with potential incompatibility and sub-optimality, since machinery and PA technology should evolve together and be used as a package. Similarly, power system technologies with potential application in agricultural machines are also evolving quickly and issues of renewability and sustainability are becoming common priorities, with demands for standardization and certification. The concept of small modular and scalable intelligent machines tries to address the challenge of gaining higher productivity with reduced costs and power. In particular, in this paper different weeding technologies were compared using performance metrics including work rate and energy density. Conventional processes, using common tractors were compared with robotic weeder designs to evaluate performance, size and energy requirements. Forecasts of possible future trends of agricultural machine size, PA technology integration and power system technology deployment were derived from this work.*

Keywords. *Precision agriculture, agricultural machinery, energy, economic analysis, robotic systems*

Introduction

Global agriculture faces the challenge to supply food to more than seven billion people around the world. According to Zimdahl (2013), several obstacles to sustainable food production exist including physical,

economic, environmental, biological and political constraints. Environmental constraints are problems related to water, soil, and crop management that includes weed control. In any cropping system, various operations are dedicated to the control of weeds. People use around thirty percent of the earth's land for crops and pastures, and problems caused by the indiscriminate use of chemicals that leads to air, water and soil pollution that could become a risk to ecosystems and human health (FAO, 2013).

The current trend is to use more efficient agricultural processes to increase food production (Ahmad, 2012, Zentner, et al. 2004, Ortiz-Canavate and Hernanz, 2013). Precision agriculture (PA) technology provides the means to increase equipment productivity and field and input efficiency. The concept of small modular and scalable intelligent machines tries to address the challenge of more productivity with the goal of reduced cost and power. In addition, power system technologies with potential application to agricultural machines are evolving quickly and issues of renewability and sustainability are becoming common priorities, with demands for standardization and certification (Bongiovanni and Lowenberg-DeBoer, 2004, Cordill and Grift, 2011, Nørremark, et al. 2008, Nielsen, et al., 2002, Slaughter, et al., 2008).

Currently, in the area of weed control, there are several strategies for controlling weed infestations in crop production, such as chemical control, mechanical cultivation, thermal treatment among others (Zimdahl, 2013, Ahmad, 2012). All of these strategies have different power and energy requirements, and sustainability could be improved from each of these strategies (Zentner, et al., 2004). This paper provides a case study with a prototype mechanical weed control system powered by electrical power. This prototype was analyzed using performance metrics such as work rate and energy requirements per area across different moisture contents of soil and depths. Several different weed control technologies were compared on an energy and cost basis to determine how agricultural precision information can be used to reduce energy requirements.

Materials and Methods

The energy overall performance of cropping systems have been evaluated by different methods. These methods involve the identification of all direct and indirect energy working into the fabrication, design, packing, supply, transportation, conservation, and application of all inputs used in each crop production system (Zentner, et al. 2004). We reviewed these methods to identify an approach to evaluate only the weed control system of different crop systems. Weed control is an important and, in a sustainable point of view, critical process in cropping systems. Usually, we have methodologies to estimate the overall energy balance, such as used in evaluation of ethanol from different crops (Pimentel and Patzek, 2005, Green Design, 2006, Nemecek and Kagi, 2007, Schmer, et al., 2008, Shah, 2013) but in these methods, the weed control energy is not computed separately. The methodology to perform energy requirements of different weed control systems is explained in the following sections.

Energy in Machinery Methods:

The embodied energy of machinery were estimated in terms of "steel-mass" basis. This approach is well known by researchers and assumes that the machinery are made of steel alone. Shah (2013) considered that the overall energy used by the manufacturing process includes the energy for producing steel and an additional 50% of energy for the fabrication and assembly of the equipment. We assumed with the value of 25MJ Kg^{-1} for the energy for producing steel (Shah, 2013). This energy was related to the equipment life and work rate of the designated weed control process (Pimentel, 1980, Green Design, 2006) and was calculated by:

$$E_M = \frac{1.5\, S_m M}{L\, W_R}$$

(1)

where:

E_M = Energy embodied in the machinery (MJ ha^{-1});
S_m = Energy used at Steel manufacturing (MJ Kg^{-1});
M = Total weight of machinery used to manage the crop field (kg);
L = Estimated Lifetime for the machinery (hr); and
W_R = Work rate of the weed control process (ha hr^{-1}).

