Energy use and time requirements for different weeding strategies in grain corn

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Laguë, C. and Khelifi, M. 2001. **Energy use and time requirements for different weeding strategies in grain corn**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada. **43**: 2.13-2.21. The efficiency of ten weeding strategies in grain corn in terms of energy use and time requirements was investigated. These strategies involved different combinations of weed control operations: rotary hoeing (before the emergence of the crop), post-emergence mechanical cultivation (between the rows, on the rows), post-emergence thermal weeding (on the rows), herbicide spraying (full or banded coverage), and cover crop seeding (between the rows) that were used under two different primary tillage methods: conventional moldboard plowing at 150 mm and reduced tillage using a chisel plow. For each strategy, the energy budget based on the equipment, applied products (herbicides and propane), and fuel used as well as the energy input of the operator was computed. Results of this two-year study showed that the type of primary tillage prior to the weeding operations did not have any significant effect on the time required by the field operations nor on their fuel requirements ($p = 0.05$). However, the effects of the different weed-control operations were found to be highly significant ($p = 0.0001$). Broadcast herbicide was the least time-consuming weeding strategy (0.293 h/ha) while pre-emergence rotary hoeing followed by two passes of a cultivator/flamer later during the season required the most time at 1.923 h/ha. Total energy requirements were the lowest (370 MJ/ha) for the strategies that required one pass of the rotary hoe and one pass of the mechanical cultivator. Weeding strategies involving one or two passes of the cultivator/flamer required five to ten times more energy. **Keywords**: corn, cultivation, energy balance, flaming, herbicide, mechanical, weed control, time requirements.

Dix stratégies de désherbage différentes pour le maïs-grain ont été étudiées au niveau de leurs besoins énergétiques et du temps nécessaire à leur réalisation. Différentes combinaisons d'opérations de désherbage ont été utilisées afin d'obtenir les dix stratégies retenues aux fins de cette étude : passage d'une houe rotative en pré-émergence de la culture, sarclage mécanique en post-émergence (entre les rangs, sur les rangs), désherbage thermique en post-émergence (sur les rangs), pulvérisation d'herbicides (couverture totale ou en bandes) et semis d'une culture intercalaire entre les rangs. Deux types de travail primaire du sol ont été comparés: labour conventionnel à une profondeur de 15 cm et travail du sol réduit à l'aide d'un chisel. Pour chacune des stratégies étudiées, des bilans énergétiques prenant en compte les équipements, les intrants appliqués (herbicides, propane), le carburant nécessaire de même que les besoins énergétiques des opérateurs ont été établis. Les résultats de cette étude menée durant une période de deux années démontrent que le type de travail primaire du sol n'a pas eu d'effets significatifs ni sur le temps requis pour compléter les opérations au champ ni sur les besoins énergétiques des différentes opérations de désherbage ($p = 0.05$). Cependant, les opérations de désherbage ont eu des effets significatifs sur ces deux paramètres ($p = 0.0001$). Au niveau du temps requis, la stratégie faisant appel à un passage d'un pulvérisateur en couverture totale s'est révélée la plus efficace (0,293 h/ha) tandis que celle nécessitant un passage de houe rotative suivi de deux passages d'un pyrosarcloir (sarclage mécanique entre les rangs et désherbage thermique sur les rangs) plus tard durant la saison était la moins efficace (1.923 h/ha). Les stratégies pour lesquelles les besoins énergétiques globaux ont été les plus faibles (370 MJ/ha) étaient celles faisant appel à un passage de la houe rotative suivi d'un passage du sarcloir mécanique en post-émergence (entre les rangs ou entre et sur les rangs). À l'autre extrémité de l'échelle, les stratégies nécessitant un ou deux passages du pyrosarcleur ont requis entre cinq et dix fois plus d'énergie.

INTRODUCTION

Grain corn is the most important commercial crop in Québec. In 1994, 281,000 ha of grain corn were harvested in the province, representing a gross value of Can$272 M (Filion 1995). Weeds remain the major problem affecting the yields of this crop. Each year about 45% of the herbicides used in Québec are applied on corn fields (MEF 1995). Application of chemical herbicides may lead to the degradation and the contamination of surface and ground waters, the development of resistant weed biotypes, and increases in annual grass weed populations that are more difficult to control (MEF 1995). Consequently, it is becoming necessary to rationalize and to reduce the quantities of herbicides that are applied to this major field crop. This could be achieved by using alternative weed-control strategies such as mechanical cultivation, thermal weeding, use of cover crops, or some combinations of these.

