Corn Production, Utilization and Environmental Assessment

A REVIEW

CANADA'S GREEN PLAN

LE PLAN VERT DU CANADA

Agriculture and
Agri-Food Canada

Agriculture et
Agroalimentaire Canada

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SUMMARY

Corn has been grown in Canada for over 500 years, but area and rate of production have increased dramatically during the past four decades and corn has become an essential component of the agricultural industry of Central Canada. Corn production practices continue to evolve in response to economic pressures, in particular, competition with the world's largest producer of corn, the US. In addition, increased use of conservation tillage and integrated weed management practices have enhanced the economical and environmental sustainability of the corn production system. The main use of corn is as an animal feed but corn is also increasingly used as a source of industrial products, including corn-derived ethanol as a source of renewable fuel energy. This report presents an overview of the production and utilization of corn in Canada, with special attention to the agronomy, the industrial utilization, and the energy and carbon balances of corn production.

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1. INTRODUCTION AND HISTORY

Corn (*Zea mays* L.), or maize as it is called outside Canada and the United States, is probably the first man-made crop species. Although relatively little consensus exits as to the origin and early evolution of corn, there is general agreement that corn was first domesticated 7,000 to 10,000 years ago in southern Mexico. After domestication, corn spread throughout the Americas, reaching the northeastern United States and southern Canada prior to European colonization. Corn pollen evidence for Indian agriculture in the lower Great Lakes region has been recorded at Silver Lake in Ohio, in a lake at Huronia near Barrie, Ontario, and near a former Indian settlement in the Crawford Lake Conservation Area, near Guelph, Ontario. In the latter location, a heavy concentration of pollen was found in the sediments dated between 1434 and 1450.

Domesticated corn in North America evolved into a large number of racial groups. Modern corn hybrids for commercial production in North America have been largely derived from two of these racial groups: the Northern Flints of the northern U.S., southern Canada, and central Europe; and the Corn Belt dents. In Canada, open-pollinated varieties were replaced by hybrid corn in the 1940s. Early grain-corn production in Canada was restricted mainly to the counties of Essex and Kent in southwestern Ontario. The introduction of early-maturing hybrids in the late 1950s resulted in a rapid expansion of the corn area into short-season regions of Ontario and Quebec during the subsequent three decades. In addition, corn yields increased during this period at a rate of 1.5% per year (Fig. 1.1), resulting in a more than seven fold increase in total grain-corn production in Ontario from 1961 to 1991.

The rapid expansion of the area grown under corn in Eastern Canada during the 1960s and 1970s was associated with increased inputs of non-renewable resources and intensive tillage systems. Prompted by concerns about ground- and surface-water contamination and soil erosion associated with intensive management systems, corn-production practices have changed substantially during the past 10 to 15 years. Conservation tillage and integrated weed management practices have reduced the impact of corn production on the environment. It is anticipated that significant progress in crop management will continue to increase profitability and environmental neutrality of corn production.

Recent concerns about global warming, in general, and increasing CO_2 levels, in particular, have prompted efforts to reduce the burning of fossil energy. Corn, converted to fuel ethanol, has been proposed as an alternative source of renewable fuel energy for transportation. Corn is the most efficient crop in converting incident solar energy into chemical energy that is contained in the carbon-to-carbon bonds of plant dry matter. Whereas corn *per se* is a renewable energy resource, production and processing requires considerable energy input, which has raised questions about the net benefit of the use of corn for this purpose in terms of economics and the energy/carbon balance.

This report summarizes aspects of corn production and utilization in Canada. Detailed information on production, genetics, economics, chemistry, and utilization of corn can be found in reference books and scientific publications in the list of references.

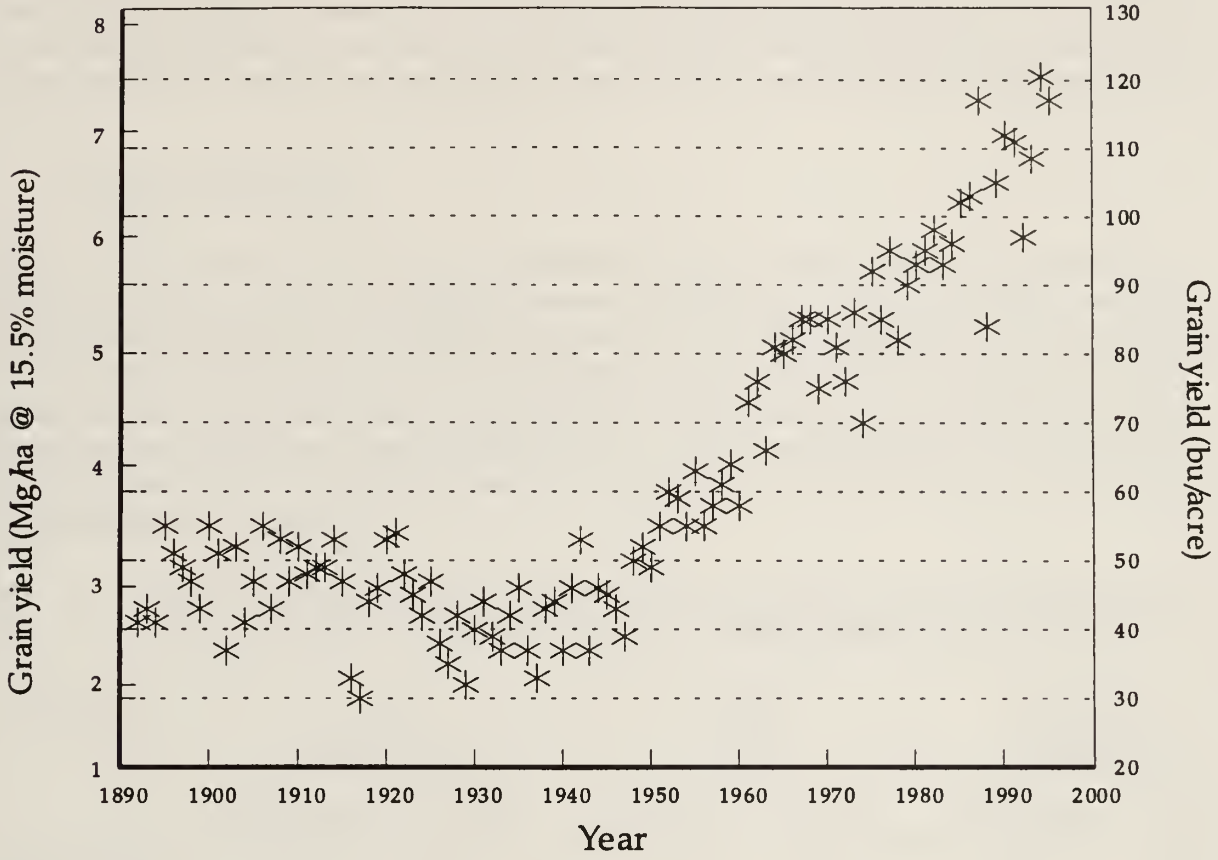


Fig. 1.1 Average corn grain yield in Ontario from 1892 to 1995

2. CURRENT MARKETS

I. WORLD PRODUCTION

World production of grain corn from 1985 to 1995 has ranged from a low of 401 million tonnes in 1988 to a high of 555 million tonnes in 1994. Corn production in 1995 was 507 million tonnes which compared to a projected world production of 533 million tonnes for wheat and 530 million tonnes for rice. The United States produced approximately 40% of the total corn produced in the world. The United States and France are the most producers of corn among the major corn-producing countries (i.e., average yields range from 7.2 to 7.8 t/ha).

II. CANADIAN PRODUCTION

Grain-corn production in Canada has remained relatively stable during the period from 1985 to 1995, with a high of 7.4 million tonnes in 1991 and a low of 5.4 million tonnes in 1988. Virtually all the corn in Canada is produced in Ontario and Quebec, which produced 71% and 28%, respectively, of the total Canadian production in 1995. Whereas Ontario production has remained stable or has declined slightly during the 1985-1995 period, the production in Quebec has almost doubled from 1.1 M tonnes in 1986 to 2.0 M tonnes in 1995. The efficiency of corn production in Canada (i.e., 7.26 t/ha in 1995) is similar that of the United States and France.

Table 2.1 Area of production, yield, and production of grain corn by major producing countries during 1985-1994 and 1995. Canada Grains Council (1995)

Country	Area (1,000,000 ha)		Yield (t ha)		Production (1,000,000 t)	
	1984-1994	1995	1985-1994	1995	1985-1994	1995
United States	27.8	27.8	7.26	7.60	198.2	198.9
China	20.3	21.3	4.23	4.79	86.3	102.0
Brazil	13.4	14.0	2.05	2.36	27.5	33.0
Mexico	6.8	7.5	1.96	2.20	13.5	16.5
France	1.8	1.7	7.13	7.78	12.9	13.0
Former USSR	3.5	3.1	3.14	2.72	11.3	8.4
World	129.1	129.9	3.71	3.90	479.1	507.0

In addition to the more than 1 million ha utilized for grain-corn production in Canada, silage corn was grown on 171,500 ha in 1995. Again, most of the silage-corn was produced in Ontario (68%) and Quebec (15%), although some corn-silage production occurred also in Manitoba (7%), B.C. (5%), and Alberta (2%). The area of silage-corn production in Ontario and Quebec has declined steadily from 279,000 ha in 1985 to 143,400 ha in 1995.

Table 2.2 Area of production, yield, and production of grain corn in Canada during 1985-1994 and 1995. Canada Grains Council (1995)

Province	Area (1,000 ha)		Yield (t/ha)		Production (1,000 t)	
	1985-1994	1995	1985-1994	1995	1985-1994	1995
Nova Scotia	1.7	2.2	4.79	6.00	8	13
Quebec	263.9	280.0	6.16	7.17	1632	2000
Ontario	712.9	700.0	6.63	7.35	4727	5131
Manitoba	26.9	18.2	3.88	5.17	104	94
Alberta	3.1	2.0	5.47	6.35	17	13
Canada	1008.5	1002.5	6.43	7.26	6487	7251

Table 2.3 Area of production, yield, and production of silage corn in Canada during 1985-1994 and 1995. Canada Grains Council (1995).

Province	Area (1,000 ha)		Yield (t/ha)		Production (1,000 t)	
	1985-1994	1995	1985-1994	1995	1985-1994	1995
Nova Scotia	1.9	1.9	24.3	30.1	48	57
New Brunswick	0.7	2.0	23.9	27.2	16	54
Quebec	43.5	26.0	30.4	29.2	1359	760
Ontario	151.2	117.4	29.5	27.8	4454	3266
Manitoba	11.0	12.1	19.6	24.7	216	299
Alberta	6.7	4.0	32.8	36.3	219	145
B.C.	10.0	8.1	43.4	53.8	435	435
Canada	225.2	171.5	29.9	29.3	6751	5017

III. WORLD TRADE

World trade in corn during the period from 1992 to 1994 was between 64 and 73 million tonnes Tables 2.4 and 2.5). The US dominated the corn export market with a market share of more than 55%. Asian countries were the distination of a large proportion of corn in the world trade; Japan had about a 25% share of the total world corn import market. Canadian exports varied between 360 and 400 thousand tonnes per year during the 1992 to 1994 period, whereas imports varied between 740 to 840 thousand tonnes per year during this period. Consequently, net imports of corn in Canada were 390 thousand tonnes or about 5% of total corn production in Canada (Table 2.2).

Table 2.4 Export of grain corn by major exporting countries during 1992-1994 (FAO, 1995).

Country	Year		
	1992	1993	1994
		---- 1,000 t ----	
United States	43,236	40,365	35,877
China	10,340	11,098	8,740
France	7,042	7,758	8,013
Argentina	6,093	4,872	4,154
South Africa	524	216	4,000
World	72,730	67,506	63,846

Table 2.5 Import of grain corn by major importing countries during 1992-1994 (FAO, 1995).

Country	Year		
	1992	1993	1994
	---------- 1,000 t ----------		
Japan	16,382	16,863	15,930
South Korea	6,612	6,207	5,749
China	5,355	5,466	5,602
Russia	5,490	4,391	901
Benelux	3,857	3,420	3,728
Mexico	1,306	211	2,747
Spain	1,790	2,401	2,339
Egypt	1,444	2,148	2,021
World	72,139	68,554	62,213

3. AGRONOMY

I. GROWTH AND DEVELOPMENT

Corn plants come in various sizes and shapes depending on their relative maturity, origin, and specific end use, or the environmental conditions under which they are grown. However, all corn plants go through the same phases of development from planting to maturity. An understanding of the development of corn is essential in corn management, in particular, as it relates to pest management and climatic effect on yield.

Development of corn can be divided into four distinct phases (Table 3.1): a period of predominantly vegetative growth (the leaf growth phase), a period during which dry matter is allocated predominantly to the reproductive organs (the grain filling period), a transition period between the two former phases (the flowering period), and the final period of corn development during which no translocation occurs between the plant and the grain (period of grain dry down). A detailed illustration of how a corn plant develops has been published by Ritchie et al. (1992).

Table 3.1 Phasic development of corn

1. *The leaf growth phase*
   - 1.1 Imbibition of the seed
   - 1.2 Plant emergence
   - 1.3 Transition from predominantly heterotrophic to predominantly autotrophic growth
   - 1.4 End of Juvenile phase
   - 1.5 Tassel initiation
   - 1.6 Initiation of topmost ear
   - 1.7 Emergence of topmost leaf

2. *The flowering period*
   - 2.1 Tassel emergence
   - 2.2 Anthesis
   - 2.3 Silking
   - 2.4 Fertilization of the florets

3. *The grain filling period*
   - 3.1 Onset of lag phase of grain d. m. accumulation
   - 3.2 Onset of rapid grain d. m. accumulation
   - 3.3 End of rapid grain d. m. accumulation
   - 3.4 Half milk line

4. *The period of grain dry down*
   - 4.1 Black layer formation
   - 4.2 15.5% grain moisture

Duration of the phases of development is influenced by climatic factors (temperature in particular) and the relative maturity of the hybrid, but management factors such as soil fertility, plant density, and pest management also affect rate of development. Prediction of the exact date at which a particular stage of development will occur is virtually impossible. Even the heat unit accumulation (CHU) to a given stage of development will vary widely among management practices and years. Examples of approximate dates and accumulated heat units for various stages of corn development of a 2600-CHU hybrid and a 3200-CHU hybrid grown at their respective heat-unit location are presented in Table 3.2.

