Comparison of energy inputs for inorganic fertilizer and manure based corn production

N.B. McLAUGHLIN[1], A. HIBA[2], G.J. WALL[3] and D.J. KING[4]

[1]Eastern Cereal and Oilseed Research Centre, Research Branch, Agriculture and Agri-Food Canada, K.W. Neatby Building, 960 Carling Avenue,Ottawa, ON, Canada K1A 0C6; [2]Greenhouse and Processing Crops Research Centre, Research Branch, Agriculture and Agri-Food Canada, Research Centre, Highway 18 East, Harrow, ON, Canada N0R 1G0; [3]Soil Resources Group, Unit 1, 503 Imperial Road, Guelph, ON, Canada N1H 6T9; and [4]Upper Thames River Conservation Authority, 1424 Clarke Road, London, ON, Canada N5V 5B9. *Eastern Cereal and Oilseed Research Centre Contribution No. 001503. Received 13 June 1999; accepted 24 November 1999.*

McLaughlin, N.B., Hiba, A., Wall, G.J. and King, D.J. 2000. **Comparison of energy inputs for inorganic fertilizer and manure based corn production**. Can. Agric. Eng. **42**:009-017. Energy inputs were calculated for grain corn production with data from field experiments utilizing inorganic fertilizer and liquid swine manure as sources of plant nutrients. The calculations utilized energy coefficients taken from the literature and actual application rates of the various input products including seed corn, starter fertilizer and regular inorganic fertilizer, herbicides, fuel for field operations, and grain drying. The results showed that grain corn could be produced successfully by substituting manure for inorganic fertilizer. The energy savings in the manured treatments resulted largely from eliminating the energy in fertilizer manufacture and ranged from 31 to 34% of the energy input for inorganic fertilizer based grain corn production. Published agricultural statistics were used to extrapolate the results to the entire Mixedwood Plains Ecozone which covers the lower Great Lakes and St. Lawrence River Valley regions of Ontario and Quebec. An estimated upper bound of 4.6 PJ (1 petajoule = 10^{15} joules) of energy could be saved annually by substituting livestock manure for inorganic fertilizer in the production of the entire acreage of grain corn grown in the ecozone. This estimate is based on the assumptions of availability of sufficient manure, and no credits being given for manure presently being used. Spatial analysis identified South Western Ontario and the Richileau - St. Hyacinthe region of Quebec as the areas where the potential energy savings would be greatest.

La consommation énergétique requise pour la production du maïs grain a été calculée avec des données provenant de champs expérimentaux où des fertilisants inorganiques et du lisier de porc étaient utilisés. Pour les calculs, on a utilisé des coefficients énergétiques tirés de la littérature, et les taux d'application réels d'intrants pour le semis, le démarreur et les fertilisants organiques réguliers, les herbicides, le carburant pour les opérations dans les champs et pour le séchage du grain. Les résultats ont montré qu'il était possible de produire avec succès du maïs grain en substituant le lisier de porc aux fertilisants organiques. Les économies d'énergie résultant de l'utilisation du lisier pouvaient être, dans une large mesure, attribuées à l'élimination de l'énergie utilisée pour produire les fertilisants inorganiques, et représentaient de 31 à 34% de la consommation d'énergie nécessaire à la production de maïs grain avec des fertilisants inorganiques. En utilisant les statistiques agricoles publiées, il fut possible d'extrapoler les résultats à toute la zone écologique de la forêt mixte qui couvre la partie inférieure des Grands-Lacs et la vallée du St-Laurent en Ontario et au Québec. On a estimé qu'une quantité maximale de 4.6 PJ (1 petajoule = 10^{15} joules) pourrait être économisée annuellement si on substituait du lisier de porc aux engrais inorganiques sur toute la superficie en maïs de la zone écologique. Cette évaluation repose sur l'hypothèse qu'il y a du lisier en quantité suffisante, et qu'on ne tient pas compte du lisier actuellement utilisé. Avec cette analyse spatiale, on a identifié que le potentiel d'économie d'énergie serait le plus grand dans le sud-ouest de l'Ontario et la région Richelieu-St-Hyacinthe au Québec.

INTRODUCTION

Primary production in the agricultural industry is highly dependant upon fossil fuels and accounts for 3.1% of Canada's total commercial energy consumption (Sidaway-Wolf 1984). The inevitable decrease in the availability of fossil fuels, coupled with the continuing increase in demand for food to feed an ever increasing world population, has driven the development of sustainable agricultural practices. Although no system that is dependent on finite non-renewable resources can be truly sustainable, conservation measures can increase the time over which quasi-sustainablity is possible.

Energy conservation in primary agricultural production must make the most efficient use of non-renewable energy resources while integrating on-farm resources such as biological cycles and controls (Gold 1994). At the same time, the conservation measures must strike a balance with the industry-wide goal of maximizing food production and economic returns froma given land base. Historically, this goal has been achieved through development of new plant cultivars and substantial increases in the use of mechanical energy, inorganic fertilizers, and pesticides. A comparison of the 1975 and 1991 energy input data show a recent trend of a decrease in energy input per unit product, confirming the economic viability of employing energy saving practices (Swanton et al. 1996; Pimental 1990).