LITERATURE REVIEW

The use of chemical herbicides to control weeds has high economic and environmental costs (Marer et al. 1988). Nevertheless, the development, commercialization, and use of new herbicides for corn and other crops have been continuously increasing since the 1950s (Shaw 1985). To reduce both the quantities of herbicides used as well as the costs associated with chemical weed control, the banded spraying technique was proposed. This technique is generally coupled with some form of mechanical cultivation between the rows. Eadie et al. (1992) estimated that a 300-mm banded spraying application could reduce the total quantity of herbicides applied by 60% compared to standard broadcast application. Bicki et al. (1991) also reported a 31.5% reduction of the costs of one 200-mm banded spraying application of atrazine and alachlor at a rate of 1.4 and 2.24 kg AI/ha (kg of active ingredients per hectare), respectively, coupled with a mechanical cultivation between the rows when compared to broadcast herbicide spraying. Most of the studies related to banded spraying in corn crops have emphasized the effectiveness of this technique when it is combined with mechanical cultivation (Mulder and Doll 1994; Bicki et al. 1991; Buhler et al. 1995).

Mechanical cultivation is one of the oldest and still widely used weed control method (Kepner et al. 1978). For row crops such as corn, cultivation could be achieved prior to planting, in pre-emergence (rotary hoe), or in post-emergence between the rows (row-crop cultivator). Corn yields may be increased following mechanical cultivation between crop rows (Coote and Saidak 1984); however, the efficacy of cultivation is highly related to the weed density in the field (Forcella et al. 1993) and to the species of weeds (Froud-Williams et al. 1983). In addition, this technique remains very dependent upon the meteorological conditions as well as upon the weed development stages (Hartzler et al. 1993). A good example is the efficacy of rotary hoeing against germinated weeds that no longer exists after those weeds have emerged from the soil. Cultivation between the rows in post-emergence is efficient when weeds are less than 150 mm tall whereas cultivation on the rows is only efficient when weeds are less than 50 mm tall (Schweizer et al. 1994). Overall, excessive cultivation is not recommended as it can induce soil compaction and erosion (Raghavan et al. 1978), deteriorate the soil structure (Saini and Grant 1980), cause the loss of organic matter (Martel and Mackenzie 1980), and result in yield losses because of damage that may be inflicted to the root system of the crops by the cultivation equipment. The improved effectiveness of cultivation equipment, especially for row crops, is credited for the widespread popularity of this weed-control technique (Wilkinson et al. 1999).

The first applications of flaming or other thermal control techniques to control weeds in field crops, such as cotton, date back to the 1940s (Kepner et al. 1978). Corn is one of the few crops that is well adapted to this particular weeding technique (Kepner et al. 1978). Research carried out at Université Laval proved the technical and agronomic feasibility of this method and allowed for the development of flaming equipment adapted to this crop (Laguë et al. 1997). It was found that corn is most susceptible to heat damage when the plants have between two and seven leaves. Thermal treatments are also more effective against weeds that are in their early stages of development (Wilkinson et al. 1999). It is therefore possible to complete thermal weeding treatments over the entire field surface no later than the two-leaf stage of the corn plants if the weeds have already emerged by that time. After the seven-leaf stage, heat treatments can also be applied on the rows and combined with a mechanical cultivation between the rows. Wilkinson et al. (1999) reported that the environmental impacts of flame weeding are minimal, but that the costs involved are too expensive for widespread application of this technology.

Cover crops may be planted between the rows of a main crop to compete with weeds without adversely altering its development. Among the advantages of using cover crops are the control of soil erosion, improved water infiltration, good conservation of soil fertility, reduced weed infestations, and reduced disease incidence (Wall et al. 1991). For example, the use of subterranean clover (*Trifolium subterraneum*) as a cover crop in corn resulted in a comparable or even better weed control under conventional and reduced tillage compared to the use of atrazine and metolachlor at a rate of 1.3 and 1.7 kg AI/ha, respectively (Enache and Ilnicki 1990).

Clements et al. (1995) concluded that most alternative methods of weed control are more energy efficient than conventional weed control practices. Pimentel and Burgess (1980) have reported extensive labor and energy data for corn production in the USA. Total energy inputs ranging from 16.38 (South Dakota) to 145.1 (Texas) GJ/ha and labor requirements ranging from 5.2 (North Dakota) to 31.3 (California) h/ha for a complete production cycle are reported by these authors. Energy inputs associated with herbicides (manufacturing and transport) were highly variable, ranging from 0.11 (Michigan) to 4.0 (North Carolina) GJ/ha. Peart (1999) reported total energy inputs ranging from 20.61 to 29.29 GJ/ha for corn grown in Florida and in South Carolina with pesticides (herbicides and insecticides) accounting for 1.68 GJ/ha of that total.