Table 3.2 Approximate dates and accumulated heat units (CHU) for various stages of corn development of a 2600-CHU and a 3200-CHU hybrid grown at their respective heat-unit location during an "average" year.

Stage of development	2600-CHU hybrid		3200-CHU hybrid	
	Date	CHU	Date	CHU
Seeding	15 May	0	5 May	0
Emergence [1.2]	30 May	190	17 May	190
4-leaf stage [1.3]	9 June	340	27 May	340
12-leaf stage	2 July	890	17 June	890
Tasselling [2.1]	19 July	1300	17 July	1550
Silking [2.3]	22 July	1390	21 July	1650
Start of grain filling [3.2]	10 Aug	1850	6 Aug	2100
Half milkline [3.4]	14 Sept	2450	11 Sept	2950
Black layer [4.1]	26 Sept	2680	21 Sept	3200

Various important events in the development of corn from seeding to maturity can be identified.

The leaf growth phase. Corn seedlings can emerge in as few as 5 days after planting under warm conditions and in moist soil. Emergence can be delayed by up to 30 days in a cool soil. Corn seedlings are susceptible to disease organisms and insects, especially in a cold soil. Application of a seed treatment and insecticides is important to ensure a uniform stand.

Even though leaves are emerging above ground, the growing point of the corn is below ground until the 4- to 5-leaf stage. It is the soil temperature rather than the air temperature that influences rate of development during this phase. At about the 4-leaf stage (four leaves visible) the corn plant has a short "growth crisis:" the transition from heterotrophic to autotrophic growth (i.e., until this point most of the resources for growth have been supplied by the reserves in the seed and, subsequently, photosynthesis of the seedling supports all growth). The seedling is susceptible to unfavourable conditions during this stage and effects of tillage and/or soil compaction on seedling growth and development become apparent.

All leaves have been initiated by the time the plant reaches the 8- to 10-leaf stage, the stage of tassel initiation. Leaves continue to emerge and expand. Plant height starts to increase rapidly at about the 12-leaf stage; plants are about knee high at this point. The tassel will become visible soon after the topmost leaf has emerged from the whorl. The duration from planting to the emergence of the topmost leaf is directly related to the total number of initiated leaves. Duration from planting to silking is longer in long-season than in short-season hybrids because long-season hybrids initiate more leaves.

Corn plants usually have one ear per plant, although up to eight ears may have been initiated. Ear initiation starts about 10 days after tassel initiation in the axis of the fifth to seventh leaf from the top, and this initial ear usually will be the only one that sets grain. The initiation will progress down the plant in lower axillary nodes. Ears in these nodes will abort before silking, unless the environmental conditions for the plant are very favourable (e.g., plants in outside rows that receive more solar irradiance). When conditions are particularly unfavourable for corn growth, even the topmost ear may abort or fail to set grain (i.e., barren plants).

The silking or flowering period. Corn attains its maximum height, pollen are shed from the tassel at the top of the plant, and silks are emerging from the earshoot during the flowering period. This period is critical for grain yield. Pollen production is abundant, as many as 10 million pollen grains are shed per day per plant. Fertilization of the florets on the ear is seldom limited by insufficient pollen. Silks that emerge from the earshoot should be pollinated within 7 days after emergence. After a pollen grain lands on a silk, the pollen grain germinates to produce a "pollen tube" which must grow down the entire length of the silk before fertilization can occur. Fertilization of the florets may not occur, or kernels that have been fertilized may abort during the first few days after fertilization, due to stress caused by drought, nutrient deficiency, pests, or high plant density. The result is incomplete seed set and reduced yields. The corn crop is prone to stress during the flowering period because crop growth and, consequently, the demand for resources for plant growth, is at a peak. In addition, flowering usually occurs during a period when daily temperatures are high (i.e., second half of July, early August).

The grain filling period. Rapid filling of the grain starts 2 to 3 weeks after silking. Grain grows at a rate of 3 to 4% of final yield per day during the period of rapid grain growth. The rate of grain growth is directly related to the prevailing temperature and is largely independent of crop dry matter accumulation. If grain growth is more rapid than crop dry matter accumulation, dry matter for grain growth is remobilized from stems, leaves, and husks (mainly stems). Stress during this period can, therefore, result in increased lodging and premature leaf death.

The advance of grain maturity can be traced by following the progress of the "milk line" in the kernels. When the kernels have dented pick an ear and break it in two. The exposed face of the upper end of the ear will reveal the smooth surface of the kernels. The milk line should be visible near the top of the kernels. This line represents the boundary between the solid, starchy portion of the kernel and the milky, lower part. As the grain matures, the line moves downward towards the tip of the kernel. When the milk line is halfway down the kernel, the grain moisture content will be about 40%. The line will disappear at the tip of the kernel shortly before black layer formation, giving a good indication of when the crop is about to reach physiological maturity.

Maximum whole-plant dry matter is usually reached when the grain moisture is 40 to 45% (i.e., half milk line). Maximum corn silage yields can be obtained by harvesting at this stage. Grain will continue to grow, although at a much lower rate, until the formation of a distinct black layer at the base of the kernel.

The period of grain dry down. The decline in moisture content of the grain is rapid during the grain filling period when water in the kernel is replaced by starch and other constituents of the grain. Drying occurs more slowly after black layer formation. Moisture loss during this phase is exclusively a function of (i) the difference in moisture content of the kernel and the humidity of the air surrounding the plants and (ii) physical barriers such as the kernel pericarp and the husks that restrict the flow of water vapour. Grain dry down is slow when the humidity of the air is high (e.g., when the temperature is low) and/or when the husks are tightly fitted around the ear (e.g., immature ears).

II. CLIMATE

Climate influences all aspects of corn management, ranging from planting date/hybrid selection to weed control and grain drying. Because the climate at any particular location is variable and unpredictable from year to year, risks and opportunities associated with a range of possible climatic scenarios should be assessed in corn management.

The most important climatic factor to corn production is temperature. Corn cannot tolerate subzero temperatures and, therefore, duration of the growing season of corn is restricted by late frosts in the Spring and early frosts in the Fall. Rate of corn development is approximately linear between 12 and 27°C. Rate of development is close to zero for temperatures below 10°C, attains a maximum at 31°C, and declines when temperatures increase beyond 31°C. Corn-growing areas are classified according to the number of accumulated daily heat units in the frost-free period (i.e., the number of heat units per day quantifies the rate of development as a function of the daily maximum and minimum temperature). In Canada, Crop Heat Units (CHU) are used to classify the length of the growing season and the relative maturity of the hybrids. Information on the Crop Heat Unit system can be found in the OMAFRA Factsheet, *Heat Units for Corn in Southern Ontario*, Agdex 111/31 and maps of crop heat unit isotherms for Ontario and Quebec are depicted in Figures 3.1 and 3.2. Relative maturity of hybrids in Ontario range from 2200 to 3400 CHU. This range corresponds to approximately 75 to 115 on the Minnesota Relative Maturity Scale and 100 to 600 in the European FAO system. In general, highest yields will be obtained when relative hybrid maturity matches the heat-unit accumulation in the frost-free period. If relative hybrid maturity is too high (i.e., a late hybrid), yields will be reduced because grain filling will cease prematurely and grain moisture will be high. If relative hybrid maturity is too low (i.e., an early hybrid), yields will be reduced because the hybrid will not utilize the full growing season. Crop heat-unit accumulation refers only to the relationship between temperature and corn development and heat-unit accumulation does not necessarily quantify the impact of temperature on other corn production processes.

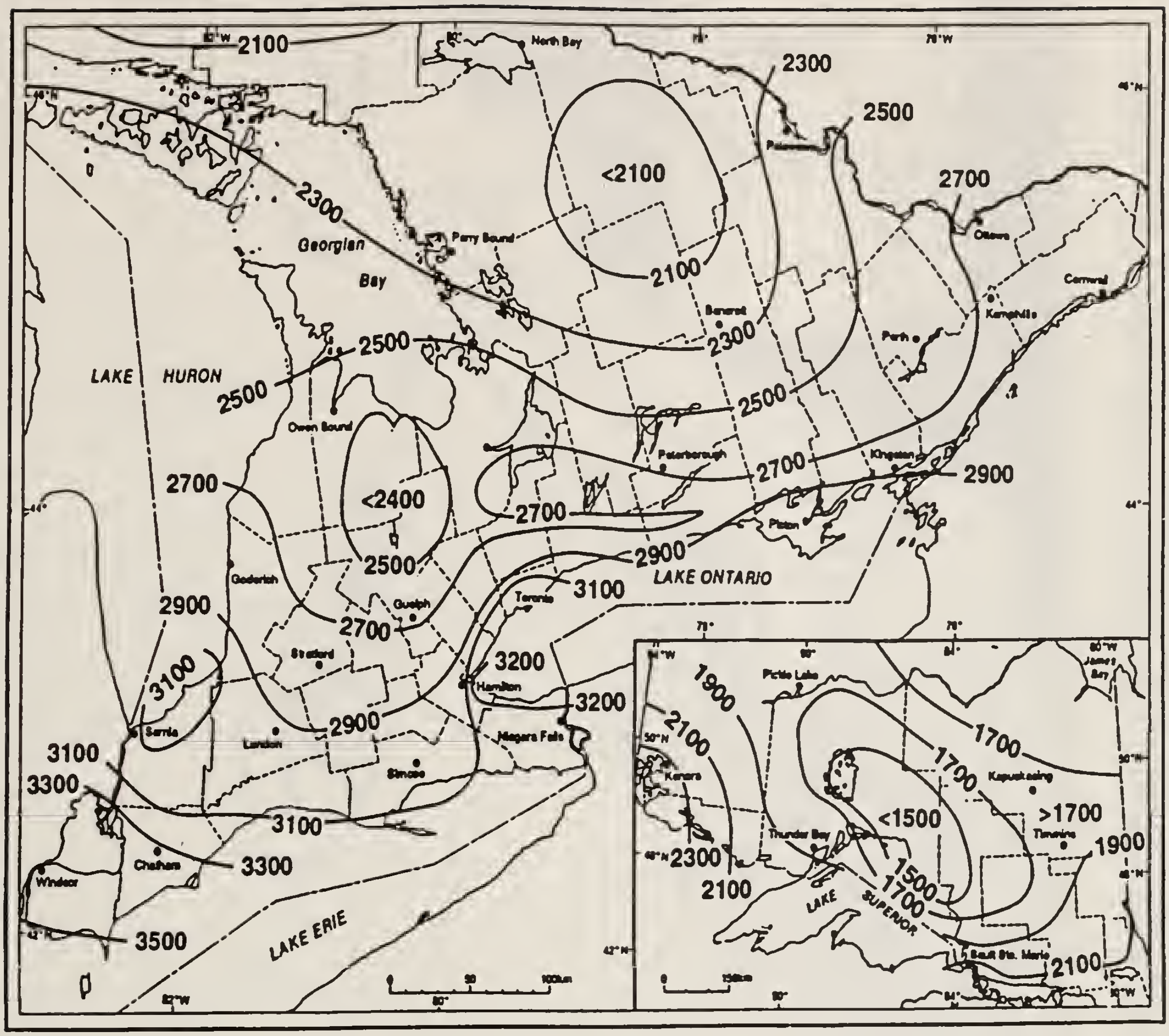


Fig. 3.1 Accumulated seasonal Crop Heat Units (CHU) isotherms for corn production in Ontario

Incident solar radiation and precipitation are two other important factors in corn production. Crop productivity is related to the solar energy absorbed by the leaf canopy of the crop. The absorbed energy is used in photosynthesis to reduce CO_2 into plant dry matter. Variations in incident solar radiation are small among locations in Southern Canada or, for that matter, among locations in most of the corn-growing areas in North America. Corn utilizes approximately 700 L of water for each kg of grain (e.g., a corn crop that produced 8 t/ha of grain, utilized 5.6 million litres or 560 mm water). Demand for water is particularly high during the month centred by silking, i.e., from early July to early August. The amount and distribution of rainfall in the corn-growing areas of Central Canada is generally suitable for good corn production, although moisture stress can frequently be a problem on course-textured (sandy) soils. Irrigation of corn is a common practice in Alberta.

Fig. 3.2 Accumulated seasonal Crop Heat Unit (CHU) isotherms for corn production in Quebec for the period from 1970 to 1978, with a probability level of 80% (J. Chevrette, P.A. Dube and Y. Castonguay).

Table 3.3 Approximate values for number of frost-free days, Crop Heat Units (CHU) and total incoming solar radiation from 1 May to 30 Sept. for various locations in Southern Canada. (Tollenaar, 1983).

Location	No. of frost-free days	CHU	Incident solar radiation (1 May-30 Sept.)
			GJ m^{-2}
Agassiz (B.C.)	180	2700	3.00
Lethbridge (Alta.)	110	2000	3.25
Swift Current (Sask.)	105	1900	3.15
Winnipeg (Man.)	110	2200	3.00
Guelph (Ont.)	140	2600	3.05
Quebec (P.Q.)	120	2300	2.90
Charlottetown (P.E.I.)	130	2100	2.75

III. HYBRIDS

Yield, relative maturity (i.e., grain moisture at harvest), and utilization (e.g., silage, grain, special food products) are the most important criteria used in hybrid selection. Other desirable attributes such as standability, pest resistance (e.g., mycotoxins), and bushel weight are usually also considered. A common question asked by corn producers is whether the best corn hybrids under high-input management practices are also the best performers under low-input conservation practices.

Most of the corn hybrids grown in Canada are single-cross hybrids, i.e., seed is produced by crossing two inbred lines. Corn hybrids replaced open pollinated varieties in the 1940s because of their higher yields and greater uniformity. Initially, corn hybrids were four- or three-way crosses (i.e., involving, four or three inbreds, respectively), but as seed production of inbred lines improved they were replaced by single-cross hybrids. Some 20 companies sell corn seed in Ontario and several of these companies are involved in research to improve yield and other agronomic attributes of the hybrids. In Ontario, the Ontario Corn Committee conducts a series of trials throughout Southern Ontario each year to evaluate corn hybrids for yield, maturity, and standability. A list of recommended hybrids is published, which serves as a guide for corn producers. Yield improvement of corn hybrids in Ontario has been in the order of 1.5% per year and, each year, new hybrids are added and older hybrids are deleted (on average, a particular hybrid will spend 7 years on the list of recommended hybrids).