Energy consumed in primary agricultural production is classified as either direct or indirect use. Direct energy use is the consumption of fossil fuels for various farm operations such as fuel for tractors or fuel for crop drying. Indirect energy use is the conversion of fossil fuels into other products such as fertilizers or pesticides. Numerous studies have been done to quantify energy consumption in agricultural production (Heslop and Bilanski 1989; Ouellette-Babin 1982; Swanton et al. 1996; Vinten-Johansen et al. 1990; Zentner et al. 1984, 1989; Zucchetto and Bickle 1984). Stout (1984) categorized the North American agricultural industry and quantified the fraction of the total energy consumed by each category as: 1) manufacture of inorganic fertilizer (31%); 2) operation of field machinery (19%); 3) transportation (16%); 4) irrigation (13%); 5) raising livestock (8%); 6) crop drying (5%); 7) pesticide production (5%); and 8) miscellaneous (3%).

Several methods of energy analysis have been reported in the literature and include statistical analysis, input-output analysis, and process analysis (Fluck and Baird 1980). Statistical analysis using global statistics such as fertilizer sales is used to arrive at an estimate of total energy use but does not achieve the accuracy which can be obtained with other methods. Input-output analysis utilizes a square matrix of energy inputs and is most valid for nationwide analysis. Zucchetto and Bickle (1984) claim that input-output analysis can also be appropriately used when analyzing an agricultural system having several rather than a single output. Process analysis is considered to be the most suitable and accurate method of data analysis for a specific single output production system and was used in this study. The processes used to produce a crop are identified and analyzed to quantify their respective energy inputs (Fluck and Baird 1980). The results can then be expressed as energy productivity in terms of joules of energy required per kilogram of crop yield (Lockeretz et al. 1984; McKyes et al. 1986; Vinten-Johansen et al. 1990).

The agricultural industry is highly dependent upon fertilizers to supply the nutrients required by crops to achieve optimum yields. Production of nitrogen (N) fertilizers represents a large component of the energy for production of all inorganic agricultural fertilizers. Depending on the type of nitrogen fertilizer produced and the efficiency of the process, production of a kilogram of N requires from 51 to 68 MJ (1 megajoule = 10^6 joules) of energy (Bhat et al. 1994). For comparison, a litre of diesel fuel has an energy content of about 37.4 MJ (Goering 1989).

Traditionally, mixed farming agriculture utilized manure from farm animals to provide nutrients for crop production. It has been estimated that about 0.7 million tonnes of N are excreted annually by farm livestock in Canada (Patni 1991). Using the previous figures, approximately 35 to 48 PJ of fossil fuel energy would be required to produce this quantity of inorganic N fertilizer.

According to the 1995 Farm Inputs Management Survey (Economic and Policy Analysis Directorate 1997), approximately 40% of the Canadian farms surveyed applied inorganic fertilizers to land having already undergone manure application and in many cases no credit whatsoever was given for the manure nutrients applied. In these cases, the economic and energy savings through use of the manure is not realized, and the over application of nutrients could potentially contaminate the environment. Detailed studies have been performed to quantify the savings that could be achieved through the utilization of organic fertilizers and have demonstrated that the greatest impact on reducing indirect energy requirements is made when maximizing the use of manure nutrients (Karlen et al. 1995; Lockeretz et al. 1984; McKyes et al. 1986; Pimentel et al. 1983, 1984; Pimentel 1993).

This paper compares the energy inputs for corn production in South Western Ontario utilizing inorganic fertilizer and manure as plant nutrient sources.

MATERIALS and METHODS

Energy analyses were conducted on data from field experiments originally established to study the effect of liquid manure application method on water quality of subsurface drainage effluent (Wall et al. 1998). Three locations with different soil textures were studied, course (Brisbane series sandy loam, Gleyed Gray Brown Luvisol) near Putnam, ON (43E02' N, 80E59' W), medium (Embro series silt loam, Gleyed Gray Brown Luvisol) near Kintore, ON (43E10' N, 81E03' W), and fine (Perth series silty clay loam, Gleyed Brunisolic Gray Brown Luvisol) near Strathroy, ON (42E02' N, 81E44' W). The coarse and medium textured sites had two years of experimental data while the fine textured site had only one year. Each site consisted of 12 plots (6 m x 60 m) arranged in a randomized block design with four treatments and three blocks or replicates. The four treatments were control with inorganic fertilizer, and liquid swine manure with three different application methods.

A no-till corn crop was planted at each site using cooperator owned no-till planters fitted with coulters and trash whippers for residue management. Inorganic starter fertilizer was applied to all plots (both the manured and inorganic fertilized treatments) with the planting units at rates ranging from 3-35 kg N/ha, 12-35 kg P_2O_5/ha, and 0-35 kg K_2O/ha according to the personal preference of the different producer cooperators with the highest rates applied at the fine textured site (Table I). Inorganic fertilizer was applied to the control (no manure) plots at planting time. The rate for each site was according to producer preference and was not always according to soil test recommendations. Rates ranged from 57-161 kg N/ha, 0-32 kg P_2O_5/ha, and 0-55 kg K_2O/ha with the medium textured site receiving the highest N rates (Table I). Herbicide treatments were at recommended rates and typically included preplant burndown with glyphosate and post emergent 2,4-D or atrazine.

Liquid swine manure was applied to the manured plots as side dress at the four to six leaf stage and at rates to provide approximately 90% of the total N requirements. The three application methods were surface applied (SA), conventional inject (CI), and modified inject (MI). The surface applied method used inter-row drop tubes to place the manure on the soil surface with minimal plant contact. The conventional inject system used narrow (50 mm wide) injectors to minimize soil disturbance and subsequent damage to the growing plants. The modified inject system consisted of a leading coulter and narrow (50 mm) cultivator tooth in front of a 50 mm wide injector to provide a small amount of pre-tillage. Equipment for the three manure application treatments is described in detail by Hilborn et al. (1994) and McLaughlin et al. (1997).