OBJECTIVES

The first objective of the study reported in this paper was to determine the energy input for a number of different weed control strategies in grain corn grown under two different primary tillage modes based on the equipment and products used. The other objective of the research was to evaluate the time and labour requirements for each of those weed control strategies. This engineering study was an important component of a multidisciplinary research program that was aimed at evaluating selected weeding techniques in grain corn production at the agronomic, economic, engineering, and environmental levels (Leroux et al. 2000).

MATERIALS and METHODS

Weeding strategies

Seven different weeding operations were selected for the purpose of this study. Table 1 presents the equipment used to complete those operations along with the abbreviations used in the rest of the text when referring to them. All these operations, except for MT which was still at the development stage, were representative of corn management systems used by commercial corn growers in the province of Québec. These seven weed control operations were then combined into ten different weeding strategies: H + PM1; H + PM2; H + CM1; H + CM2; H + MT1; H + MT2; CC; PC + PM1; PC + PM2; and PC + PMC, that were deemed to be representative of weed control management practices by commercial corn growers. Six of those strategies (H + PM2; H + CM2; H + MT2; CC; PC + PM2; and PC + PMC) were also evaluated at the agronomic (crop yield, weed control), environmental (soil and water contamination), and economic levels by other members of the research team (Leroux et al. 2000).

Field trials and equipment

All field experiments were repeated during the 1998 and 1999 growing seasons (two replications) at the Agronomic Research Station of Université Laval located in Saint-Augustin-de-

Table 1. Characteristics of the weeding operations and equipment used in this study.

Weeding operation[1]	Equipment	Width (m)	Travel speed (km/h)
H	Integral rotary hoe	3.05	10
PM	Row-crop cultivator 1 (4 rows)	3.05	6
PMC	Row-crop cultivator 1 with seeding equipment	3.05	6
CM	Row-crop cultivator 2 (4 rows) with rotary tools for on-the-row cultivation	3.05	6
MT	Row-crop cultivator 1 with flaming components	3.05	6
CC	Integral broadcast sprayer	6.10	8
PC	Spraying equipment mounted on corn planter (4 rows)	3.05	8

[1] H Hoeing: pre-emergence rotary hoeing over the entire field area
PM Partly Mechanical: post emergence mechanical cultivation between the crop rows
PMC Partly Mechanical + inter-row Cover crop: post emergence mechanical cultivation and seeding of the rye cover crop between the crop rows
CM Completely Mechanical; post-emergence mechanical cultivation between and on the crop rows once (CM1) or twice (CM2)
MT Mechanical Thermal: post-emergence mechanical cultivation between the crop rows and flame cultivation on the rows once (MT1) or twice (MT2)
CC Completely Chemical: broadcast spraying of herbicides in pre-emergence of the crop
PC Partly Chemical: banded spraying of herbicides on the rows at planting

Desmaures, Québec. Two blocks of large experimental plots (0.75 ha each) were used for the study. There were seven plots (one per weeding operation) within each block. In the first block, conventional primary tillage consisting of fall moldboard plowing at a depth of 150 mm was used. Reduced primary tillage (chisel plow in the fall) was completed in the second block of plots. Secondary tillage operations were the same for both blocks and were completed in the spring prior to planting.

The herbicides used for both broadcast (CC) and banded (PC) spraying operations were atrazine and metolachlor. Application rates of 1.125 and 1.92 kg AI/ha (kg of AI per unit area of treated land), respectively, were used. The broadcast spraying treatments were carried out using a fluid application rate of 225 L/ha. The banded spraying treatments were completed at the time of sowing using planter-mounted spraying equipment.

Post-emergence mechanical cultivation between the rows (PM) was completed using a standard 4-row cultivator with five S-shanks mounted on each cultivation unit.

Thermal weeding (MT) was performed using dedicated equipment developed at Université Laval and mounted on the first cultivator (CRH 1995). The flaming equipment consisted of two burners per row directed toward the base of the row. The burners were located 90 mm on each side of the row, 80 mm above the ground, and tilted 30° with respect to the vertical. Each pair of burners was longitudinally offset by 100 mm to avoid flame interference which may cause undesirable heat rising toward the crop leaves. The burners used liquid propane at a pressure of 414 kPa.