Several factors should be considered in the selection of a hybrid. First, the hybrid should reach maturity in the particular location for which it is selected. Under good growing conditions, grain filling will cease when the kernel is packed full of starch and protein granules and a black layer develops at the base of the kernel. In this case, kernel moisture will be about 25 to 32%. Black layer formation (or physiological maturity), however, can occur earlier when filling of the grain ceases because biotic or abiotic factors stop the translocation of soluble sugars and amino acids into the kernels. In that case, kernel moisture can be appreciable higher than 32%. In practice, the maturity of a hybrid is determined by its grain moisture content and hybrids on the list of recommended hybrids in Ontario are ranked according to their grain moisture at harvest for each location and year.

Grain moisture at harvest can vary considerably from year to year. For instance, heat unit accumulation at the Elora Research Station from 20 May to 30 October was 2800 CHU in 1991 and 2360 CHU in 1992. There is a 10% probability that heat unit accumulation will be either 210 CHU above or below the average value for the location. In addition, rate of corn development relative to CHU accumulation may be lower during periods of extreme low or high temperatures, and excess moisture or moisture stress and, consequently, grain moisture will be higher at maturity. Management practices also influence the relative maturity of the hybrid. Planting date is crucial. The old rule of thumb is "a loss of 1 Bu/A per day for each day that the corn is planted after the recommended planting date in May." Research has confirmed this relationship between planting date and yield (and grain moisture), although later planting results occasionally in relatively higher yields and lower grain moisture when temperatures are unseasonably low during early periods of the growing season. Other management practices such as plant density, tillage, and soil fertility can also influence grain moisture at harvest.

The relative yield performance is given for each hybrid on the list of recommended hybrids. Like grain moisture at harvest, grain yield can vary widely with environmental conditions and management practices. Hybrid ranking can vary, although the best hybrids under favourable conditions are generally also the highest yielding hybrids under unfavourable conditions. Standability, or lodging, should be considered when selecting hybrids for yield, since a high-yielding crop is of little value if it is severely lodged. Lodging can increase substantially under poor conditions. Some hybrids are relatively lodging resistant due to physiological and/or physical attributes.

Utilization is the third consideration in the selection of a hybrid. If the corn is used for silage, relative maturity of the hybrid can be 100 to 200 CHU later than that selected for grain (because harvest occurs at 40 to 45% grain moisture). Research has demonstrated that hybrids producing high grain yields also produce high silage yield. In addition, stem lodging is a minor consideration in silage production. If the corn is to be used for special food or industrial products, selection is in some cases restricted to hybrids that consistently meet the quality specification of the processors (see 5.II).

IV. PLANT DENSITY AND PLANT SPACING

Selection of the plant density (or plant population) that results in maximum grain yield is an important management decision. The plant density, or the range of plant densities, at which maximum grain yield is obtained can vary among corn hybrids, management practices, soil types, locations, planting dates, and years. The best plant density of corn for any particular farm or field will always remain a guesstimate because climatic conditions for the growing season cannot be predicted, but a good estimate of the best plant density can be made by using records of previous years and a basic understanding of the relationship between plant density and corn grain yield.

Plant density is the number of plants per unit area (e.g., 60,000 plants/ha) present during the growing season. Plant density can be 5 to 15% lower than the seeding rate because of failure of kernels to germinate or emerge (e.g., due to a hard layer in the top soil) and/or losses of seedlings due to pests. When plant density is increased from low to slightly higher plant densities, grain yield will increase linearly with plant density (see Fig. 3.3). When plant density is increased from a medium to high plant density, yield may still increase but the increased ear number per unit area will be offset to some extent by decreases in kernel number per ear and weight per kernel. However, grain yield will decline when plant density is increased at high plant densities (see Fig. 3.3). This decrease in grain yield is attributable to a decline in grain yield per plant, sometimes resulting in barren plant (i.e., plants without grain-bearing ears). Consequently, the corn plant density was too high if there is a relatively large number of barren plants (e.g., >2%) at maturity. In contrast, plant density was likely too low if there are a large number of plants with two grain-bearing ears at maturity (note that plants in the outside row of the field have frequently two ears and these plants should not be included in the analysis).

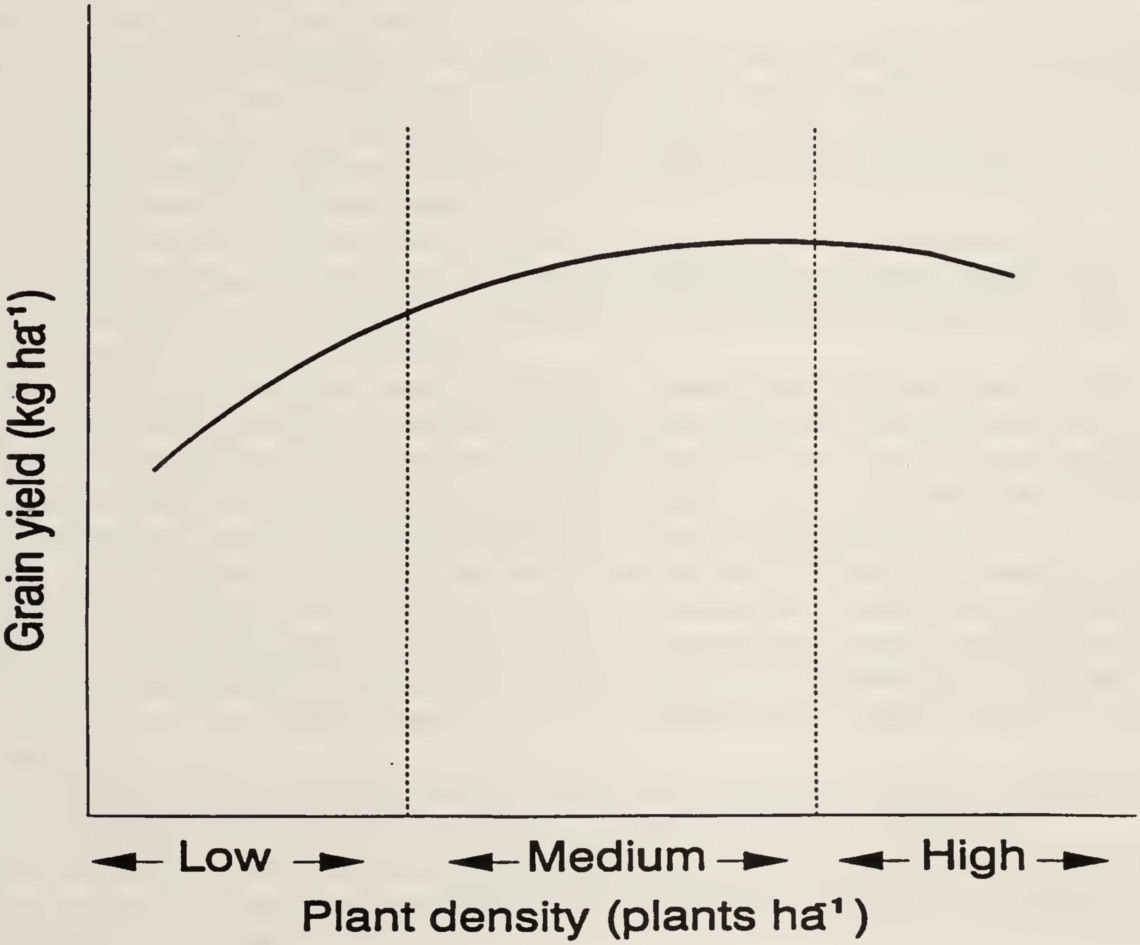


Fig. 3.3 Effect of plant density on grain yield in corn

How does one estimate the optimum plant density? The optimum plant density can be determined by planting a number of hybrids at three or more different plant densities (e.g., 60,000, 70,000, and 80,000 plants/ha) and measuring yield at maturity. However, optimum plant density will vary among various tillage practices, crop rotations, planting dates, and years. In addition, new and improved hybrids replace older hybrids every 4 to 7 years and new cropping systems such as strip cropping may have quite different optimum plant densities. There is no need, however, to repeat plant-density experiments for each particular situation. The optimum plant density can be "finetuned" using rules of thumb that are based on the physiological response of corn to plant density. It should be noted that "the optimum plant density" consist really of a range of approximately 10,000 plants/ha (e.g., 60,000 to 70,000 plants/ha).

The optimum plant density for a number of scenarios is discussed below. For those interested in the mechanisms of the plant-density response of corn, the next paragraph of this section summarizes the physiological response of corn to plant density.

(i) *Stress.* Plant density should be reduced when there is a probability that stressful conditions will occur during the growing season. High plant density is a stress and stresses due to weeds, insects, diseases, and inadequate soil fertility serve to exaggerate the stressful effects of high plant density.

(ii) *Soil texture.* Corn grown on soils with a poor water-holding capacity frequently experience drought stress during periods of rapid corn growth. Corn yield is particularly susceptible to drought stress during the period from the middle of July to the middle of August. Plant density should be reduced by up to 20,000 plants/ha depending on the probability of a severe moisture stress.

(iii) *Hybrid maturity.* The optimum plant density is lower for late maturing hybrids than for early maturing hybrids. For instance, the optimum plant density under good growing conditions may be 60,000 plant/ha for 3200-CHU hybrids, whereas it could be 75,000 plants/ha for 2600-CHU hybrids.

(iv) *Planting date.* Plant density should be reduced when planting relatively late. In general, plant density should be reduced by approximately 5,000 plants/ha for each 10 days delay in planting from the optimum planting date. In practice, earlier maturing hybrids should be planted when planting is substantially delayed and, in that case, plant density should be reduced by less than 5,000 plants/ha for each 10 days (see iii above).

(v) *Hybrid stress tolerance.* Potential differences in optimum plant density among corn hybrids that are listed on the Ontario Corn Committee list of recommended hybrids could be in the order of 5,000 to 10,000 plants/ha. Percentage of broken stalks at maturity (see list of recommended hybrids) is one of the criteria used in assessing the optimum plant density (i.e., plant density should be lower for hybrids with a relatively high lodging percentage).

(vi) *Cropping system.* Plant density should be reduced for cropping systems that are expected to result in more stressful conditions for corn growth (e.g., zerotill vs. conventional tillage, continuous corn vs. crop rotation). In contrast, plant density should be increased when conditions are favourable for corn growth such as in strip cropping corn with soybeans and wheat.

Table 3.4 Effects of plant density on leaf area index (LAI), light interception, dry matter, and dry grain yield at maturity on early-maturing and late-maturing hybrids grown at the appropriate location in Ontario. [Light interception is calculated from the equation 1 - exp (-0.65 x LAI), dry matter is estimated to change proportionally with light interception, and grain yield is estimated based on an optimum plant density of 7 and 6 plants/m^2 for the early- and late-maturing hybrid, respectively].

Plant density (Plants/ha)	Early-maturing hybrid				Late-maturing hybrid			
	LAI (m^2/m^2)	Light interception (%)	Dry matter (t/ha)	Grain yield (t/ha)	LAI (m^2/m^2)	Light interception (%)	Dry matter (t/ha)	Grain yield (t/ha)
40,000	2.0	73	14.0	7.0	3.0	86	18.0	9.0
60,000	2.8	84	16.1	8.1	4.2	93	19.5	9.8
80,000	3.5	90	17.3	8.1	5.3	97	20.3	9.4
100,000	4.1	93	17.8	7.8	6.3	98	20.5	8.8

The response of corn yield to plant density can be predicted to a large extent from the physiological mechanisms underlying corn production and plant density can be adjusted to maximize yield accordingly. Corn production is (i) the capture of incident solar radiation and (ii) the conversion of captured solar energy into economically usable forms of energy (i.e., feed and food). The impact of plant density on light interception, dry matter, and grain yield of a hypothetical early-maturing and a late-maturing hybrid has been illustrated in Table 3.4. Light interception during the period of full leaf-area expansion (i.e., from approximately early July to early September) increases from 73 to 93% in the early maturing hybrid and from 86 to 98% in the late-maturing hybrid when plant density is increased from 40,000 to 100,000 plants/ha (16,200 to 40,500 plants/acre). Total corn biomass increases about proportionally to the increase in light interception. Grain yield, however, levels off and, subsequently, declines when plant density increased beyond the optimum plant density because of increased stem lodging and the increased frequency of barren plants (i.e., plant without a grain-bearing ear).

The positive effect of increased light capture should be balanced with the negative effect of lower utilization efficiency when plant density is increased. Increasing plant density beyond LAI = 4 will not increase grain yield because increases in light capture will be minimal. Late maturing hybrids have generally a larger LAI than short-season hybrids and, consequently, the optimum plant density of late maturing hybrids is lower than that of short-season hybrids. Finally, the optimum plant density is lower under stressful conditions because stress reduces utilization efficiency.

Row spacing and strip cropping. Crop management practices, other than plant density, that are used to manipulate the capture of incident solar radiation include width of row spacing and growing alternating strips of two or three crops in the same field.

Until the 1930s, row width in corn was determined by the size of the horse's rump, not by yield considerations. Research during the 1960s showed that corn yields increased by 5 to 10% when row width was reduced from 102 cm (40 inches) to 76 cm (30 inches) and most corn was by then grown in the 76-cm row spacing. Farm trials were carried out during the 1970s and 1980s to investigate whether a further reduction in row width would increase corn yield. Results of these studies were variable, with changes in yield ranging from -5% to +10% when row width was reduced from 76 to 38 cm (see Internet "http://info.aes.purdue.edu/agronomy/corn-09.htm"). The reason for the potential yield increase due to reduced row width is the more even distribution of leaf area across the field, which will increase light interception during early phases of development when leaf area is small and concentrated within the row. Research on narrower row width, however, has not shown consistent increases in either light interception during the growing season or yield when row width was reduced from 76 to 38 cm (Westgate et al., 1996). The potential small increase in yield when switching from 76-cm to narrower row widths will, in general, not justify the costs involved in converting to narrower-row equipment.