The plots were combine harvested individually in the fall and yield determined by weighing with a weigh wagon (Table II). Additional agronomic, management, and yield data for the plots are given by Wall et al. (1998).

Energy analysis procedures

Energy inputs for inorganic fertilizer and manure based corn production at the three sites were analyzed using the process method (Fluck and Baird 1980) and considered both the direct (planting, pesticide application, manure and fertilizer application, harvest, transport, and grain drying) and indirect (energy for production of seed corn, inorganic fertilizer and pesticides) energy inputs. Data concerning the type of field operations performed, the type and application rates of various products (seed, herbicide and fertilizer), and subsequent crop yields were obtained from Wall et al. (1998). Energy coefficients for each process in the cropping system were taken from the literature (Table III). Energy input for each process was then calculated, and the total expressed both as energy consumption on a per area basis (GJ/ha) and specific energy consumption on a per unit of crop produced (MJ/kg).

Direct energy inputs

To compare all manure and fertilizer treatments, and all soil textures on an equal basis, the same sizes of field machinery were assumed for all sites. Energy coefficients for planting with a six row planter, herbicide application, harvesting with a six row combine, and hauling no more than 32 km to a drying facility (Table III) were used to calculate energy inputs on a per hectare basis. It was assumed that the corn was dried from 28 to 15.5% moisture content using a commercial dryer with an energy requirement of 4.73 MJ/kg of moisture removed (Southwell and Rothwell 1977). Fuel consumption for manure application was measured at each field site with Agriculture and Agri-Food Canada’s instrumented research tractor (McLaughlin et al. 1993; Wall et al. 1998).

Indirect energy inputs

For each site, the same planting rate, starter fertilizer, and herbicide application program were used for both the inorganic fertilizer and manure treatments. The indirect energy inputs for these processes were calculated using the actual application rates given in Table I and the energy coefficients from Table III. The energy value for the blended fertilizers was assumed to be the energy for blending (Bhat et al. 1994) plus that of individual components of urea, triple superphosphate, and muriate of potash.

Energy exclusions

Energy to extract, refine, process, and transport fossil fuels was not included in the analysis for either direct or indirect energy inputs. Energy for the manufacture of the machinery used in crop production was also excluded. Machinery is a long term agricultural consumable and must be amortized over more than one growing season (Lockeretz et al. 1984). Ouellette-Babin (1982) performed a production energy analysis on grain corn production wherein machinery depreciation energy was included as an input and constituted only 3% of the total. Hence, omission of the machinery factor was not expected to impact greatly upon the total energy calculations.

Human labour is not considered a non-renewable resource depleting function and was also not included. Food is consumed for purposes other than work, making it difficult to accurately quantify the human energy expended for labour (Stout 1990). Manure was also not considered an energy input since it is an ever present by-product of livestock production. Livestock are raised for purposes other than manure production, and therefore the energy for manure production would be expended regardless of the method of manure use or disposal (McKyes et al. 1986; Pimentel 1993). Energy for the transport of manure from storage to the field was not included. It was assumed that this energy would be expended for alternate manure disposal methods which respect environmental laws and is therefore an energy cost associated with livestock production. There was also no allowance made for energy removed from the soil in the form of plant nutrients or for the energy captured from the sun by plants.

Energy analysis

Energy inputs were calculated both on a per unit area (GJ/ha) and per unit corn produced (MJ/kg) basis for each plot at each site. The data for each soil texture were considered as a factorial experiment with factors of year, replicate, and treatment, and were subjected to Analysis of Variance (ANOVA) using the general linear model (GLM) procedure in SAS (SAS 1996), with a separate ANOVA for each soil texture. For the fine textured site which had only one year of data, the year factor was omitted. Duncan’s Multiple Range test was applied to determine differences among the means for the manure and fertilizer treatments within soil texture.

Extrapolation of data to the Mixedwood Plains Ecozone

The results of the energy analysis from the field experiments were extrapolated to the Mixedwood Plains Ecozone to estimate the potential energy savings that could be achieved if manure was substituted for inorganic fertilizer for all grain corn grown in the ecozone. The Ecological Stratification Working Group (1995) defines ecozones as “Areas of the earth’s surface representative of large and very generalized ecological units characterized by interactive and adjusting abiotic and biotic factors”. The Mixedwood Plains Ecozone covers the lower Great Lakes and St. Lawrence River Valley regions in Ontario and Quebec. Grain corn yields reported in Ontario and Quebec survey data for individual counties within the Mixedwood Plains Ecozone (Anonymous 1992; Bureau de la statistique du Québec 1992) were overlaid with Soil Landscapes of Canada (SLC) Ecozone polygons using the 1991 Canada Census of Agriculture data reconfigured for Soil Landscape Unit (SLU) polygons (Huffman and Unrau 1995). Grain corn yields for each SLU polygon were then estimated by weighting the area for the polygon within each county with the respective county average yield. The SLU polygons were grouped into three broad soil texture categories, fine, medium, and coarse. It was assumed that the three experimental sites previously discussed were representative of these three soil texture categories across the entire ecozone. Total energy requirements for grain corn production for each soil type in the entire Mixedwood Plain Ecozone were then calculated for both fertilization with surface applied liquid manure and with inorganic fertilizer. The difference represents the potential energy savings achievable by substituting manure for inorganic fertilizer in grain corn production.

RESULTS and DISCUSSION

Field data analysis

Analysis of Variance of the yield data showed that no significant difference ($P > 0.05$) existed among the inorganic fertilizer and manure treatments for all three soil textures. The inorganic fertilizer treatments always had significantly ($P < 0.05$) higher energy inputs than the manure treatments, both on a per hectare and per kilogram of crop produced, but the three manure treatments were not significantly different from each other (Tables IV and V).