Embodied Energy in Herbicides:

The methodology to quantify the embodied energy in herbicides for chemical weed control used the energy value of the active ingredient of the herbicide formulation and the chemical application rate for the crop

(Zentner, et al. 2004, Rathkea, et al. 2007, Pimentel and Pimentel 2008, Schmer, et al. 2008, Zimdahl 2013). This method was represented mathematically by:

$$E_{CH} = X_h R_h \tag{2}$$

where:

E_{CH} = Energy embodied of herbicide (MJ ha^{-1});

X_h = Active ingredient energy value (MJ kg^{-1}); and

R_h = Application Rate for a particular crop (kg ha^{-1}).

Operating energy requirements

The operating energy requirements for the machine to carry out a weed control process were estimated in terms of fuel consumption. We assumed that the liquid fuel used is diesel for the machinery based process and the chemicals spread and the operation energy was estimated by:

$$E_{FC} = F E_F \tag{3}$$

where:

E_{FC} = Energy of fuel consumption (MJ ha^{-1});

E_F = Energy content of fuel (MJ l^{-1}); and

F = Average of fuel consumption (l ha^{-1}).

Energy requirement of Prototype Weed control system:

A prototype of a mechanical intra-row weed control system weed control system was developed by Ahmad (Ahmad, 2012). Based on this prototype the embodied energy was estimated using Eqn 1 and the operating energy was estimated by an experimental data. The experiments were conducted at the Agricultural Engineering ISU Advanced Machinery Systems Laboratory, Ames, Iowa. The prototype is composed of a rotating tine mechanism attached to a custom-fabricated implement chassis, Figure 1. To measure the power energy, we used only the rotating tine mechanism in a soil bin (Figure 2). The rotating tine mechanism was operated by a 24V brushless DC electrical motor (SmartMotor Model SM23165DT, Moog Animatics, Milpitas, CA) powered by a VDC source. In these experiments, the power consumption was measured. We assumed the prototype would be towed by a 37.3 kW 2WD tractor (model 2600, Ford). The energy consumption of a prototype was calculated using the measured power relative to the work rate. To address the overall energy losses, we included the battery efficiency with the charge and discharge cycles. We assume that the electrical energy for charge the batteries is supplied by a renewable primary source, such as photovoltaic or wind systems and does not have requirements for additional fuels. The total energy of the prototype was the sum of the embodied energy plus the operating energy measured and is represented mathematically by the equation:

$$E_P = E_{MP} + 3.6 \frac{P}{W_R \eta_B} \tag{4}$$

where:

E_P = Total Energy of prototype weed control system (MJ ha^{-1});

E_{MP} = Energy embodied in the prototype weed control system (MJ ha^{-1});

η_B = Overall efficiency of the batteries (dimensionless); and

P = Power consumption of prototype weed control system (kW).

Figure 1: Prototype mechanical weed control system developed at Iowa State University (Ahmad 2012).

Figure 2: Prototype mechanical weed control in a soil bin

Total Energy Requirements

The total energy requirements of three different weed control systems: (i) conventional mechanical cultivation; (ii) chemical weed control system (considering glyphosate the active ingredient used) and (iii) the prototype mechanical weed control system. Even though the mechanical weed control system was designed for vegetable production, for the purposes of this study, it was applied to a US corn production system for a fair comparison with the other methods and availability of data. To estimate the embodied energy of the mechanical cultivation case, weed control was assumed to represent 20% of total machinery per hectare used

in a corn yield. Pimentel (2005) used the average value of 55 kg per hectare of machinery in the entire process of U.S. Corn Production.

The total energy requirements by these weed control systems were estimated using the embodied energy in the machinery and chemicals plus the operating energy requirements of each case:

$$E_T = [E_M + E_{CH}] + E_{FC} \qquad (5)$$

where:

E_T = Energy total associated with each weed control case (MJ ha^{-1}).