Alternating crops in strips across the field has been practiced for years in the US to reduce soil erosion, but the use of narrow strips (e.g., six 0.76-cm corn rows) alternating corn and soybeans or corn, soybeans, and wheat is a relatively recent phenomenon in North America. When corn is grown in strips with soybeans, yield of the outside corn row is about 25% higher compared to the yield of corn that is bordered by three or more corn rows. When rows run North and South, yield increases in outside rows facing East and West are approximately equal. However, the outside row facing North with rows in a East-West orientation does not show a consistent yield advantage. The yield increase in the outside rows can be attributed predominantly to increase light interception. (This is the reason that experimental research plots are always bordered by at least three guard rows.) Some corn growers increase the plant density of the two outside rows (e.g., from 75,000 plants/ha for the center rows of the strip to 100,000 plants/ha for the outside rows), but the effect of those very high plant densities on the yield of the outside rows will likely be minimal. In general, the increase in corn yield in the strips is offset by a similar proportional decline in soybean yield, as the outside soybean rows will be shaded by the taller corn. Assuming an approximately equal net return per ha for corn and for soybeans, higher corn yields when strip cropping corn and soybeans will not necessarily increase the overall economic return due to lower soybean yields.

V. SOIL FERTILITY

Providing adequate fertility is an essential step in producing a profitable corn crop. Because crops can obtain nutrients from the reserve in the soil, grain yield is not always directly related to rate of applied fertilizer. In the long term, the amount of nutrients removed from the soil by harvested grain or whole-plant silage, and by leaching, volatization, and surface runoff, should be replaced. No simple model can be used to define the nutrient additions for corn as soil fertility varies from soil to soil, and with cropping history. In addition, nutrient requirement of the crop is related to the targeted yield. For instance, grain corn crops of 6 and 10 t/ha will remove approximately 76 and 127 kg N ha^{-1}, respectively. Nitrogen application rates recommended in OMAFRA Publication 296, *Field Crop Recommendation*, for these two scenarios are 100 and 135 kg N ha^{-1}, respectively, in Central Ontario and 140 and 160 kg N ha^{-1}, respectively, for side-dressed nitrogen in South-Western Ontario.

Phosphate (P) and potash (K) additions should be based on soil tests and recommendations in OMAFRA Publication 296. Fertilizer requirements do not differ among tillage systems. In a conservation system, root depth tends to be shallower and nutrients accumulate in the top soil layer. Consequently, it is recommended that soil P and K levels are relatively high when soil management is changed from conventional to conservation tillage.

The replacement of nutrients can be in the form of manure, other organic material, the incorporation in the soil of N_2-fixing cover crops (e.g., alfalfa), and the applications of inorganic fertilizer. Whereas the impact of various forms of nutrient replacement on crop yield is the subject of some controversy (e.g., inorganic fertilizer vs. composted manure), maintaining adequate fertility should always be the guiding principle. The supply of more than adequate fertility for crop growth (irrespective of the form of nutrient replacement) is economically unjustified and can be harmful to the environment because of contamination of the groundwater (e.g., nitrogen) and pollution of the surface water (e.g., phosphorus). These factors constitute a strong incentive for regular reliable soil tests. The ability of soils to store nutrients (i.e., to serve as a buffer) varies greatly, depending on soil type and field history. A profitable/responsible fertilization program should, therefore, be based on cropping history, soil texture and structure, expected yield level, and soil tests at the start of the growing season.

VI. WEED CONTROL

Adequate weed control is essential in profitable corn production. Weed competition is a greater problem in corn than in most other crops such as cereals and forage crops, because of the relatively slow leaf area development of corn during early phases of the growing season. The critical period for weed control is between the four and twelve leaf stage of corn, i.e., if corn is weed free during this period no yield reduction will ensue. If weeds are not controlled in corn, yields may be reduced by up to 100%, depending on environmental conditions and weed pressure. Weeds compete with corn for incident solar radiation, soil moisture, and soil nutrients. In addition, weeds can create harvesting problems and increase harvest losses. Traditionally, weed control in corn in Canada relied to a relatively large extent on the use of chemical herbicides. Recently, however, weed control has been focused more on crop management practices that increase the competitiveness of corn relative to weeds, i.e., integrated weed management. The shift from traditional weed-control practices to integrated weed management has been accelerated by the need to reduce inputs in profitable corn production, the increase in the number weed species that have developed herbicide resistance, and environmental concerns about contamination of ground and surface water.

Proper crop management establishes the framework for an effective and efficient weed-management program. A competitive crop canopy is the most effective and efficient form of weed control. In addition, the impact of weed interference on crop yield can be reduced or sometimes even be nil if soil nutrients and soil moisture are not limiting. Consequently, management practices that maximize corn productivity will also reduce the impact of weed interference on corn yield (e.g., adequate soil fertility, adequate soil moisture, tillage that is favourable for early corn growth, and use of the optimum corn plant density). Crop rotation is also useful as crop competitiveness vs. specific weed species varies among crop species (e.g., competition with early vs. late emerging weeds), thereby reducing the risk that one or a few weed species become dominant.

Weed-control strategies should be tailored to the specific weed problems present in a particular field. Proper weed identification is an essential first step. Some weeds are susceptible to only one herbicide so it is critical that the herbicide program be matched carefully with the weeds present. Sometimes weeds can be controlled by band application over the corn row plus inter-row cultivation. Sometimes spot application of a herbicide in infested areas will result in adequate control, thereby reducing costs and potentially adverse environmental impacts of herbicide use. Herbicides used in other crops will control some weeds that cannot be controlled in corn and crop rotation can be helpful in controlling these weeds. Current weed-control recommendations are found in OMAFRA Publication 75, *Guide to Chemical Weed Control.*

Chemical weed control is a contentious issue and the Government of Ontario has addressed this problem by a program designed to reduce herbicide application by 50% in the year 2002. It is likely that this target will be reached, but pressures to reduce herbicide use will not likely stop there. Integrated weed management, new herbicide-application technology, new herbicides that can be applied at very low rates and degrade rapidly, computer simulation models that can predict the impact of a weed population on corn yield and the weed-seed bank, and combine yield-monitors with or without a global positioning system (GPS) will make weed management potentially more cost effective and increase environmental neutrality. Above all, however, it will depend on the knowledge of corn-weed interactions and the ability to implement the new tools in weed management, whether the goal of a more cost-effective, reduced-herbicide-input, weed-management strategy will be attained by corn producers.

VII. DISEASE AND INSECT CONTROL

There are relatively few disease and insect problems that are of economic importance in commercial corn production in Ontario. Only the most important disease and insect problems will be discussed here. Consult OMAFRA Publications 13, "Corn Production," and 296, "Field Crop Recommendations", for more detailed descriptions and recommendations on control of diseases and insects in Ontario.

Stalk and ear rots are the most important diseases in Ontario corn production. Stalk rots are associated with stem lodging, resulting in harvest losses. Stem lodging can be minimized by selection of hybrids with superior standability and the use of cultural practices that minimize adverse effects on plant health (e.g., optimum plant density). Effects of ear rot on grain yield are much less important than the potential of ear rot for mycotoxin contamination of the grain. Selection of corn hybrids that are less susceptible to ear rot and minimizing stress during pollination through proper cultural management can reduce the risk of mycotoxin contamination of the grain. A list of Ontario hybrids that have been rated for susceptibility to gibberella ear rot has been included in the 1996 report of the Ontario Corn Performance Trials. Corn diseases are not chemically controlled in field corn production. Detailed descriptions and illustrations of corn diseases can be found in "A Compendium of Corn Diseases" (Anonymous, 1977).

Several species of insects can cause damage to corn. Some insect and pest problems occur frequently but the impact on yield is small or non-existent and control measures are not warranted (e.g., slugs, aphids, corn earworms). Other insect problems occur infrequently and chemical control may be justified in isolated cases (e.g., army worms, potato stem borer, cutworms). Wireworms feed on germinating seeds and seedlings and seed treatments containing an insecticide offer some protection against this insect.

The two most important insects in corn production in Ontario are corn rootworms and the European corn borer. Corn rootworms can damage the root system, resulting in lack of vigour and plant lodging early in the season (i.e., root lodging which may lead to 'goose necking' of plants prior to silking). Since rootworms adults lay their eggs almost exclusively in corn fields, crop rotation provides an effective control. Chemical control of rootworms in Ontario has been reduced substantially, as crop rotation is now practiced by most Ontario corn producers.

The European corn borer tunnels into the stem, tassel and earshoot. Yield reductions result primarily from increased stem lodging (i.e., harvest losses), but some losses may also occur due to severance of assimilate translocation from the top to lower parts of the plant. Chemical control for corn borer is not warranted and selection of hybrids with good standability provides the best means of avoiding economic losses. The recent introduction of corn hybrids containing one or more Bt genes may provide the corn producer with a means of entirely eliminating economic losses caused by the European corn borer.

Grain corn is dried as one means of extending the shelf life of the corn. Dry grain can be kept for longer periods of time at a wide range of ambient temperatures. Figure 3.4 shows that corn with a higher moisture content is really best stored under cold ambient temperatures for short periods of time. The level to which corn is dried is directly tied to the end use destined for this product. As an example, if corn is being used for on farm feed, a moisture content of it could be dried to a moisture content of 18% and easily kept in condition until late spring or early summer. Many factors should be considered for the selection of the best corn drying system:

1) Type of corn to be dried.
2) Volume of corn to be dried.
3) How fast should the corn be dried?
4) Is corn to be used as feed on farm, sold off-farm, or sold to a specialty market.
5) Does the corn require special handling or drying requirements? (no augers, no high temperature exposure, minimum relative humidity of the air).
6) How much time is required to operate the dryer?
7) How much maintenance will be required for the drying system?
8) What is the system drying efficiency? (kJ per kg of water removed).
9) Will the size of the dryer be the bottleneck if grain throughput increaes?
10) Cost of operation per tonne of corn, including fuel, electricity for motors, wet-corn loading and dry-corn unloading equipment, insurance, depreciation, and labour costs.

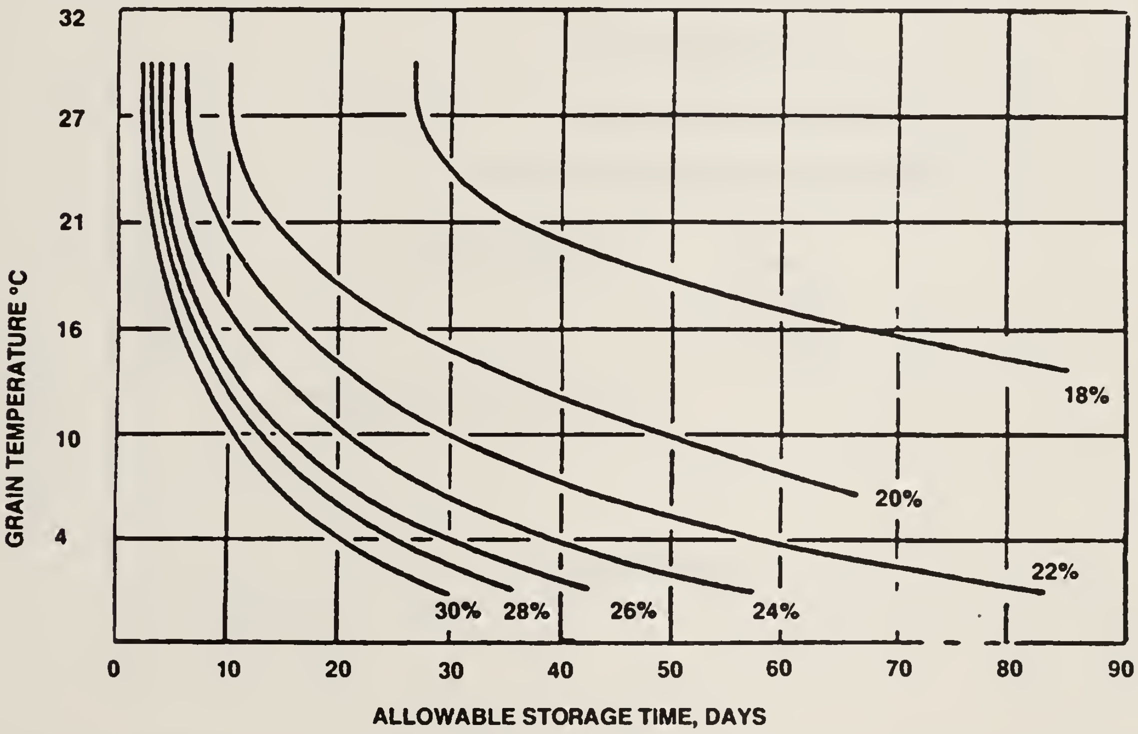
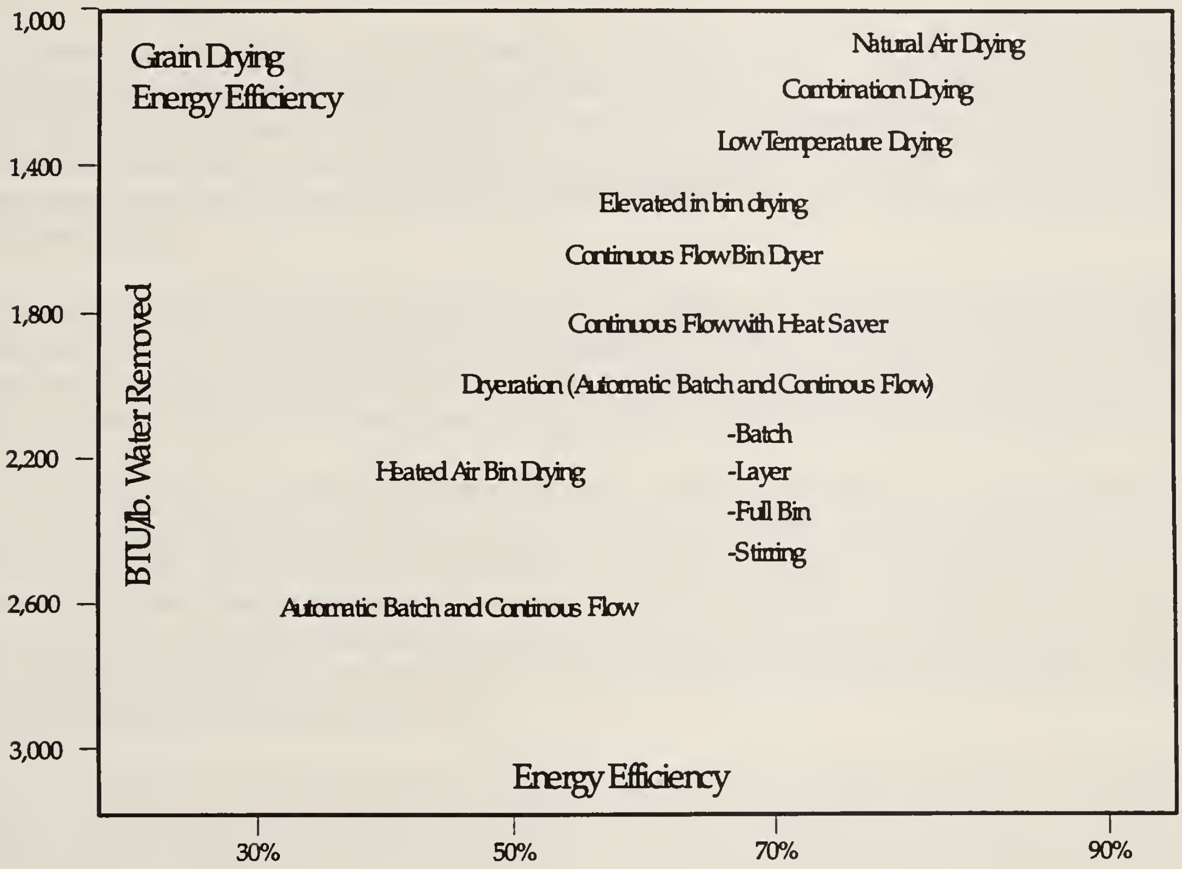


Fig. 3.4 Effect of temperature and moisture content on safe storage life of corn

Grain-Drying Efficiency

Grain-drying efficiency of various corn-grain dryers is depicted in Fig. 3.5. Efficiency of the dryer is expressed in kJ per kg of water removed (or in BTU per pound of water). In theory, 2454 KJ is required to evaporate 1 kg water at 20°C (which is equivalent to 1056 BTU per pound of water), but efficiency of dryers can be as low as one third of the theoretical efficiency.