Energy inputs expressed in absolute terms (GJ/ha) for seed corn, starter fertilizer, and herbicide were the same for both the manure and inorganic fertilizer treatments within the same year and soil texture site (data not shown). This is because the same seed and seeding rate, starter fertilizer, and weed control program was used for all twelve plots (both inorganic fertilizer and manure treatments) within a site. The drying energy was slightly different for the manure and inorganic fertilizer treatments which resulted from slightly different (not significant) yields. However, when expressed as a percentage of total, there was a substantial difference in energy input between the inorganic fertilizer and manure treatments owing to the much lower total energy input for the manure treatments (Table VI).

The largest single energy input for the inorganically fertilized plots on all three sites was for the manufacture of the inorganic fertilizer and ranged from 33 to 54% of the total energy input (Table VI). Grain drying was the second largest energy input and ranged from 21 to 27% of the total for the inorganic plots and 30 to 46% for the manured plots. The manured plots had slightly higher fuel consumption energy than the inorganic fertilizer plots (data not shown). This difference is the difference in fuel consumption to apply the liquid manure with a four row spreader and to apply inorganic fertilizer which is normally broadcast. The difference was dwarfed by the potential energy savings which can be realized by utilizing manure as a plant nutrient source.

Fuel consumption for field operations and transport of grain to a drying facility ranged from 4 to 10% of the energy input. This was surprisingly low, but would be somewhat higher for a conventional tillage crop production system which requires a minimum of two tillage operations. Many producers think that fuel consumption is the major energy input, probably because it is the only energy input that they actually see. The energy component for the other inputs is not readily obvious as it is consumed in the production before the products arrive at the farm gate.

Variability in energy input was expected among the different sites with different soil textures and different management styles. The experiments were conducted on producer owned land, and the individual producers' preferences were followed for starter fertilizer blend and rate, corn hybrid, planting population, and weed control program. Differences in management history and natural soil fertility at the three sites were reflected in differences in soil test results. The different producers used different philosophies for applying fertilizer and consequently, there were substantial differences in applied nutrient rates for the inorganic fertilizer treatments among the three sites with the different soil textures. This was particularly true for N fertilizer where the rate used on the medium textured site was about double that for the other two sites (Table I). The higher input energy for the inorganically fertilized treatment in the medium textured site is mainly due to the higher rate of N fertilizer applied at this site compared to the fine and coarse textured sites (Tables I and IV). Differences in herbicide programs also contribute to differences in input energy. It is likely that the energy inputs for the three sites are more affected by differences in management strategies among the three producer cooperators than by soil texture. The field experiments were originally designed for another purpose, and the soil texture is confounded with the producer management style in this analysis.

Comparison of the energy inputs from the present experiment with studies done in the past show a shift in the area of greatest energy consumption. From the 1950's to the 1970's, the energy associated with inorganic fertilizer use and grain drying increased while fuel consumption was brought down by increasingly efficient farm machinery (Smil et al. 1983). From the 1970's to the 1990's, the energy associated with the use of inorganic fertilizers has leveled off. This is partly a consequence of agricultural research having determined the optimum nitrogen levels for crop production as well as increased efficiency in the production of inorganic nitrogen fertilizers. Energy consumed for the purpose of drying grain has continued to increase with time which is partly due to increasing yields. The energy for production of hybrid seed corn given by Pimentel (1980) as 104 MJ/kg is approximately 30 to 50 times the 2 to 3 MJ/kg (Table V) calculated for inorganic fertilizer based commercial corn production in the present experiment. This energy component cannot be ignored.

Table V shows the specific energy input (MJ/kg of corn produced) for the three soil textures and fertilizer and manure application methods. The specific energy input for the inorganic fertilizer site was significantly different ($P < 0.05$) from the manured treatments, but the differences in specific energy among the three manure application methods (MI, CI, and SA) were not significantly different from each other ($P > 0.05$). Specific energy for fertilization with swine manure ranged from 1.30 to 2.01 MJ/kg compared with 2.16 to 2.92 MJ/kg for the inorganic fertilizer. Specific energy input for the manured treatments on the fine textured site was higher than the manured treatments on either the medium or coarse textured sites. This was mainly due to the lower yield on the fine textured site (Table II). Even though the medium textured site had higher yield than the fine textured site, the much higher N fertilizer rate on the medium textured site resulted in higher specific energy input for the inorganic treatment on the medium than either the fine or coarse textured sites (Table V).

There was no significant difference ($P > 0.05$) in yield among the inorganic and manure treatments. Previous studies also demonstrated that when appropriately managed, use of swine manure in lieu of inorganic fertilizers can result in equal yields (McKyes et al. 1986). Since the yields were equal, the lower energy input achieved in the manure treatments was due to elimination of the energy factor associated with manufacture of the inorganic fertilizer. The energy savings achieved by fertilizing with liquid manure instead of inorganic fertilizer ranged from 36 to 52% (calculated from Table IV data) over the three test sites. This is in good agreement with McKyes et al. (1986) who reported energy savings ranging from 38 to 47% when manure was substituted for inorganic fertilizer.

Current recommendations are to incorporate manure, either by cultivation or subsurface injection to reduce both odor and ammonia losses which represent a loss in nitrogen available for crop production. The potential energy savings available through direct injection of liquid manure into the soil rather than surface application of liquid manure were highly variable in the present experiment and no trend could be established. Other studies have determined that the potential energy savings resulting from direct injection of liquid manure are less than 10% of the overall potential energy savings and it is therefore more important to choose to utilize manure than to decide between surface application or direct injection (Vinten-Johansen et al. 1990).