The cultivator used to weed between and on the rows of corn (CM) was also developed at Université Laval. This cultivator covered four rows and consisted of conventional S-shank tools for weeding between the rows and of rotary tools for weeding on the rows (Ben Yahia et al. 1999). The rotary tools were placed in pairs face-to-face, 90 mm away from the corn rows and their operating depth was set at approximately 30 mm.

The cover crop used was rye at a rate of 120 kg/ha. Rye was sown between the corn rows during a mechanical cultivation operation (PMC) that was completed about three weeks after the emergence of the corn when the weeds were less than 150 mm tall. Rye seeds were distributed between the shanks of the first row-crop cultivator over a 600-mm width using deflector plates located above the shanks.

Energy inputs

Machines and equipment Global energy requirements associated with the use of agricultural machines and equipment to perform the weeding operations were obtained by adding the unit requirements associated with:

1. the fabrication of machines and equipment (raw material, fabrication activities, etc.);
2. the transport of machines and equipment from their fabrication site;
3. repairs, maintenance, and spare parts supply during their useful life period; and
4. the field operation of the machines and equipment.

Values for these first three components for the particular agricultural machines and equipment used within this research study were computed from Fluck (1992). The mass of the machines and equipment was determined using two portable vehicle scales having a precision of ± 91 kg. The useful life periods of the equipment were computed from ASAE Standards data (ASAE 1999). Based on values for these two parameters, the energy requirements were then expressed on an hourly basis.

Field operations For each operation, the tractor fuel consumption was determined using a calibrated 1 L reservoir installed for this purpose at the inlet of the fuel tank. At the beginning of each operation, the reservoir was filled to a predetermined level. At the end, the reservoir was again filled to that same level and the fuel required represented the effective fuel consumption for a given operation.

The total time required for each weeding operation, including filling, headland turns, and travel and field adjustments, was recorded. Unit time requirements for each operation were determined by dividing this value by the area of the experimental plots and expressed in units of time per unit area.

The energy requirements associated with each weeding field operation were then computed by summing up the following unit requirements :

Table 2. Unit energy requirements for the fabrication, transport, and maintenance of the field machines and equipment used in the study (Fluck 1992).

Field equipment	Unit energy requirement (MJ/kg)			
	Fabrication	Transport	Repairs and maintenance	Total
Tractor	90	9	45	144
Corn planter	90	9	43	142
Rotary hoe	90	9	53	152
Row-crop cultivator	90	9	52	151
Spraying equipment	90	9	33	132

Table 3. Equipment characteristics (mass and useful life) and resulting unit energy requirements expressed on an hourly basis.

Field equipment	Mass (kg)	Useful life (h)	Unit energy requirements (MJ/kg)	(MJ/h)
Tractor	3530	12,000	144	42.3
Banded spraying equipment on corn planter	54.4	1500	132	4.8
Corn planter	885	1500	142	83.7
Rotary hoe	420	2000	152	31.9
Row-crop cultivator 1[1]	941	2000	151	71.1
Row-crop cultivator 2[2]	919	2000	151	69.3
Broadcast sprayer	261	1500	132	23.0

[1] Machine used to complete treatments PM, PMC, and MT

[2] Machine used to complete treatment CM

Table 4. Unit energy requirements for the fuel, herbicides, and operator inputs.

Input	Unit energy requirements
Diesel fuel[1]	46.49 MJ/L
Liquid propane[2]	61.62 MJ/kg
Atrzine[3]	205.4 MJ/kg
Metolachlor[3]	296.9 MJ/kg
Operator energy input[4]	1.054 MJ/h

[1] Diesel fuel No. 2-D having a high heating value of 37.95 MJ/L (Goering 1992)

[2] Propane fuel having a high heating value of 50.30 MJ/kg (Goering 1992)

[3] Manufacturing, formulating, packaging, distributing (wholesale and retail), and transporting to farm gate (Green 1987)

[4] Energy expenditure for tractor driving (Stout 1990)

1. the energy contained in the machines and equipment (energy/time * time/area);
2. the fuel used (volume/time * time/area * energy/volume);
3. the weeding products (i.e. herbicides or propane) used (mass/area * energy/mass); and
4. the energy input of the operators (energy/time * time/area).

Unit energy requirements for fuel, herbicides, and human labour were obtained from the literature and are presented in the results and discussion section.