Fig. 3.5 The energy efficiency ranges shown in the graph are based on the results of research projects and the opinions of manufacturers. There is no standard method of measuring a reporting dryer efficiency, so use these figures only as a rough guideline. Grain moisture, temperature, physical properties of grain, resistance to airflow, humidity and design of the fan, burner and ducting system all will effect actual dryer performance.



Grain-drying efficiency is influenced by the thickness of the grain column and the rate of air flow. If air moves rapidly through the grain (e.g., because of a small grain column and/or fast flow rate), water removal from the grain will be less than potential because not all energy used to heat the air is used to remove water from the grain. For instance, continuous flow dryers have a low drying efficiency because they were designed for high throughput capacity. The efficiency of these dryers can be reduced by recirculating warm "dry" air from the dryer. Heat recovery may increase dryer efficiency by up to 30%. In contrast, efficiency dryers which are shown in the top of Fig. 3.5 have greater grain columns and generally lower air flow rates. Consequently, air that exits the grain column in these dryers will be almost completely saturated with water vapour.

Elevated in-bin dryers have improved efficiency over bin dryers because of their design. The corn is first dried in the top of the bin and, subsequently, the partially dried grain is dropped to the bottom of the bin. Air at air temperature is blown through the column of partially dried corn in the bottom, thereby both removing water from the grain and heating the air; the heated air from the bottom of the bin is subsequently used to help dry the wet corn in the top of the bin.

Stress Cracks. Stress-cracked kernels are broken kernels held together by only a thin pericarp which surrounds the kernel. Although stress-cracked kernels may hold together long enough to grade well upon initial inspection, the pericarp is easily ruptured during handling. Sever stress-cracking can make corn unsuitable for industrial users and may limit the export opportunities for Ontario corn.

Stress cracks result mainly from rapid cooling of hot corn. When hot grain is cooled rapidly, which happens in most continuous-flow dryers, the outer layers of the kernel become cool while the centre remains hot. The resulting stresses cause the kernel to fracture. If corn is intended for industrial or export markets, consideration should be given to systems which reduce stress cracking. These include dryeration, cooleration, low temperature drying and natural air drying.

Dryeration/Cooleration. In both dryeration and cooleration, the cooling portion of the dryer (or the cooling cycle in batch dryers) is eliminated. Producers in Ontario have only be able to remove a point of moisture, one and a half points maximum using these systems. Corn is dried down to 16% to 18% moisture content, then transferred hot to an aeration bin.

The corn is then left to temper or allowed to steep without aeration for 1 to 12 hours. It is then cooled for an additional 6 to 12 hours at an aeration rate of 9.0 to 18 litres per second per tonne of corn. This is up to 7.5 times the aeration rate used in conventional aeration systems. Dryeration and cooleration does help in (i) reducing fuel usage, (ii) increasing dryer throughput, and (iii) maintaining corn quality (reduced stress cracks). A higher degree of management is required to maintain the drying system operation and scheduling of bin filling, steeping and cool-down aeration.

Aeration. One of the biggest problems in stored grain is the migration of moisture through the grain mass caused by temperature differences within the grain. This occurs whenever the difference in temperature between the grain mass and the outside air is greater than 5 to 10°C. The migration of moisture results in condensation of moisture and spoilage of the corn.

The purpose of aeration is to: (i) to remove field heat from the corn, (ii) to equalize the moisture content and temperature of the grain mass, and (iii) to remove moisture caused by temperature changes of the outside air. Throughout the storage period the corn temperature should be maintained within 5 to 10°C of the average outside air temperature. The grain should be cooled down as winter approaches and cooled further during the winter months. Bins shuld be checked after a short warm spell or after extended periods of sunny weather. Bin surfaces will be warmed by these conditions which will initiate convective air movements inside the bin. Bins should be checked at least every month, preferably every two weeks. These routine inspections should include:

(1) Visual check of the grain.
(2) Check for signs of moisture condensation on the underside of the roof.
(3) Turn on the fan and check for off-odours.
(4) Note changes in static pressure from last inspection (increase in static pressure means something has changed - investigate).

Prevention of Grain Spoilage. Damage from molds can be prevented by proper drying and aeration of the corn as outlined above. However, considerable damage can also be caused by insect infestations which can occur in dry corn. Insects are present in most grain-handling systems and it is almost impossible to eliminate them completely. However, loss from insect damage can be kept to minimum by using the following program (For more detailed information see OMAFRA Publication 229):

(1) Remove all dust and old grain from bin walls, ceilings, floor and aeration ducts before refilling the bin.
(2) Repair cracks where insects might enter.
(3) Spray inside the bin with a residual insecticide at least one week before storing new grain.
(4) Never store new corn on top of old since insects will move from the old grain into the new.
(5) Cool grain as quickly as possible. Insects cannot reproduce at temperatures below 18°C.
(6) Check stored grain regularly to detect hot spots.
(7) Employ aeration and/or cold weather transfers to reduce temperatures.
(8) Fumigate difficult insect infestations.

4. CONSERVATION APPLICATIONS

Intensive agriculture is frequently associated with degradation of soil and water resources, risks of environmental pollution, and reliance on fossil fuels. Agricultural sustainability and environmental neutrality of crop production are related directly to the impact of crop management on soil structural stability. A decrease in soil structural stability results in increased erosion rates, thereby lowering the production potential of the land and increasing off-farm deposit of sediment, nutrients, and pesticides. In corn production, management practices such as conservation tillage systems, crop rotations, and cover crops are used to maintain or increase soil structural stability and to reduce fossil-fuel inputs. It is now widely recognized that conservation practices are beneficial to farm operations and ecosystems, although best management practices vary with soil type, crop rotation, and climatic condition.

I. CONSERVATION TILLAGE

Soil has traditionally been prepared for corn production by autumn moldboard plowing followed by spring secondary tillage. In this system, most of the residue of the previous crop is covered. In conservation tillage, soil disturbance is minimized and more than 30% of the soil surface remains covered with crop residue after planting. Conservation tillage systems range from the total absence of tillage except for a single coulter in front of the seed disc openers at planting (i.e., no-till), to chisel plowing in the fall and secondary tillage just prior to planting with a cultivator or tandem disk.

The effectiveness of a conservation tillage system in reducing soil erosion and water runoff is proportional to surface residue cover. Reduced tillage can also increase soil structural stability in the surface of the topsoil, which makes the soil less susceptible to erosion. The increased soil structural stability is associated with increased organic matter levels in the 15-cm topsoil surface layer.

Reduced tillage systems can sometimes result in yield reductions, particularly on fine-textured soils. Long-term studies in Ontario have shown that yields of continuous corn were 11% lower when planted without tillage compared to fall moldboard plowing. Yields did not differ, however, when corn followed corn on well-drained gravely loam soils or following alfalfa/timothy sod mixtures. Reductions in grain yield associated with no-tillage were not the result of inadequate fertility, inadequate weed control, improper planter adjustment, soil moisture, or soil temperature. Relatively poor no-till corn performance in drier growing seasons, despite the higher soil-moisture content in no-till systems, suggests that changes in soil structure inhibited corn root growth.

Yield reductions in no-till compared to conventional tillage systems can sometimes be eliminated by modifying the no-till system. Planting corn in a roto-tilled zone that was only 8 cm deep x 30 cm wide, i.e., strip tillage, or clearing a 15-cm band of corn residue from the row area using planter-mounted disc furrowers, could, on occasion, result in corn yields that were similar to spring moldboard plowing. Alternatively, corn can be planted on ridges that have been formed in an otherwise no-till system (i.e., ridge-till planting system). Research in southern Ontario has indicated that a ridge planting system in which the ridge top is disturbed by some type of strip tillage resulted in increased corn yield in comparison with zero till, but yields were still lower than under conventional tillage. It has been suggested that ridge-till systems will be restricted to the warmer regions of Ontario, due to soybean yield reductions with wide row spacings in cooler regions and the unsuitability of cereals and forages for the ridge-till system.

A chisel plow tillage system leaves more crop residue on the soil surface than moldboard plowing, but less than under no-till. Corn yields after chisel plowing are often higher than those after no-tillage and similar to yields after moldboard plowing, although results are highly dependent on soil type and the preceding year's crop.

In conclusion, a growing awareness of soil erosion and deterioration of soil structure association with conventional tillage has led to increased adoption of reduced-tillage systems by corn producers. It has been estimated that conservation tillage will be used on 50% of the corn area in Ontario by the year 2000. Selection of a single conservation tillage system is difficult due to the diversity of crops and soil types. However, few situations exist in which a properly managed reduced-tillage system cannot ensure agronomically acceptable yields.

II. CROP ROTATIONS

Whereas continuous corn was predominant in Ontario during the 1960s and 1970s, a survey in 1990 showed that some form of crop rotation was used for 47% of the area planted to corn in Ontario. Crop rotation may result in increased soil structural stability in comparison with continuous corn, improved pest control, and provide residual nitrogen from legume crops. Biomass productivity of corn is higher than that of any other crop and, consequently, more organic matter is returned to the soil in grain corn production than in the production of other crops. However, soil structural stability is not only a function of total organic matter content but is also a function of the composition of the organic matter. While some parts of the organic matter are very stable, the active fraction or organic matter is important in holding soil aggregates together. This fraction is largely based on the roots, exudates from roots, and microbial activity associated with the soil organic matter. The structural stabilities of two soils may differ even if the soils don't differ in texture and organic matter content, due to differences in the quality of the soil organic matter. Quality of the soil organic matter varies among crops.

Research in Ontario has shown that soil structural stability was generally highest with continuous alfalfa and corn that is grown for the first year following alfalfa or winter wheat plus red clover. Barley or winter wheat without red clover (in rotation with corn) seldom resulted in improvement in soil stability. In contrast, structural stability after two years of soybeans was lower than that following grain corn. Factors like the fineness, distribution, composition, and quantity of roots as well as the quality of the root exudate and the microbes involved in the decomposition of the crop residue may be involved in the effect of crops on structural stability.

The effects of crops on soil structural stability, however, vary among soil types, tillage methods, and climatic conditions. For instance, a 28-yr tillage experiment in Ohio on a silt loam soil showed that rotation treatments (continuous corn, corn-soybean rotation, and corn-oat-meadow rotation) had not effect on soil aggregate size. Surprisingly, soil bulk densities increased from 1.18 in continous corn to 1.28 in the corn-oat-meadow rotation and soil organic content declined, accordingly, from a relative value of 100 in continuous corn to 63 in the corn-oat-meadow rotation. There was, however, a significant interaction for organic content between rotation and tillage treatments. Within the no-till system, for instance, the highest level of organic content was for continuous corn. In contrast, the highest level of organic content for the chisel-plowing system was in the corn-soybean rotation, and for the moldboard-plow system was in the corn-oat-meadow rotation.

Crop rotations vs. continuous corn can have beneficial effects on yield in addition to increased soil structural stability. Crop rotation may reduce the risks of crop diseases and insects, such as corn root worm, and may provide residual nitrogen from a preceding legume crop. Ontario research has shown that corn grown in rotation with crops such as barley, winter wheat, soybeans, and alfalfa yields higher than continuous corn. Vyn (1987) reported that the yield difference between corn in rotation with other crops and continuous corn was 6 to 8% on a loam soil, 8 to 12% on a silt loam soil, and 6 to 8% on a clay loam soil. Rotating corn with soybeans and winter wheat increased both moldboard- and chisel-plowed corn yields relative to continuous corn, but highest yields were obtained following underseeded red clover at a silt-loam soil near Elora (Fig. 4.1). Corn yields following wheat plus clover were 4% higher compared to those after wheat alone. Similarly, underseeding red clover in wheat increased corn yields at a silt-loam soil at Chatham and a clay-loam soil at Maidstone (Fig. 4.2). The use of legumes in the rotation increased corn yields even at high nitrogen rates.