It should be emphasized that the savings reported for the manure based corn production are energy inputs and not necessarily economic. Many producers cite extra cost of manure based over fertilizer based corn production as a reason for not exploiting the manure resource. Most fertilizer application is done by the supplier/custom applicator and is only a phone call away. Manure based corn production requires extra labor and equipment and requires an additional level of management to ensure proper application uniformity, rate, and timing.

Extrapolation to the Mixedwood Plains Ecozone

The annual potential energy savings that could be realized if manure was substituted for inorganic fertilizer for all acreage (as per 1991 statistics) of grain corn production in the Mixedwood Plains Ecozone was estimated at 4.6 PJ. This is equivalent to the energy for manufacture of approximately 70,000 tonnes of inorganic N fertilizer.

The extrapolation is based on a number of assumptions. First, it is assumed that sufficient manure is available within a reasonable transportation distance for the production of the crops. It is likely that in some areas of intensive cash cropping such as in South Western Ontario, that there presently is an insufficient livestock base to provide all of the manure needed for crop production. Second, it is assumed that all of the land base currently receiving manure also receives the full complement of inorganic fertilizer with no credit given for the nutrient content of manure. Although it is known that this occurs in about 40% of the cases (Economic and Policy Analysis Directorate 1995), many producers do give credits for manure nutrients and reduce inorganic fertilizer rates accordingly. Since neither of these two assumptions are 100% valid, the estimate of 4.6 PJ represents an upper bound on the potential annual energy savings in the entire ecozone.

The spatial distribution of potential energy savings across the ecozone is given in Fig. 1. The map shows the areas with greatest potential for energy savings to be in South Western Ontario and in the Richelieu and Saint Hyacinthe regions of Quebec. This spatial distribution closely resembles the spatial distribution of grain corn production within the ecozone.

The accuracy of the extrapolation is unknown and depends largely upon the underlying assumptions and the errors introduced through their use. We are presently working with statistics on the spatial distribution of livestock and fertilizer consumption in an attempt to refine the estimate. In spite of the unknown accuracy, the map in Fig. 1 clearly shows areas with the greatest potential for energy savings. Such maps are valuable to policy makers in targeting areas for implementing energy conservation programs.

CONCLUSIONS

Grain corn was grown in field experiments at three sites with different soil textures near London, Ontario. Nutrients were supplied as inorganic fertilizer and as liquid swine manure. For each site, there were no significant differences ($P > 0.05$) in yields between the inorganic fertilizer and swine manure treatments demonstrating that manure can provide the nutrients for grain corn production.

An analysis of direct (fuel for field operations and grain drying) and indirect (energy for production of seed corn, fertilizer, and herbicides) energy inputs was conducted for all three sites. The analysis showed that the indirect energy requirement for the manufacture of inorganic fertilizer (starter fertilizer plus general broadcast fertilizer) represented the single largest energy input for no-till grain corn production and ranged from 40 to 50% of the total energy input. The analysis clearly shows the potential for substantial reduction in energy requirements for crop production by using livestock manure in place of inorganic fertilizer.

Energy data for the field experiments were extrapolated to the Mixedwood Plains Ecozone using published census and agricultural statistics data. An estimated upper bound of 4.6 PJ energy could be saved by substituting liquid swine manure for inorganic fertilizer in corn production. This energy is equivalent to that required for the manufacture of approximately 70,000 tonnes of inorganic N fertilizer. This estimate is based on assumptions of availability and proximity of adequate manure supplies and no credits given for nutrients in manure already being used for corn production. Spatial analysis identified south western Ontario and the Richelieu and Saint Hyacinthe regions of Quebec as the two areas where the greatest energy savings could be achieved from use of manure as a nutrient source.

REFERENCES

Anonymous. 1992. 1991 Agricultural Statistics for Ontario. Publication 20. Toronto, ON: Ontario Ministry of Agriculture Food and Rural Affairs.

Bhat, M.G., B.C. English, A.F. Turhollow and H. Nyangito. 1994. Energy in Synthetic Agricultural Inputs: Revisited. Oak Ridge National Laboratory Report ORNL/Sub/90-99732/2. Oak Ridge, TN: Oak Ridge National Laboratory.

Bureau de la statistique du Québec. 1992. 1991 Statistiques de l'Agriculture des Pêches et de l'Alimentation. Québec, QC: Information and Document Centre, Institut de la statistique du Québec.

Davis, S.C. 1997. *Transportation Energy Data Book*, 17th edition. ORNL - 6919. Oak Ridge, TN: Oak Ridge National Laboratory.

Ecological Stratification Working Group. 1995. A national ecological framework for Canada. Ottawa, ON: Agriculture and Agri-Food Canada, Research Branch, Centre for Land and Biological Resources Research and Environment Canada, State of the Environment Directorate, Ecozone Analysis Branch.

Economic and Policy Analysis Directorate. 1997. Manure, fertilizer and pesticide management in Canada - Results of the 1995 Farm Inputs Management Survey. In Review. Ottawa, ON: Policy Branch, Agriculture and Agri-Food Canada.

Fluck, R.C. and C.D. Baird. 1980. *Agricultural Energetics*. Westport, CT: AVI Publishing Co.

Goering, C.E. 1989. *Engine and Tractor Power*. St. Joseph. MI: ASAE.