Results

Conventional Mechanical Cultivation

The calculation was performed for embodied energy and power requirements, and the total energy associated at this process is 1225.44 MJ ha^{-1} (Table 1). Table 1 shows the results of total energy required per hectare for conventional mechanical cultivation to control weeds in U.S. Corn Production.

Table 1: Total energy required per hectare for conventional mechanical cultivation to control weeds in U.S. Corn Production

Embodied Energy (MJ ha^{-1})	Diesel Consumption (l ha^{-1}) [a]	WR (ha hr^{-1}) [a]	Energy content-Diesel [b] (MJ l^{-1})	Operating Energy (MJ ha^{-1})	Total Energy (MJ ha^{-1})
412.50	18.48	1.2	43.99	812.94	1225.44

[a]: Source Appendix A9 and A10 (Nemecek and Kagi 2007)

[b]: : Source (Zentner, et al. 2004)

Chemical Weed Control

The total energy for chemical weed system to corn yield was 1318.78 MJ ha^{-1} (Table 2). Table 2 shows the results of total energy required per hectare for chemical weed control in U.S. Corn Production.

Table 2: Total Energy required per hectare for Chemical weed control in U.S. Corn Production

X_h (MJ kg^{-1}) [a]	R_h (kg ha^{-1}) [b]	Embodied Energy (MJ ha^{-1})	Diesel Consumption (l ha^{-1}) [c]	WR (ha hr^{-1}) [c]	Energy content-Diesel (MJ l^{-1})	Operating Energy (MJ ha^{-1})	Total Energy (MJ ha^{-1})
511.00	2.40	1226.40	2.10	0.7	43.99	92.38	1318.78

[a]: Source (Zentner, et al. 2004)

[b]: Source (BIOGRACE 2012)

[c]: Source Appendix A9 and A10 (Nemecek and Kagi 2007)

Prototype Weed control system:

The prototype energy calculations include the energy requirements tractor used to propel the weed control system. We assumed that the overall efficiency (charge/discharge) for the batteries was 80%. For the energy of the prototype, we consider the experiment results with 0.15 kmh^{-1} with the weed canopy area decreases about 60% (Ahmad, 2012). Table 3 shows the results of Total Energy required per hectare for Prototype weed control in U.S. Corn Production, considering different soils (wet/dry) and depth (1' and 2').

Table 3: Total Energy required per hectare for Prototype Weed control system in U.S. Corn Production

Soil/ Depth	P mean (kW)	WR (ha hr^{-1})	Energy Prot. (MJ ha^{-1})	Embodied Energy (MJ ha^{-1})	Diesel Con. (l ha^{-1}) [a]	Operating Energy Tractor (MJ ha^{-1})	Total Energy (MJ ha^{-1})
No load	0.01	0.01	5.02	8	4.14	182.03	195.05
Dry Soil – 1'	0.02	0.01	6.28	8	4.14	182.03	196.32
Dry Soil – 2'	0.02	0.01	7.83	8	4.14	182.03	197.86
Wet Soil – 1'	0.01	0.01	6.09	8	4.14	182.03	196.13
Wet Soil – 2'	0.02	0.01	7.66	8	4.14	182.03	197.70

[a]: Source (Leviticus 1976)

Discussion

The energy requirements of the prototype weed control system were 85% less than the chemical weed control case and about 84% than that associated with the mechanical cultivation. The results showed the potential of the prototype to weed control, in terms of less energy requirements.

Conclusion

The comparison among of the energy requirements of weed control systems shows the potential of the small vehicles use to weed control. The total energy of prototype mechanical weed control system represents less than 20% of that associated with conventional cultivation and chemical weed control. If this prototype was self-propelled and autonomous, the amount of energy could be decreased further. Precision agriculture technologies can enable the reduction of energy requirements for different agricultural processes and use of electrically-powered machines.

Acknowledgments

References

Ahmad, M T. 2012. "Development of an automated mechanical intra-row weeder for vegetable crops." *Master degree Thesis.* Ames, Iowa: Iowa State University.