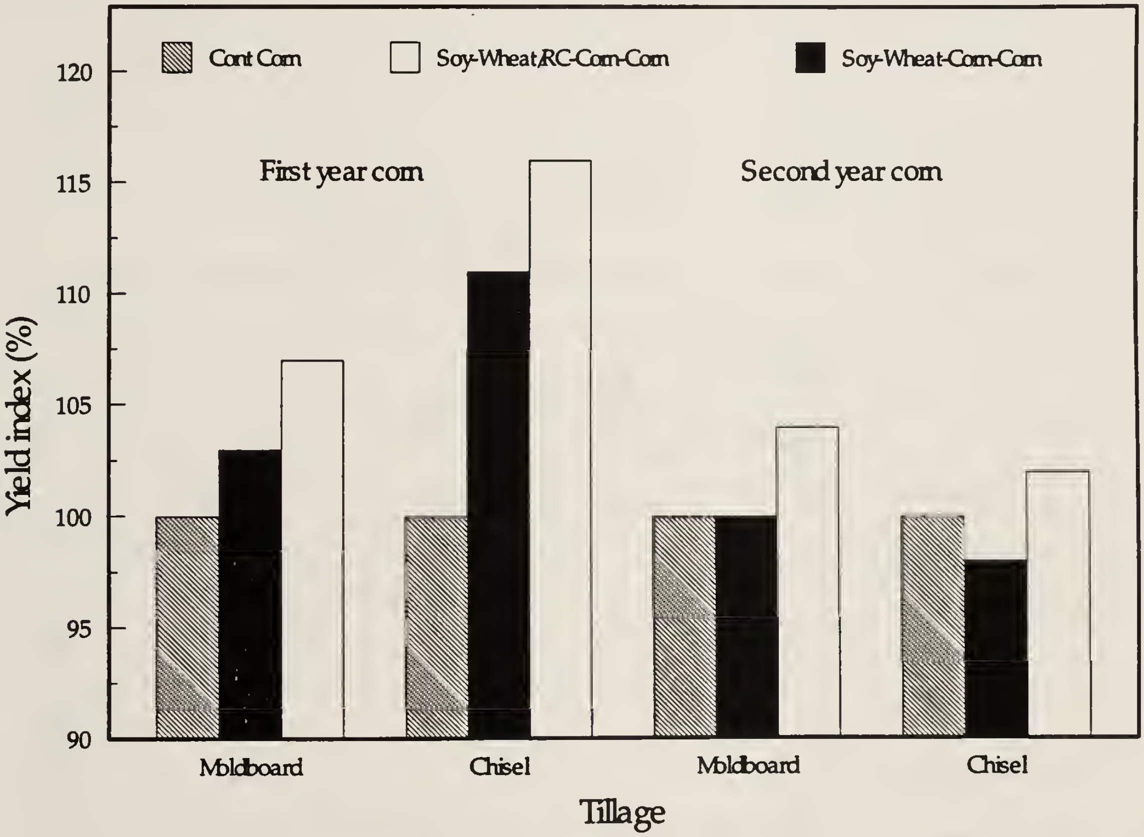
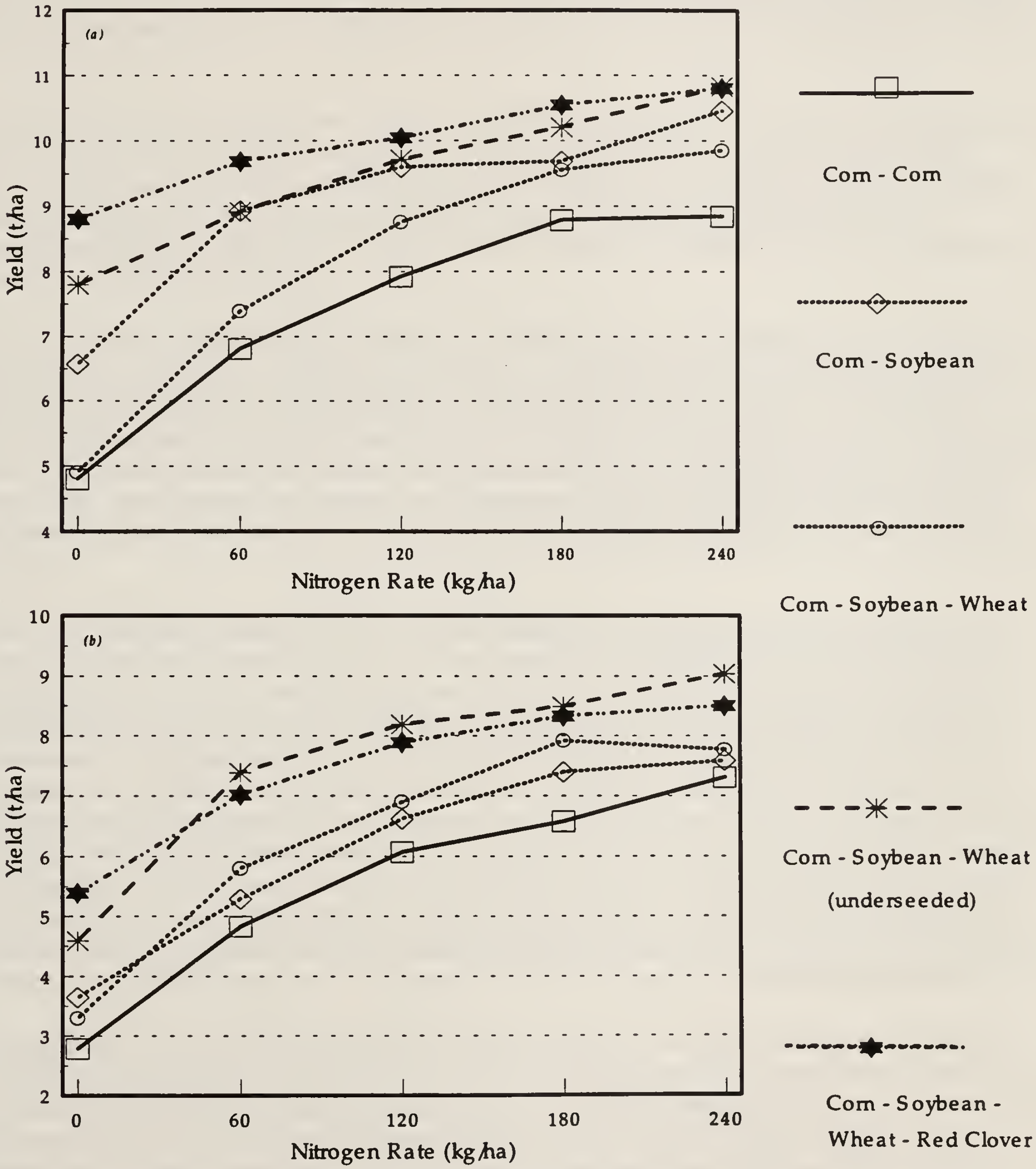


Fig. 4.1 Average first year (1990-92) and second year (1991-93) corn yields expressed as a percentage of continuous corn on a silt loam soil at Elora, Ontario. (Janovicek and Vyn, 1994)

In summary, rotating corn in a two or multiple year cycle with other crops may increase the soil structural stability and reduce erosion rates, and generally results in increased corn yield. Generalizations for best management practices are difficult to formulate because

Fig. 4.2 Effects of crop rotation and nitrogen fertilization on corn yields at Chatham (a) and Maidstone (b) during 1990-93 (Young, 1994)



results are highly dependent on soil type, tillage method, and climatic conditions.

III. COVER CROPS

Several potential advantages may accrue from cover crops grown in sequence with continuous corn or crop rotations including corn. Cover crops may reduce late fall and early spring soil erosion and improve soil structure (i.e., improve water penetration and retention and increase soil organic matter). Cover crops have also been used to cycle nitrogen, either by leguminous crops that fix atmospheric nitrogen or by crops that capture soil nitrates remaining after corn harvest in the fall which may be otherwise lost by leaching. In addition, there has recently been interest in the role of cover crops in suppressing weeds in conservation tillage.

Although the primary benefit in erosion control from overwinter cover crops is reduced wind erosion, in particular on sandy soils, cover crops may also reduce water erosion. The erosion-control benefits are most likely when cover crops are used following low residue-producing crops such as silage corn and soybeans. Little, if any, additional erosion protection is likely to ensue from cover crops following a high residue producing grain-corn crop under conservation tillage.

Little is known about the nitrogen benefits of various cover crops. Red clover is known to be capable of supplying a substantial proportion of the nitrogen requirements of corn (see Fig. 4.1). Red clover that is underseeded in cereal crops may be left to overwinter and killed with herbicides in the spring before corn planting. Alternatively, annual and perennial grasses and oilseed radish can absorb soil nitrates in the fall. Although the total nitrogen content of the cover crop may appear to be important, the optimum nitrogen rates after short-term legume or cereal cover crops seem to have little relationship to total nitrogen in the residue.

Besides the potential benefits of cover crops, research in Ontario has shown that cover crop can also have detrimental effects on corn yield. Corn yields were reduced by 10 to 20% after a rye cover crop and maturity was also delayed (Table 4.1). The reduction in corn-silage was most evident with zero tillage. Tillage prior to corn planting reduced the adverse effect of the rye cover crop on corn yield but additional nitrogen application, to compensate for possible nitrogen immobilization by the rye residue, did not improve corn yields. Removal of rye residue out of the row area increased corn yield in comparison with zero till but the most effective cover-crop management was to kill the rye at least 2 weeks before planting corn. It is not clear yet whether early rye kill is beneficial because of lower rye biomass or because a delay allows some decomposition and leaching of allelopathic chemicals in the rye residue. Another potential problem associated with zero-till planting of corn into rye residue is armyworm infestation, which may require insecticide application.

Corn yields were sometimes reduced after direct-seeded red clover cover crop. Yields of zero-till corn after spring chemical kill of red clover were generally similar to yields of corn after moldboard or chisel plowing in the fall (Table 4.2). In some years, however, corn plant density was 35 to 44% lower in the zero-till treatment (Table 4.2, 1986), which was associated with insect damage to corn plants after emergence. Slugs seem to do more damage to zero-till corn after red clover than after other crops. Potato stem borer may also reduce the corn plant density if grassy weeds or cereals are also present.

In conclusion, the use of cover crops in corn production has several potential benefits, but cover crops must be managed in such a way that there is not a detrimental effect on the corn crop. More research is needed on alternative cover-crop species, establishment methods, weed, and soil fertility to refine recommendations to corn producers.

Table 4.1 Corn-silage yield (dry matter) and percent moisture at harvest for rye and tillage treatments at Elora (mean of three corn planting dates in 1982 to 1984) and Woodstock (mean of 1982 to 1984) (Tollenaar et al., 1992).

Treatment	Silage yield (t/ha)		Silage moisture (%)	
	Elora	Woodstock	Elora	Woodstock
No rye/rototill	13.6	15.0	67.0	67.1
Rye/rototill	12.4	13.5	67.1	68.3
Rye/no-till	10.3	12.9	69.9	68.8

Table 4.2 Effect of various tillage options after direct seeded red clover on corn grain yield for a loam soil and a clay loam soil near Woodstock (Vyn, 1987).

Tillage Treatment	Loam soil			Clay loam soil	
	1984	1985	1986	1985	1986
Fall moldboard plow	9.8	9.4	7.7	9.4	8.8
Fall chisel plow	9.7	9.2	7.7	9.2	8.4
Zero tillage	9.8	9.4	4.0	8.8	6.7

5. UTILIZATION

Corn is one of the most efficient plants in harvesting solar energy, i.e., converting solar energy into starch, and corn places the starch in an easily stored and transportable package, the corn kernel. The main use of corn is as an animal feed (approximately 65% of corn production in Ontario), but corn is also increasingly used as a source of industrial products (approximately 22% of corn production in Ontario). Corn is used in numerous food and industrial products (Table 5.1): of 10,000 items in a typical grocery store, at least 2,500 items use corn in some form during the production or processing. The utilization of corn for industrial processing has increased substantially during the past decade which is associated with the introduction of High Fluctose Corn Syrup (HFCS) and the use of corn-derived ethanol in gasoline. Future uses of corn may include the use of corn kernels to produce and store completely different compounds, such as pharmaceuticals and industrial chemicals.

Corn is a seed, containing an embryo, endosperm, and a seed coat (pericarp). The major component of corn is starch, of which 98% is in the endosperm (Table 5.2). Starch consists of two types, amylose (about 27%) and amylopectin (about 73%) in "normal" corn. The ratio of amylose and amylopectin in endosperm starch may vary in mutants, such as in waxy corn (100% amylopectin) and high amylose corn (50 to 70% amylose). Protein represents about 9% of the corn kernel and is of generally low biological value because it does not supply the essential amino acids either in adequate quantities or in adequate proportions. An exception is the mutant *opaque*-2 corn, which has higher contents of lysine and tryptophan compared to "normal" corn. Yields of *opaque*-2 hybrids, however, are only 80 to 90% of those of normal corn. Oil comprises nearly 5% of the corn kernel. The relatively high degree of unsaturation of corn oil is a desirable attribute in human nutrition, although unsaturation is not desirable for swine feeding. The "unaccounted" fraction in Table 5.2 is predominately fibre.

Table 5.1 A selection of food and industrial product that use corn in some form during the production or processing. Source: Ontario Corn Producers' Association.

Adhesives (glues, pastes, mucilages, gums, etc.)
Aluminum
Asbestos Insulation
Aspirin
Automobiles (Everything on Wheels)
- cylinder heads
- gasoline (fuel ethanol)
- spark plugs
- synthetic rubber finishes
- tires

Baby Food
Batteries, Dry Cell
Beer
Board (corrugating, laminating,

Fructose
Gypsum Wallboard
Ink for Stamping Prices in Stores
Insecticides
Instant Coffee & Tea
Insulation, Fibre Glass
Jams, jellies and preserves
Ketchup
Latex Paint
Leather Tanning
Licorice
Livestock Feed
Malted Products
Margarine
Mayonnaise

cardboard)
Breakfast Cereals
Candies
Canned Vegetables
Carbonated Beverages
Cheese Spreads
Chewing Gum
Chocolate Products
Coatings on wood, paper & metal
Colour Carrier in Paper & Textile Printing
Corn Meal
Cosmetics
C.M.A. (calcium magnesium acetate)
Crayon and Chalk
Degradable Plastics
Dessert Powders
Disposable Diapers
Dyes
Edible Oil
Ethyl and Butyl Alcohol
Explosives - firecrackers
Finished Leather
Flour & Grits
Frozen Foods
Mustard, prepared
Paper Manufacturing
Paper Plates & Cups
Peanut Butter
Pharmaceuticals - The Life Line of The Hospital
  - antibiotics
  -IVs (Dextrose)
  - penicillin
Potato Chips
Rugs
Salad Dressings
Shaving Cream & Lotions
Shoe Polish
Soaps and Cleaners
Soft Drinks
Starch & glucose (over 40 types)
Syrup
Textiles
Toothpaste
Wallpaper
Wheat Bread
Whiskey
Yogurts

Table 5.2 Weight and composition of component parts of dent corn kernels from seven Corn-Belt hybrids, dry weight basis (Watson, 1987).