Gold, M.V. 1994. Sustainable agriculture: definitions and terms. SRB 94-05. Beltsville, MD: U.S. Department of Agriculture.

Green, M.B. 1987. Energy in pesticide manufacture, distribution and use. In *Energy in Plant Nutrition and Pest Control*, ed. Z.R. Helsel, 165-177. Amsterdam, The Netherlands: Elsevier.

Helsel, Z.R. 1992. Energy and Alternatives for Fertilizer and Pesticide Use. In *Energy in Farm Production*, ed. R.C. Fluck. Amsterdam, The Netherlands: Elsevier.

Heslop, L.C. and W.K. Bilanski. 1989. Productive worth of different tillage machinery across soil types. ASAE Paper No. 89-1615. St. Joseph, MI: ASAE.

Hilborn, D., C. Brown, D.J. King, G.J. Wall, D. Hayman, G.C. Watson and B.A. Grant. 1994. Design of manure applic-ation equipment to reduce transport of pollutants to the field tile. ASAE Paper No. 94-351. St. Joseph, MI: ASAE.

Huffman, T. and E. Unrau. 1995. Socioeconomic farm data and the soil landscapes of Canada. In PARI Factbook: Bringing Conservation Technology to the Farm, eds. G.P. Lafond, H.M. Plas and E.G. Smith, 149-151. Lethbridge, AB: Agriculture and Agri-Food Canada.

Karlen, D.L., M.D. Duffy and T.S. Colvin. 1995. Nutrient, labour, energy and economic evaluations of two farming systems in Iowa. *Journal of Production Agriculture* 8(4):540-546.

Lobb, D. 1989. A study of the impact of no-till on tractor fuel cost vs crop returns as affected by various no-till planter modifications. Report No. 89-1504. Guelph, ON: Agricul-tural Energy Centre of the Ministry of Agriculture and Food.

Lockeretz, W., G. Shearer, D.H. Kohl and R.W. Klepper. 1984. Comparison of organic and conventional farming in the corn belt. In *Organic Farming: Current Technology and Its Role in a Sustainable Agriculture*, 37-48. Madison, WI: American Society of Agronomy.

McKyes, E., G. Owen and J. Kelly. 1986. Energy analysis model of various tillage and fertilizer treatments on corn silage production. *Canadian Agricultural Engineering* 28(2):101-105.

McLaughlin, N.B., B.A. Grant, D.J. King and G.J. Wall. 1997. Energy inputs for a combined tillage and liquid manure injection system. *Canadian Agricultural Engineering* 39(4):289-295.

McLaughlin, N.B., L.C. Heslop, D.J. Buckley, G.R. St.Amour, B.A. Compton, A.M. Jones and P. Van Bodegom. 1993. A general purpose tractor instrumentation and data logging system. *Transactions of the ASAE* 36:(2) 265-273.

Mudahar, M.S. and T.P Hignett, 1987. Energy requirements, technology, and resources in the fertilizer sector. In *Energy in Plant Nutrition and Pest Control*, ed. Z.R. Helsel, 25-61. Amsterdam, The Netherlands: Elsevier.

Ouellette-Babin, D. 1982. Energy input and output of grain corn and soybean production. Factsheet, Agdex 100/708. Toronto, ON: Ontario Ministry of Agriculture and Food.

Patni, N.K. 1991. Overview of land application of animal manure in Canada. In *Proceedings of National Workshop on Land Application of Animal Manure*, eds. D.A. Leger, N.K. Patni and S.K. Ho, 7-18. Ottawa, ON: Canadian Agricultural Research Council.

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

Pimentel, D. 1990. Environmental and social implications of waste in U.S. agriculture and food sectors. *Journal of Agricultural Ethics* 3:5-20.

Pimentel, D. 1993. Economics and energetics of organic and conventional farming. *Journal of Agricultural and Environmental Ethics* 6:53-60.

Pimentel, D., G. Berardi and S. Fast. 1983. Energy efficiency of farming systems: organic and conventional agriculture. *Agriculture, Ecosystems and Environment* 9:359-372.

Pimentel, D., G. Berardi and S. Fast. 1984. Energy efficiencies of farming wheat, corn, and potatoes organically. In *Organic Farming: Current Technology and Its Role in a Sustainable Agriculture*, 151-161. Madison, WI: American Society of Agronomy.

SAS. 1996. *Statistical Analysis System*. Version 6.02. Cary, NC: SAS Institute.

Sidaway-Wolf, D. 1984. An overview of energy use in food and agriculture. *Canadian Institute of Food Science Technology Journal* 17(1):4-13.

Smil, V., P. Nachman and T.V. Long II. 1983. *Energy Analysis and Agriculture - An Application to U.S. Corn Production*. Boulder, CO: Westview Press.

Southwell, P.H. and T.M. Rothwell. 1977. Report on analysis of output/input energy ratios of food production in Ontario. Guelph, ON: School of Engineering, University of Guelph.

Stout, B.A. 1984. Energy Use and Management in Agriculture. North Scituate, MA: Breton Publishers.

Stout, B.A. 1990. *Handbook of Energy for World Agriculture*. New York, NY: Elsevier Applied Science.

Swanton, C.J., S.D. Murphy, D.J. Hume and D.R. Clements. 1996. Recent improvements in the energy efficiency of agriculture: Case studies from Ontario, Canada. *Agricultural Systems* 52:399-418.

Vinten-Johansen, C., L.E. Lanyon and K.Q. Stephenson. 1990. Reducing energy inputs to a simulated dairy farm. *Agriculture, Ecosystems and Environment* 31:225-242.