Statistical analysis

Time and diesel fuel requirements were the only two independent variables that were systematically measured for all weeding operations (7 operations * 2 blocks * 2 replicates = 28 values). These data were statistically analyzed using the General Linear Models procedure of SAS software to determine significant block (i.e. type of primary tillage) and weeding operation effects. T-tests were used to differentiate means for significant weeding operation effects.

No statistical analyses were performed on the other independent variables (i.e. herbicide and propane requirements) since those were not common to all weeding operations. No statistical analyses were completed on the derived time and energy requirements for the ten weeding strategies since these data were not obtained directly from experiments. Average, minimum, and maximum values are reported in the article.

RESULTS and DISCUSSION

Unit energy requirements for the fabrication, transport, and maintenance of the different machines and equipment used in this study are presented in Table 2. These data were used, along with the measured mass of the machines and equipment and published data on their useful life, to determine the global energy requirements for each machine and equipment (Table 3).

Table 4 presents the unit energy requirements for diesel and propane fuel, chemical herbicides, and human labour. The data for diesel and propane fuels take into account the energy required to manufacture these products. Cervinka (1980) reported a value of 47.75 MJ/L for the total energy sequestrated into diesel fuel (i.e. heating value plus energy inputs for production). According to the same author, the ratio between the energy inputs for production and the fuel heating value for five different petroleum-based fuels was equal to 0.228 on average. Fluck (1980) suggested a ratio of 1.223 between the total energy sequestrated in petroleum fuels and their heating value. In their comparative study, Clements et al. (1995) used a constant value of 1.181 MJ/L for the energy inputs associated with the production of petroleum fuels, which is much lower than the values reported by the two preceding authors. Using Cervinka (1980) and Fluck (1980) estimates, the heating values of both diesel and propane were multiplied by a factor of 1.225 to determine the total energy sequestrated in both types of fuels that are presented in Table 4.

Average data (over two growing seasons) for time requirements, diesel and propane consumption, and rates of

Table 5. Experimental data for the seven weeding operations.

Weeding operation[a]	Primary tillage[b]	Time required (h/ha)	Diesel fuel (L/ha)	Propane fuel (kg/h)	Herbicides (kg AI/ha)	
					Atrazine	Metolachor
H	C	0.484	2.20	-	-	-
	R	0.446	1.70	-	-	-
PM	C	0.602	3.64	-	-	-
	R	0.673	3.61	-	-	-
PMC	C	0.716	3.73	-	-	-
	R	0.745	3.64	-	-	-
CM	C	0.656	3.90	-	-	-
	R	0.643	3.53	-	-	-
MT	C	0.717	4.09	42.4	-	-
	R	0.741	4.36	39.5	-	-
CC	C	0.290	1,27	-	1.13	1.92
	R	0.296	1.32	-	1.13	1.92
PC	C	0.703	5.02[1]	-	0.45[2]	0.76[2]
	R	0.727	5.36	-	0.45	0.76

[a] See Table 1 for codes.

[b] C = moldboard plow; R = Chisel plow.

[1] The energy input for this operation is mainly related to the operating of the planter itself; the specific fuel requirements for the banded spraying operations have been estimated at 0.1 L/ha (Fluck 1992).

[2] Application over 300-mm wide bands centered on the rows corresponding to a 39.5% coverage of the total field area.

application of herbicide products are presented in Table 5. The analysis of the variance of the data presented in Table 5 revealed that the soil tillage method did not have any significant effect on the time and energy (diesel, propane, herbicides) requirements of the field operations ($p = 0.05$). As a result, values of time, diesel, propane and herbicide requirements averaged over the two primary tillage modes were used in the rest of the analysis. Significant differences existed among the seven different weed control operations ($p = 0.0001$).

The unit time requirements of the seven weeding operations are presented in Fig. 1 (averages over two primary tillage modes and two replicates). It should be noted that the specific unit time requirements for the completion of the specific banded spraying operation (PC) are close to zero since this operation is combined with the crop planting operation itself. Figure 2 presents the diesel fuel requirements of the seven weeding operations. These data were also averaged over the two primary tillage modes and two replicates. It should be noted that the measured diesel fuel requirements for weeding operation PC were mostly associated with the operation of the planter itself. According to Fluck (1992), the specific fuel requirements for the banded spraying operation only could be estimated at 0.1 L/ha. After having corrected the experimental data for operation PC accordingly, it can be concluded that the seven weeding operations can be included within four categories for both time and diesel fuel requirements: PC, CC, H, and (PM, CM, MT and PMC). Those unit time and diesel fuel requirements have been used in the rest of the analysis to determine the global time and energy requirements for the ten different weeding strategies.