Composition	Endosperm		Germ		Pericarp		Whole kernel	
				%				
Proportion of whole kernel	83	(82-84)	11	(10-12)	5.3	(5.1-5.7)	100	
Starch	8.8	(86-89)	8.3	(5.1-10.0)	7.3	(3.5-10.4)	73	(68-74)
Fat	0.8	(0.7-1.0)	33	(31-35)	1.0	(0.7-1.2)	4.4	(3.9-5.8)
Protein	8.0	(6.9-10.4)	18	(17-19)	3.7	(2.9-3.9)	9.1	(8.1-11.5)
Ash	0.3	(0.2-0.5)	10.5	(9.9-11.3)	0.8	(0.4-1.0)	1.4	(1.4-1.5)
Sugar	0.6	(0.5-0.8)	11	(10-13)	0.3	(0.2-0.4)	1.9	(1.6-2.2)
Unaccounted	2.7		8.8		87		9.8	

I. LIVESTOCK FEED

A. Grain Corn

Corn is one of the most concentrated sources of energy because of its high starch and low fibre content. Since corn is predominantly an energy-type feed, it must be supplemented with protein, minerals, and vitamins for swine. The typical swine diet consists of up to 85% corn, with soybean meal as a source of protein, plus minerals and vitamins. Corn fed to swine is crushed or ground finely to facilitate mixing with other ingredients, although corn processing does not improve the nutritional value of corn for swine. Similarly, corn is the predominant grain fed to poultry and processing does not appear to improve its nutritional value. Corn is also the number one grain for feeding beef cattle. Beef cattle benefit more from the processing of corn than any other farm livestock. High-moisture corn, i.e., corn containing 25 to 28% moisture, is one of the simplest methods of processing corn to achieve greater utilization by cattle. Corn is fed to dairy cattle because of its high energy, but some fibrous feeds are added to make it more bulky to obtain a preferred grain mix for dairy cows of approximately 480 g/L.

B. Silage Corn

Whole-plant corn silage will surpass all other forage crops in average yield of dry matter and of digestible nutrients per ha. U.S. studies (Perry, 1988) have shown that maximum yields of both dry matter and digestible dry matter are obtained when the whole plant contained 33 to 53% dry matter. A normal range of pH (3.8+) was obtained when the plant contained from 28 to 53% dry matter. Digestibility of the dry matter was not affected by the stage at which the corn plant was harvested. However, the pH of the silage increased with increasing dry matter content and a higher pH (>6) indicates less fermentation and, hence, increased risk of spoilage. In an Ontario study (Daynard and Hunter, 1975), maximum dry matter yield was obtained at whole-plant moisture content of 66 to 70% and a grain moisture content of 45 to 50%. Whole-plant dry matter digestibility was essentially constant over a range of whole-plant moisture from 76 to 56% in one year and from 76 to 64% in another year.

Whole-plant corn silage is an excellent feed for dairy and beef cattle. A dairy cow lactation diet will contain 2% of the cow's body weight daily as air-dry (90% dry matter) hay equivalent plus concentrates to meet total nutrient requirements. Since corn silage may contain only one third dry matter, 3% of the cow's body weight may be fed as silage, plus 1% of the body weight as hay. Corn silage is a good roughage for wintering beef cows, although beef cows tend to get too fat unless the amount of corn silage given is limited.

II. FOOD AND INDUSTRIAL PRODUCTS

A. Dry Milling

Dry milling produces corn endosperm in a range of particle sizes after removal of the germ and hull: corn grits, corn meal, and corn flour. Separation of the components is achieved by mechanical grinding, in contrast to enzymatic conversion in wet milling. High quality corn is required by the dry-milling industry. Corn suitable for dry milling must have a high degree of hardness, which is closely correlated to kernel density (i.e., test weight), and low susceptibility for breakage. Harvest at relatively low grain-moisture content (20 to 25%) and low-temperature drying reduce kernel stress cracking, thereby reducing risk of kernel breakage.

Currently, there are two main dry millers operating in Ontario. KELLOG (London) uses about 90,000 t corn to manufacture grits for flaking (corn flakes) and KING MILLING (Chatham) uses about 30,000 t corn to produce grits, corn meal, and corn flour.

a. *The process*

The corn is first dry cleaned, which includes magnetic separators to remove tramp metal, aspiration to remove fines and pieces of cobs, and screening to remove broken kernels. After wet cleaning to remove dirt and dust, the corn is adjusted to about 20% moisture and placed in a tempering bin.

The product is subsequently processed in a degerminator, in which the bran or pericarp and germ are stripped from the endosperm. The fraction of large pieces of endosperm are dried, cooled, and sifted, and part of it is isolated as large flaking grits. The remainder of the endosperm is milled into smaller fractions, which are separated by sifting operations into grits, meals, and flours. The bran and germ fraction is separated into bran and germ.

b. *Products and uses*

A typical yield of products from dry milling is 60% grits, meal, and flour, and 30% hominy feed (Watson, 1988). Hominy feed is a commodity feed consisting of the germ residue blended with pericarp fractions, inseparable mixtures of endosperm, pericarp and germ, and corn cleanings. The main uses of dry-milling products are in brewing, food, non-food, and animal feed. Estimates for the proportion of these uses in the US in 1977 (Alexander, 1987) are 30, 18, 9, and 36%, respectively. Food uses include breakfast cereals, pancake mixes, baking, and snack foods. Non-food uses include gypsum board and pharmaceuticals/ fermentation. Hominy feed is used as an ingredient of pig, ruminant, and poultry feeds as a source of energy and good-quality protein. Recent developments in product volume suggest that increases in certain food applications (i.e., fast-food and Mexican-food restaurants) have been offset by decreases in brewing.

B. **Wet Milling**

The principal aim of the wet-milling process is the manufacture of pure corn starch and various products derived from corn starch. The remaining components of the kernel (protein, oil, and fibre) are primarily used for corn oil and feed production. In wet milling, shelled corn (on a dry weight basis) is converted into starch (66%), oil (4%), corn gluten feed (24%), and corn gluten meal (6%).

The raw material for wet milling is shelled corn that is free from aflatoxin, insect, and rodent infestation. Highest yield of endproducts is obtained from corn which is mature and which has not been heat-damaged during drying. Wet corn can be delivered at harvest directly to the wet-milling plant, however, problems occur if corn spoils or ensiles before delivery. Specialty corn, waxy and high-amylose corn, are purchased by identity-preserved contracts.

Two wet millers operate in Ontario, CASCO with three plants uses about 800,000 t shelled corn per year and NACAN with one plant uses about 125,000 t annually.

a. *The process*

Corn is first cleaned by screening and aspiration. Broken kernels must be screened out because they will otherwise release their starch contents into the steepwater prematurely, causing a number of processing problems. Cleanings are added to the by-product feed. The clean corn is then steeped for 30 to 35 h in warm water to soften it for the initial milling step. Coarse grinding releases the germ which is separated by flotation. The germ is washed and dried for oil recovery. After screening, the remaining coarse particles are more finely milled to release the rest of the starch. After removal of the coarser hull particles the remaining fine suspension of starch and gluten (protein) is run into high speed centrifugal machines where the heavier starch is separated from the lighter gluten particles. The starch slurry must be further purified to a final protein content of about 0.3% by diluting the starch slurry with fresh water and passing it through a series of liquid cyclones. The starch has now been completely separated from the other kernel constituents and is ready for drying or conversion into corn sweeteners. Approximately 99% of the initial corn is recovered as a useful product.

b. *Starch*

The primary product of wet milling is starch. It is recovered in purified form in a yield of 67 to 69% of dry corn (i.e., an efficiency of 92 to 96%). Nearly one quarter of the corn starch produced in the US is sold as starch products: unmodified starch, acid-modified starch, dextrins, oxidized starch, cross-link starch, chemical derivations of starch, and pregelatinized starch. Unmodified starch is the product with the largest volume. Major users of starches are the paper and paper product, textile, foundry, ore refining, fermentation, oil well drilling, and food industries.

c. *Refinery products*

A substantial amount of starch is directly converted to the sweetener products, dextrose, corn syrups, and high fluctose corn syrup (HFCS). The largest single use of dextrose is in baked goods. Other uses of dextrose are as sweeteners in food products such as candies, ice creams, jams, etc., and as the carbohydrate source for the production of sorbitol, Vitamin C, antibiotics, etc. The largest uses of corn syrup are in confections, bakery, and dairy products.

The main sweetener product is high fluctose corn syrup (HFCS). HFCS 42 is a corn syrup composed of 42% fructose and 58% glucose that is made by reacting fully converted starch hydrolysate with the enzyme glucose isomerase. The fructose fraction can be increased to 90% (HFCS 90), which in turn can be blended with HFCS 42 to produce 55% fructose syrup (HFCS 55). The higher the fructose percentage, the sweeter the product. HFCS 55 has about the same sweetness as sucrose, and HFCS 90 is 6% sweeter than sucrose. The sweetness perception of fructose is, however, affected by temperature, pH, and concentration. HFCS 42 is used extensively in the manufacture of jams, jellies, and related food products. HFCS 55 is used in soft drinks and HFCS 90 is used in low-calorie food products.

d. *Corn oil*

Corn oil is produced from corn germ isolated by wet milling or dry milling. Refined corn oil is 98% triglycerides, with 13% saturated fatty acids (palmitic, stearic, and arachidic) and 87% unsaturated fatty acids (linoleic, oleic, and linolenic). The ratio of the two principal fatty acids, linoleic (18:2) and oleic (18:1), has changed from 56 to 30% to 61 and 25% over the last 40 years in US corn, whereas the oil content dropped from 4.9 to 4.3% during this same period. A reason for the popularity of corn oil is its high content of unsaturated fatty acids which is associated lower blood cholesterol levels.

e. *By-products and animal feed*

The products remaining after recovery of the corn starch and corn oil amount to approximately 30% of the processed shelled corn. The fraction containing the pericarp is composed mainly of cellulose and hemicellulose plus residual starch and protein. Most of this fraction is blended with steepwater and spent corn germ flakes and dried to 10% moisture content to produce corn gluten feed. Corn gluten feed is used as a beef and dairy cattle feed where it is valued for its "by-pass protein" property, which tends to make it more valuable for ruminant animals, compared to other protein supplements on a per protein-percentage basis.

Corn gluten meal is extracted from the corn germ. Corn gluten meal is used in poultry feed production for its high protein percentage, its low fibre content, and its intensive yellow pigmentation.

C. **Ethanol**

Although fermentation of cereal grains for beverage alcohol is a very old industry, the development of a corn-based fuel alcohol industry is a relatively recent phenomenon in the US and is only an emerging industry in Ontario. Ethanol is sold as an automobile fuel in the form of "gasohol", gasoline containing a maximum of 10% absolute ethanol. The use of gasohol is subsidized by governments in North America for socio-economic and environmental reasons, through an exemption of part of the gasoline tax. Ethanol is a renewable fuel, reduces CO_2 emissions in the atmosphere, carbon monoxide and ozone-forming emissions from automobile exhausts, and is an anti-knock replacement for lead in gasoline. The replacement of a fraction of gasoline by ethanol reduces petroleum imports and/or avoids some of the capital and environmental costs associated with fossil fuel exploration, extraction, and transportation. Finally, the development of a fuel-ethanol industry opens new domestic markets for grain and value-added by-products and helps to diversify the economic base of the rural sector. An analysis of the beneficial effects of fuel-ethanol in terms of energy efficiency and CO_2 emission is, however, complicated by the variability in energy input/output ratios for corn production, corn processing, and ethanol production.

Approximately 100,000 to 200,000 t of corn are used by two distillers in Ontario to produce beverage alcohol. At present, the entire Canadian production of fuel-grade ethanol is just under 50 million litres per year, but Commercial Alcohols Inc. (CAI) will construct a 200-million litre per year facility at Chatham, Ontario with operations to begin in 1996. At full capacity, this plant could process approximately 500,000 t (20 million bushels) corn annually.

a. *The process*

Starch is the major component of corn that is convertible to alcohol. Wet milling and dry milling are used to concentrate the starch component of corn (see Figs. 5.1 and 5.2). Dry milling produces a substrate of about 80% starch, whereas wet milling produces purified starch that is almost completely convertible to ethanol. Dry-milling and wet-milling by-products such as corn screenings and crude corn fibre can also be used as low-cost substrates for fuel alcohol. The yield of ethanol from crude corn fibre can be increased by adding cellulose and pectinase preparations to the substrate in the fermenter (Maisch, 1987).

b. *Products and by-products*

As a rule of thumb, yield of the alcohol-distillation process is ⅓ ethanol, ⅓ CO_2, and ⅓ feed by-products. Theoretical and experimental ethanol-yield efficiencies are depicted in Table 5.3. Typically, 1 kg corn yields 0.394 L ethanol (or, 1 bushel yields 10 L ethanol). Because flavour is not important in fuel-ethanol production, lower quality corn can be used, starch conversion can be conducted with lower cost commercial enzymes, and distillation can be done at higher efficiencies in the process of fuel-ethanol production. New ethanol process and fermentation technologies are being developed that have the potential to increase ethanol conversion efficiency and economics. The feed by-products in the alcohol-distillation process constitute an important component in the overall economics of fuel-ethanol production. The major distiller's feeds produced are dried distiller's grains (DDG), distiller's dried solubles (DDS), and dried distiller's grains with solubles (DDGS). DDG contains 29% protein (dry weight basis) and is a good source of B vitamins, some of which have been produced by the yeast during fermentation. The mineral content of DDG is low because it does not contain solubles. In contrast, mineral content in DDGS is higher because solids from distiller's solubles are added to the DDG. These feed by-products of alcohol distillation are fed to ruminant animals (beef and dairy) and swine. Secondary uses for the by-products are as feed for poultry and fish, and as a component in pet foods.