Wall, G.J., B.A. Grant, D.J. King and N.B. McLaughlin. 1998. The effects of livestock manure application methods on water quality focusing on nitrogen and bacteria transport in soil. Canada-Ontario Agriculture Green Plan Final Research Report RES/MAN-005/97. London, ON: Agriculture and Agri-Food Canada.

Zentner, R.P., D.W. Campbell, C.A. Campbell and D.W. Read. 1984. Energy considerations of crop rotations in southwestern Saskatchewan. *Canadian Agricultural Engineering* 26(1):25-29.

Zentner, R.P., M.A. Stumborg and C.A. Campbell. 1989. Effect of crop rotations and fertilization on energy balance in typical production systems on the Canadian Prairies. *Agriculture, Ecosystems and Environment* 25:217-232.

Zucchetto, J. and G. Bickle. 1984. Energy and nutrient analyses of a dairy farm in Central Pennsylvania. *Energy in Agriculture* 3(1):29-47.

Table I. Agronomic inputs for corn plots with plant nutrients supplied by inorganic fertilizer and manure at 3 field sites with different soil textures.

Soil texture	Coarse		Medium		Fine
Input	1995	1996	1994	1995	1996
Seed corn (plant/ha)	73400	76100	74100	74100	74100
Starter fertilizer‡ (nutrient kg/ha)	3-15-0 †	3-15-0	3-13-3	3-12-0	35-35-35
Fertilizer § (nutrient kg/ha)	57-57-57	74-74-74	161-42-11	141-26-0	83-0-0
Manure (nutrient kg/ha)	72-72-42	104-42-70	72-32-53	144-58-122	169-112-101
Preplant Herbicide¶	Roundup + Amitrol	Roundup	Roundup	Roundup + Dual	
Pre-Emerge Herbicide		Banvel			Roundup + 2,4-D
Post Emerge Herbicide	Primextra		2,4-D		Atrazine oil

‡ Starter fertilizer applied to all plots.

§ Fertilizer applied only to inorganic fertilized plots, manure applied only to manured plots.

† Nitrogen, phosphorous and potassium nutrient rates for both inorganic fertilizer and manure are expressed as N, P_2O_5 and K_2O equivalents.

¶ Herbicide applied at recommended rates to all plots.

Table II. Mean corn yield (t/ha) for corn production based on inorganic fertilizer and manure for three soil textures.

Nutrient source	Soil texture		
	Coarse	Medium	Fine
Inorganic fertilizer	8.84 a§	7.90 a	6.78 a
Manure - surface applied	8.09 b	8.24 a	6.68 a
Manure - conventional inject	8.44 ab	8.34 a	6.82 a
Manure - modified inject	8.31 ab	8.20 a	6.38 a

§ Means in the same column and followed by the same letter do not differ significantly ($P = 0.05$) according to Duncan’s Multiple Range Test.

Table III. Energy coefficients for selected production inputs.

Category	Input	Energy coefficient	Unit of measurement	Data source
Fertilizers	Urea	68.41	MJ/kg of N	Bhat et al. (1994)
	Ammonia	50.6	MJ/kg of N	Bhat et al. (1994)
	Triple Superphosphate	6.82	MJ/kg of P_2O_5	Bhat et al. (1994)
	Muriate of Potash	2.88	MJ/kg of K_2O	Bhat et al. (1994)
	blending of compound fertilizers (fluid)	0.15	MJ/kg of NPK	Bhat et al. (1994)
	packaging and transport of N	7.05	MJ/kg of N	Mudahar and Hignett (1987)
	packaging and transport of P_2O_5	8.33	MJ/kg of P_2O_5	Mudahar and Hignett (1987)
	packaging and transport of K_2O	6.35	MJ/kg of K_2O	Mudahar and Hignett (1987)
Herbicides	2,4,D	85	MJ/kg of A.I.[1]	Green (1987)
	Amitrol[2]	190	MJ/kg of A.I.	Green (1987)
	Atrazine (Primextra)	190	MJ/kg of A.I.	Green (1987)
	Dicamba (Banvel)	295	MJ/kg of A.I.	Green (1987)
	Glyphosphate (Roundup)	454	MJ/kg of A.I.	Green (1987)
	Metolachlor (Dual)	276	MJ/kg of A.I.	Green (1987)
	packaging and transport of pesticide	3	MJ/kg of A.I.	Helsel (1992)
Fuel consumption	planting - 4-row	163.46	MJ/ha	Southwell and Rothwell (1977)
	planting - 6-row	197.88	MJ/ha	Southwell and Rothwell (1977)
	application of herbicide	30.97	MJ/ha	Lobb (1989)
	application of manure	measured site specific	MJ/ha	McLaughlin et al. (1997)
	application of fertilizer	51.62	MJ/ha	Lobb (1989)
	combining	471.46	MJ/ha	Lobb (1989)
	hauling grain corn to drying facility	165.5	MJ/ha	Davis (1997) Southwell and Rothwell (1977)
Other	seed corn	103.86	MJ/kg of corn	Pimentel (1980)
	corn drying	4.733	MJ/kg of moisture removed	Southwell and Rothwell (1977)

[1] active ingredient

[2] no energy coefficients have been calculated for Amitrol, assumed to be similar to Atrazine; the latter is a triazole, the former a triazine.

Table IV. Energy input (GJ/ha) for corn production based on inorganic fertilizer and manure on three soil textures.