The data presented in Tables 2, 3, 4, and 5 allowed us to determine the global energy requirement for each weeding operation regardless of the primary tillage method. These results

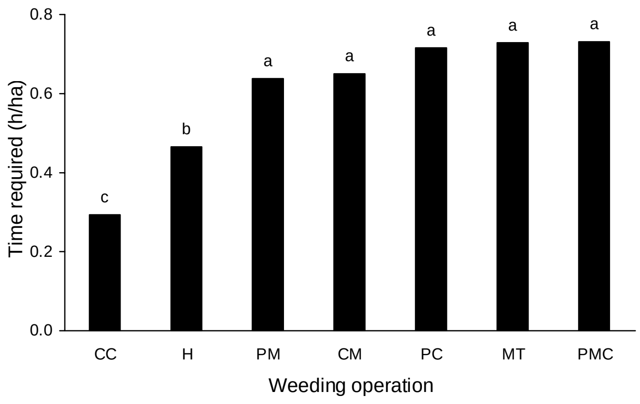

Fig. 1. **Average unit time requirements for the seven weeding operations. Means with the same letter are not significantly different at the 5% level (LSD test).**

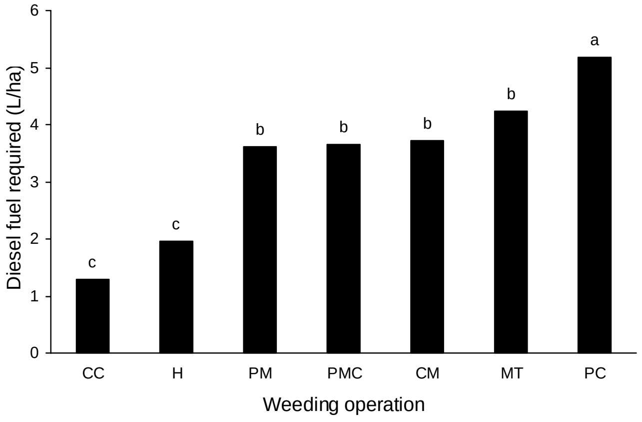

Fig. 2. **Average diesel fuel requirements for the seven weeding operations. Means with the same letter are not significantly different at the 5% level (LSD test).**

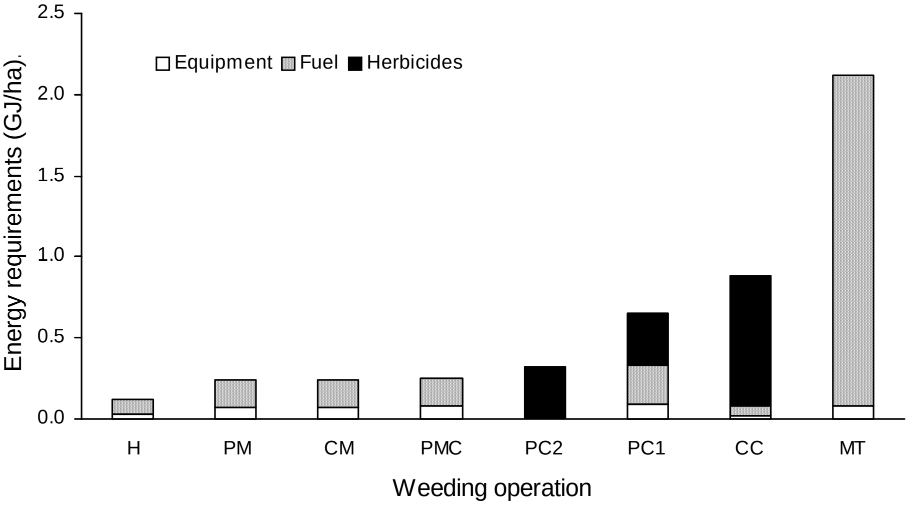

Fig. 3. Total unit energy requirements for the seven weeding operations.

Table 6. Field efficiency of the seven weeding operations.

Weeding operation[a]	Time requirements (h/ha)		Field efficiency (%)	
	Experimental	Theoretical[b]	Experimental	Reported range[c]
H	0.465	0.328	70.6	70 - 85
PM	0.638	0.546	85.6	70 - 90
PMC	0.731	0.546	74.7	70 - 90
CM	0.650	0.546	84.0	70 - 90
MT	0.729	0.546	74.9	70 - 90
CC	0.293	0.205	69.7	50 - 80
PC[1]	0.715	0.410	57.3	50 - 75

[a] See Table 1 for codes.