BIOGRACE. 2012. "Harmonised Calculations of Biofuel Greenhouse Gas Emissions in Europe." Publishable final report. www.biograce.net.

Bongiovanni, R., and J. Lowenberg-DeBoer. 2004. "Precision agriculture and sustainability." *Precision agriculture* vol. 5 (no. 4): 359-387.

Cordill, C., and T.E. Grift. 2011`. "Design and testing of an intra-row mechanical weeding machine for corn." *Biosystems Engineering* vol. 110 (no. 3): 247-252.

FAO. 2013. "Food and Agriculture Organization of the United Nations - 2013 Statistical Yearbook - World food and agriculture."

Green Design, Institute. 2006. *Economic Input-Output Life Cycle Assessment (EIO-LCA) Model.* Pittsburgh, PA: Carnegie Mellon University. www.eiolca.net.

Leviticus, L. 1976. *Test 1222: Ford 2600 and 2310 (8x2) Diesel 8-Speed.* University of Nebraska-Lincoln.

Nemecek, T., and T. Kagi. 2007. *Life Cycle Inventories of Agricultural Production Systems. Final Report ecoinvent V2.0 No. 15a.* Zurich and Dubendorf, CH: Agroscope Reckenholz- Taenikon Research Station ART, Swiss Centre for life Cycle Inventories. www.ecoinvent.com.

Nielsen, K. M., P. Andersen, T.S. Pedersen, T. Bak, and J.D., Nielsen. 2002. ""Control of an autonomous vehicle for registration of weed and crop in precision agriculture,"." *Proceedings of the 2002 International Conference on Control Applications,.* 909-914.

Nørremark, M., H.W. Griepentrog, J. Nielsen, and H.T. Søgaard. 2008. "The development and assessment of the accuracy of an autonomous GPS-based system for intra-row mechanical weed control in row crops." *Biosystems Engineering* vol. 101 (no. 4): 396-410.

Ortiz-Canavate, J., and J. L. Hernanz. 2013. *CIGR Handbook of Agricultural Engineering Volume V Energy and Biomass Engineering.* 6 vols. American Society of Agricultural and Biological Engineers.

Pimentel, D. 1980. "Handbook of Energy Utilization in Agriculture." Boca Raton, FL: CRC Press.

Pimentel, D., and Marcia H. Pimentel. 2008. *Food, Energy and Society.* Third Edition. Boca Raton, Florida: CRC Press.

Pimentel, D., and Tad W Patzek. 2005. "Ethanol Production Using Corn, Switchgrass, and Wood, Biodiesel Production Using Soybean and Sunflower." March: pp. 65-76.

Rathkea, G.W., B.J. Wienholdb, W.W. Wilhelmb, and W. Diepenbrockc. 2007. "Tillage and rotation effect on corn–soybean energy balances in eastern Nebraska." *Soil and Tillage Research* 97 (1): Pages 60-70.

Schmer, M. R., K. P. Vogel, R. B. Mitchell, and R. K. Perrin. 2008. "Net energy of cellulosic ethanol from switchgrass." *Proceedings of the National Academy of Sciences* 105 (2): Pages 464-469.

Shah, A. 2013. "Techno-economic analysis and life cycle assessment of the corn stover biomass feedstock supply chain system for a Midwest-based first generation cellulosic biorefinery." *Ph.D. diss.* Ames: Iowa State University.

Slaughter, DC, DK Giles, and D Downey. 2008. "Autonomous robotic weed control systems: A review." *Computers and Electronics in Agriculture* vol. 61 (no. 1): 63-78.

Zentner, R.P, G.P Lafond, D.A Derksen, C.N Nagy, D.D Wall, and W.E May. 2004. "Effects of tillage method and crop rotation on non-renewable energy use efficiency for a thin Black Chernozem in the Canadian Prairies." *Soil and Tillage Research* 77 (2): 125-136. doi:http://dx.doi.org/10.1016/j.still.2003.11.002.

Zimdahl, R. L. 2013. *Fundamentals of weed science.* Fort Collins, Colorado.: Academic Press.