Nutrient Source	Soil texture		
	Coarse	Medium	Fine
Inorganic fertilizer	19.1a†	22.3a	19.1a
Manure - surface applied	11.9b	10.6b	12.9b
Manure - conventional inject	11.9b	10.7b	13.0b
Manure - modified inject	11.9b	10.6b	12.8b

† Means in the same column and followed by the same letter do not differ significantly (P = 0.05) according to Duncan's Multiple Range Test.

Table V. Specific energy input (MJ/kg) for corn production based inorganic fertilizer and manure on three soil textures.

Nutrient Source	Soil texture		
	Coarse	Medium	Fine
Inorganic fertilizer	2.16a¶	2.92a	2.82a
Manure - surface applied	1.47b	1.30b	1.93b
Manure - conventional inject	1.41b	1.29b	1.91b
Manure - modified inject	1.42b	1.30b	2.01b

¶ Means in the same column and followed by the same letter do not differ significantly (P = 0.05) according to Duncan’s Multiple Range Test.

Table VI. Breakdown of energy consumption as a percent of total input energy per hectare for corn production based on inorganic fertilizer and manure for three soil textures.

Energy category	Coarse		Medium		Fine	
	Inorganic fertilizer	Manure	Inorganic fertilizer	Manure	Inorganic fertilizer	Manure
Seed corn	14.4	23.4	12.1	25.5	14.1	21
Starter fertilizer	5.5	4.1	2.1	4.3	18.6	27.5
Fertilizer	34.9	---	54	---	32.8	---
Grain drying	27.4	41.5	20.9	45.8	21	30.4
Herbicides	12.8	20.7	6.7	13.9	8.5	12.6
Fuel	5	10.3	4.2	10.5	5	8.5

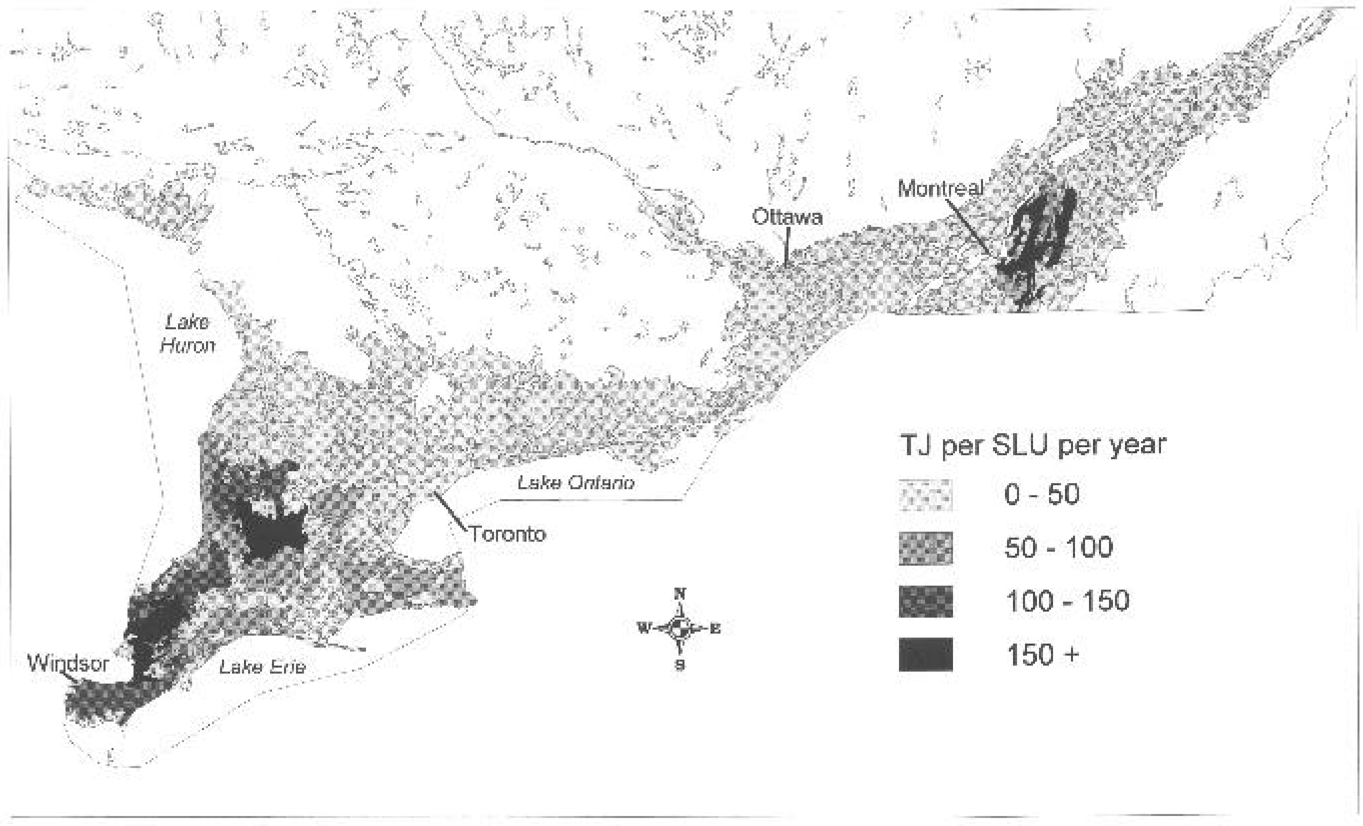

Fig. 1. Distribution of potential annual energy savings by Soil Landscape Unit (terrajoules per SLU per year) achievable by substituting liquid swine manure for inorganic fertilizer for grain corn production in the Mixedwood Plains Ecozone. Unshaded areas represent lakes or land outside of the ecozone and straight lines on the south and west represent the Canada-United States border.