[b] As computed from data presented in Table 1.

[c] From ASAE (1999).

[1] Combined planting and banded spraying operation.

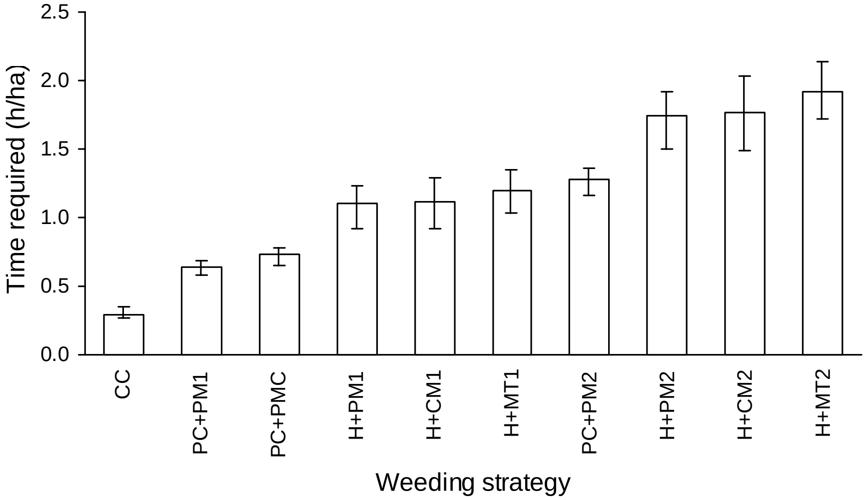

Fig. 4. Average unit time requirements for the ten weeding strategies. Minimum and maximum values are indicated by the brackets.

are presented in Fig. 3 and these data were then used to compute the global energy requirements for the ten weeding strategies used in the study. Two values are presented for the PC operations. PC2 corresponds to the unit energy requirements of the banded spraying operation only, while PC1 also includes the requirements associated with the planting operation itself. For all operations that relied on mechanical cultivation as the main method for controlling weeds (i.e. H, PM, PMC, and CM), about 70% of the total energy inputs were associated with the fuel that was used by the tractor. At the other end, the energy inputs associated with the products applied to control weeds (i.e. herbicides or propane) accounted for 85 to 98% of the total energy requirements for operations MT, CC, and PC (once the requirements for the planting operation were subtracted, i.e. PC2). The energy inputs associated with human labour were negligible for all these mechanized weeding operations, accounting for less than 0.5% of the total energy requirements.

Considering the operating width and speed of the equipment used and the measured time requirements to complete each weeding operation, the field efficiencies of these operations have been determined (Table 6). The measured field efficiency for most weeding operations was in good agreement with published values which confirmed that the experimental setup was representative of full-scale operations. The addition of either flaming or sowing components on the row crop cultivator reduced the field efficiency of the cultivation operation by more than 10% and this was mainly due to the additional time required for refilling either the propane tanks or the seed box.

The total time requirements for the ten different weeding strategies used in this study were calculated from the time-requirement data for each specific weeding operation presented in Fig. 1 and the results are presented in Fig. 4 in which average, minimum, and maximum values of time requirements based on experimental data are presented. It can be seen that the different strategies fit into four groups:

1. strategy CC that involved only one spraying operation (0.26 to 0.32 h/ha);

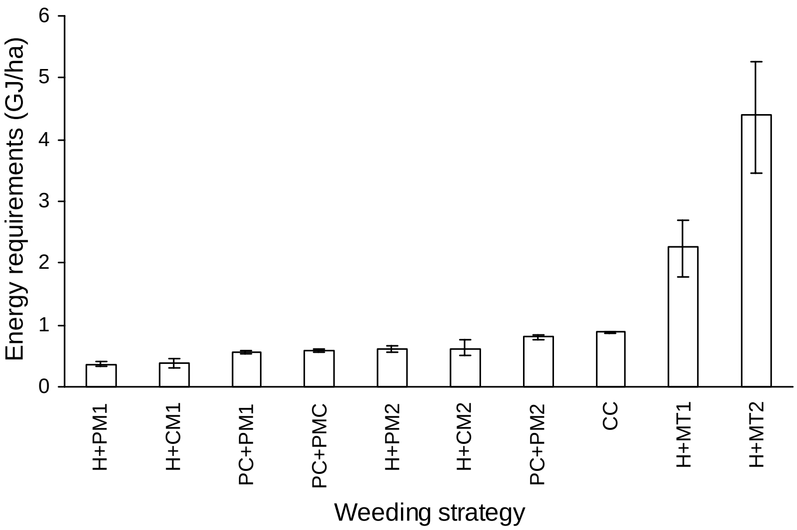

Fig. 5. Average unit energy requirements for the ten weeding strategies. Minimum and maximum values are indicated by the brackets.

2. strategies PC + PM1 and PC + PMC that both involved a single mechanical cultivation operation in addition to the banded spraying that was combined with the planting operation (0.58 to 0.78 h/ha);
3. strategies H + PM1, H + CM1, H + MT1, and PC + PM2 that involved two mechanical cultivation operations (0.92 to 1.36 h/ha); and
4. strategies H + PM2, H + CM2, and H + MT2 that involved three distinct mechanical cultivation operations during the season (1.49 to 2.14 h/ha).

In terms of minimizing the time requirements associated with the weeding operations, strategy CC showed the best results with strategy H + MT2 requiring the most time, amounting to almost seven times the time requirements of strategy CC.

A similar analysis was completed for the energy requirements of the ten weeding strategies under study and the results are presented in Fig. 5 (average, minimum, and maximum unit energy requirements). The total energy inputs for the two weeding strategies that involved thermal control were significantly higher than for all the other strategies because of the use of a non-renewable source of energy (propane) for heat generation.

Table 7. Specific time requirements and energy inputs for six of the ten weeding strategies on the basis of a unit mass of harvested grain corn.

Weeding strategy	Average grain yield (15% moisture w.b.) (Mg/ha)	Specific time requirements (h/Mg)	Specific energy inputs (MJ/Mg)
H + PM2	6.195	0.281	98.26
H + CM2	5.305	0.333	116.4
H + MT2	6.385	0.301	683.8
CC	6.910	0.0424	127.6
PC + PM2	7.800	0.164	103.7
PC + PMC	7.420	0.0985	78.33

To take into account the impact of the different weeding strategies on crop yields, the unit time requirements and energy inputs were divided by the crop yields to obtain values on the basis of 1 kg of harvested grain corn. Yield data related to six of the ten weeding strategies that were used during two full growing seasons (1998 and 1999) were obtained from Marmen (2000). The results, averaged over these two growing seasons and the two primary tillage modes (moldboard plow and chisel) are presented in Table 7. The type of primary tillage did not have any significant effect on the corn yields (Marmen 2000).

In terms of time requirements, the ranking of the six weeding strategies was only minimally affected when taking crop yields into account with strategy H + CM2 becoming the least time effective (instead of strategy H + MT2) because of the slightly lower grain corn yields that were obtained when this strategy was used. Strategy H + MT2 that involved thermal control remained by far the most energy-consuming weeding system compared to all the other weeding strategies.

This information on unit and specific time requirements and energy inputs should prove useful when one wants to assess the global efficiency of a particular production system for grain corn by taking into account agronomic, economic, energetic, engineering, and environmental considerations. For example, a weeding strategy that has low energy inputs, but requires multiple equipment passes in the field may contribute to an increase in the output:input energy ratio of the crop, but, on the other hand, it may have negative impacts on yields due to improper timeliness of the weeding operations. Appropriate weighing of the different parameters used to evaluate a crop production system from a global perspective is therefore of utmost importance.

CONCLUSIONS

The following conclusions were drawn from this comparative study:

1. The type of primary tillage (fall moldboard plowing or chisel plowing) did not have any significant effect on the time required to complete the weeding operations nor on their fuel requirements.
2. Broadcast herbicide spraying was the least time-consuming weeding strategy, requiring only 0.293 h/ha while pre-emergence rotary hoeing followed by two passes of a combined row crop cultivator/flamer later during the season necessitated 1.923 h/ha.
3. Total energy requirements were lowest at about 370 MJ/ha for two weeding strategies involving pre-emergence rotary hoeing followed by one pass

of a row crop cultivator completing either between the row cultivation or combined between and on the row cultivation. The weeding strategies that involved one or two passes of the combined row crop-cultivator / flamer required five to ten times more energy.

4. When post-emergence mechanical cultivation between the crop rows was used once, strategies H + PM1 and PC + PM1 demonstrated the best overall performances in terms of both the time requirements and the energy use. When such a mechanical cultivation was used twice during the growing season or once along with seeding rye as a cover crop between the crop rows, strategies PC + PM2 and PC + PMC were most effective.

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