Table 5.3 Calculation of ethanol yield efficiency

Theoretical yield:
1 kg starch x 1.11 (hydrolysis gain) = 1.11 kg Glucose
1.11 kg Glucose x 0.511 (ethanol factor) = 0.567 kg Ethanol
0.556 kg Ethanol ÷ 0.789 kg/L (ethanol density) = 0.719 L Ethanol
Experimental results (Maisch, 1988):
1 kg Starch → 0.514 kg Ethanol
Efficiency = 0.504 ÷ 0.567 = 88.9%
Corn yield (corn @ 15.5% moisture and 73% starch, dry weight basis):
1 kg Corn x 0.845 kg d.m./kg Corn x 0.73 kg Starch/kg d.m. = 0.617 kg Starch/kg Corn
0.617 kg Starch x 0.719 L Ethanol/kg Starch x 0.889 (efficiency) = 0.394 L Ethanol/kg Corn or 394 L/t
1 Bu Corn x 22.45 kg/Bu x 0.394 L Ethanol/kg Corn = 10.0 L. Ethanol/Bu

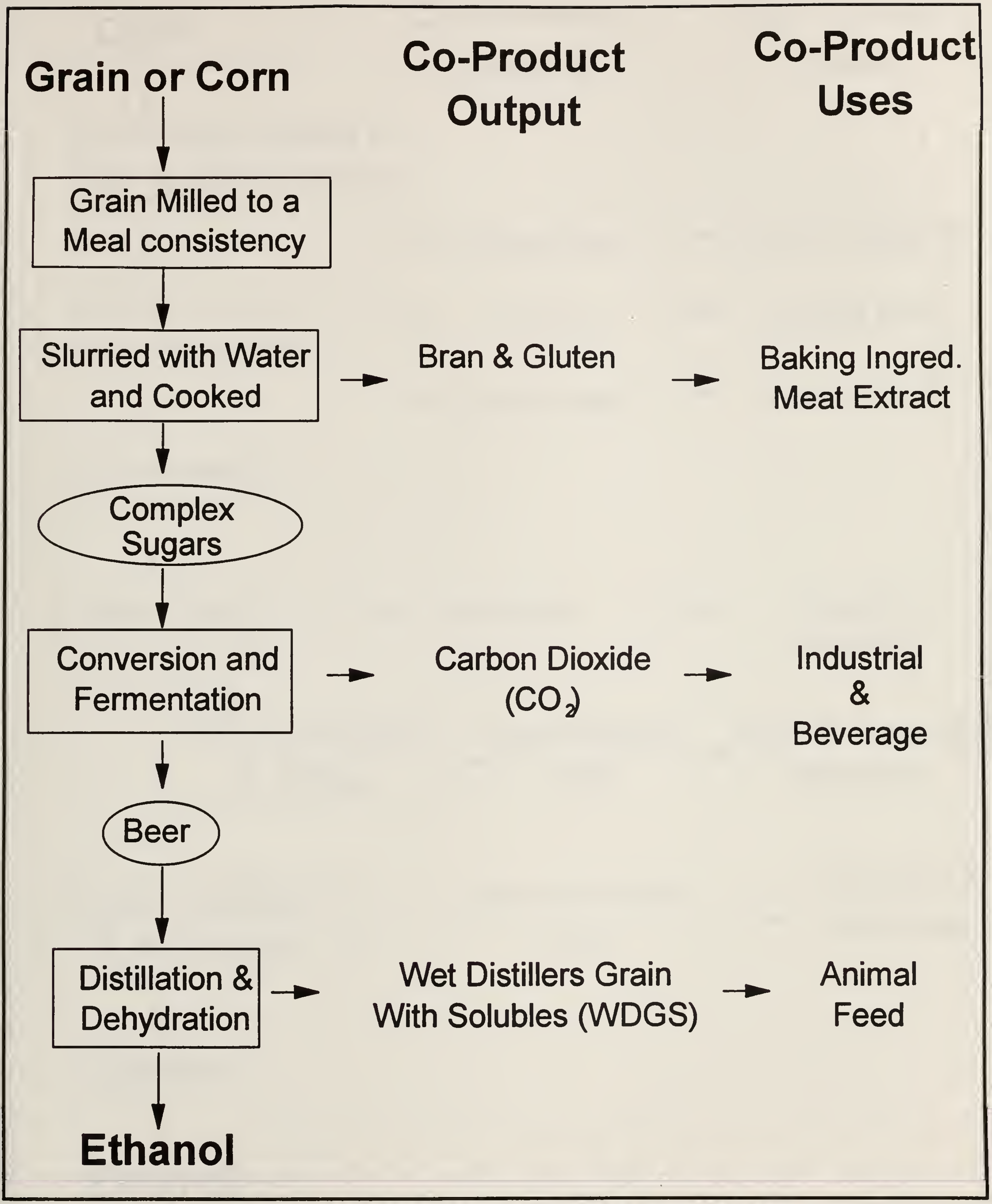


Figure 5.1 Conventional Dry Milling

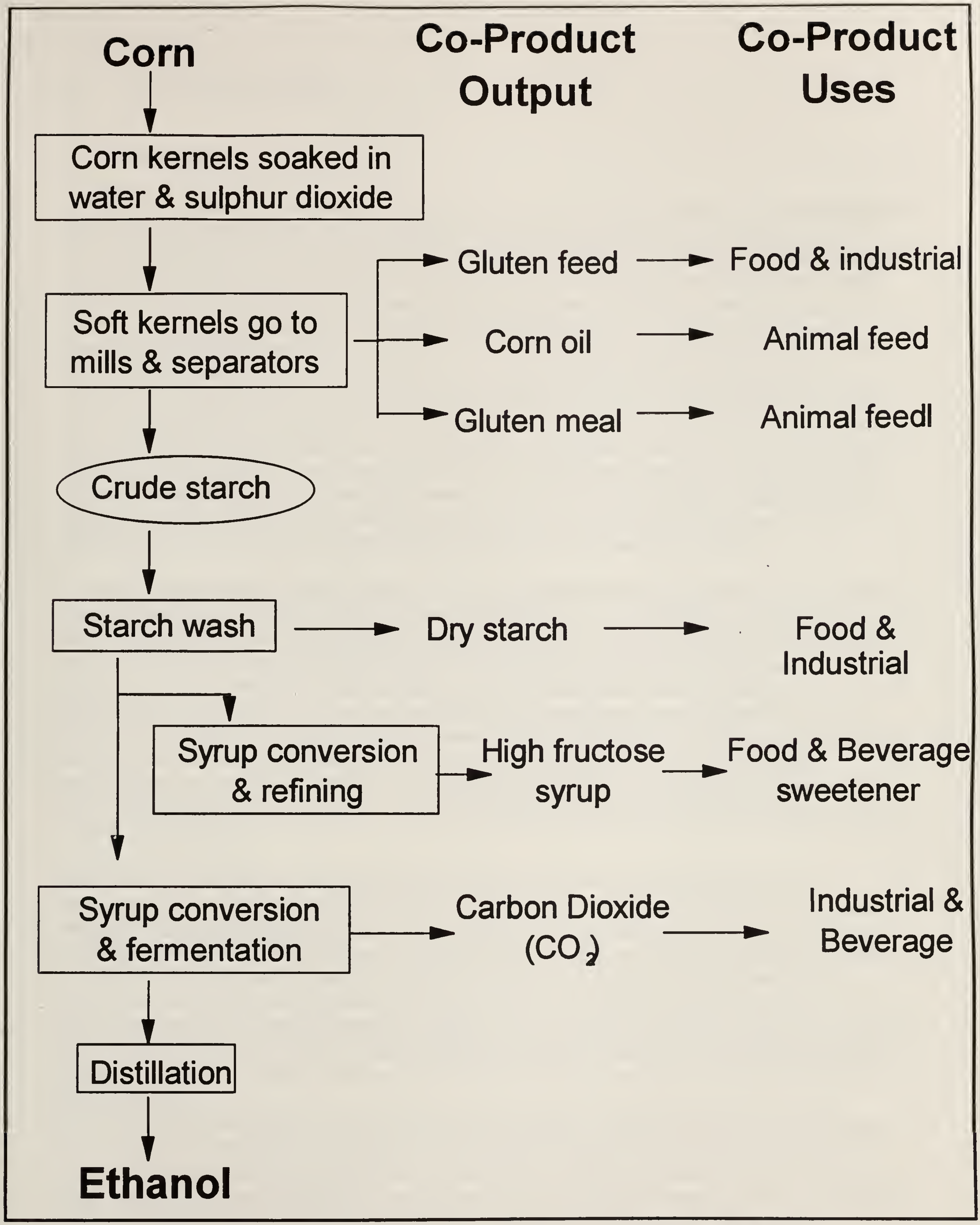


Figure 5.2 Conventional Wet Milling

6. SYSTEM ANALYSIS

I. ECONOMICS

Cost of corn production fluctuates with growing region, cultural practices, yield expectations and year-to-year variation in prices of inputs. OMAFRA prepares crop budgets annually based on price information gathered in surveys during the summer and fall of the previous year (OMAFRA Publication 60). Items tabulated for corn in this publication include seed, fertilizer, crop protectants, tractor and machine expenses, insurance, custom work, and interest on operating expenses. Total operating expenses for corn production were estimated to be $542/ha ($219.50/acre) in the 1994 cropping season. In addition, it was estimated that depreciation of machinery plus the interest on the investment of the machinery totalled $114.20/ha ($46.25/acre), resulting in a total cost of $656.20/ha. The average yield and price of grain corn in Ontario in 1994 (OMAFRA Publication 20) were 7.56 t/ha (120.6 bu/acre) and $118 /t ($3.00/bu), respectively, resulting in a gross income of $892.08/ha. Capital costs allowance for land and buildings, and land rental, and costs for grain storage, drying, and trucking were not included in the OMAFRA budget for corn. Consequently, the difference between estimated gross income and cost of production ($235.88/ha) was not the net income derived from corn production in 1994.

A more rigorous estimate of the cost of corn production has been presented by Mr. Brian Doidge, Ridgetown College of Agricultural Technology, who compiled cost for production of corn using the 1993 and 1994 tax year of the Ontario Data Analysis Project Whole Farm Survey of 30 cash crop farms (Epp, 1996). The financial and production records of 22 cash crop farms were surveyed in Essex, Kent, Lambton, and Middlesex counties in Southwestern Ontario. Only commercial scale farm operations were used in this survey (Table 6.1a), but it was suggested that these costs of production estimates can be taken as the average cost to produce corn because large commercial farms account for an inordinate proportion of the grain corn sold. It should also be noted that data depicted in Table 6.1b are means across farms and do necessarily represent costs for individual farms (e.g., land drainage).

Data in Table 6.1b show that approximately 50% of the cost of corn production is associated with labor and field operations, and the other 50% is associated with financial outlays for land, buildings, repairs, and insurance. Total operating expenses (i.e., labor, field operations, and miscellaneous) averaged across 1993 and 1994 were $566/ha which is similar to the $542 estimated for 1994 in OMAFRA Publication 60. Fertilizer costs comprised about 30% of the operating expenses, with N fertilizer contributing about 70 to 75% of the fertilizer costs (OMAFRA, Publication 60). Crop protectant and seed costs each made up about 15% of the operating expenses and labor was about 10% of the operating expenses. Herbicide costs constitute about 70% of the crop protectant total (OMAFRA Publication 60).

The cost of corn production in the US Corn Belt is similar to that in Ontario. Crop budgets for corn production in Illinois, intended to be used through 1996 (Newton et al., 1995), show that the average corn production cost in Illinois is $3.53/bu (assuming CDN $ = 0.73 US $), which is almost identical to cost of production in Ontario averaged across 1993 and 1994 in Table 6.1b (i.e., $3.49/bu). The Illinois crop budget estimated cost of corn production for continuous corn and for corn after soybeans, and for three tillage practices (clean till, mulch till, and zero till). Estimated cost of production was $0.40/bu lower for corn after soybeans than for continuous corn and $0.15 to $0.20/bu lower for zero till than for clean till or mulch till. Total costs for continuous corn production, clean till, in Northern/Central Illinois was estimated at $1342/ha, with proportionally slightly higher land costs and lower operating costs than in Ontairo (Fig. 6.1).

Table 6.1a. Description of farm operations used to estimate the cost of corn production. Data from the 1993 and 1994 tax year Ontario Data Analysis Project Whole Farm Survey in Essex, Kent, Lambton, and Middlesex Counties (ON), B. Doidge, Ridgetown College of Agricultural Technology, Ridgetown, ON.

Year	1993	1994
Number of farms	22	19
Acres worked per farm	804	871
Total acres owned	284	317
Total acres rented and sharecropped	321	354
Approximate corn acres owned	105	97
Approximate corn acres rented	120	108

Table 6.1b Cost of corn production for Essex, Kent, Lambton, and Middlesex Counties (ON) in 1993 and 1994 (Table 6.1a). Data from B. Doidge, Ridgetown College of Agricultural Technology.

Item	Cost of production		
	1993	1994	Mean
	----------- $/acre ---------		$/ha
Mortgage interest	20.50	22.48	53.06
Long-term debt principal	51.35	70.00	149.81
Rental payments	30.73	29.41	74.25
Land drainage	3.18	1.77	6.11
Total land costs	**105.76**	**123.66**	**283.23**
Capital cost allowance (CCA)	40.98	34.42	93.09
Machinery repairs	19.99	19.84	49.17
Building repairs	4.05	2.33	7.88
Total CCA and repairs	**65.02**	**56.59**	**150.14**
Insurance (theft, fire)	6.10	7.29	16.53
Crop insurance	9.38	7.71	21.10
GRIP premium	10.43	9.73	24.89
Total insurance	**25.91**	**24.73**	**62.52**
Owner/operator labor	4.00	13.04	21.04
Hired labor	0.68	4.85	6.83
Other family labor	22.61	2.88	31.47
Total labor	**27.29**	**20.77**	**59.34**
Fertilizer	55.80	75.85	162.53
Crop protectants	33.00	34.74	83.63
Seed	31.41	35.16	82.19
Storage and drying	19.70	27.06	57.73
Fuel, oil, etc.	10.91	16.75	34.15
Custom work	8.75	8.00	20.68
Propane	2.58	1.82	5.43

Item	Cost of production		
	1993	1994	Mean
Total field operations	**162.15**	**199.38**	**446.34**
Operating interest	7.49	8.81	20.12
Term interest	2.07	5.82	9.74
Other miscellaneous	2.97	22.15	31.01
Total miscellaneous	**12.53**	**36.78**	**60.87**
Total costs	398.66	461.91	1,062.44
Yield (bu/ac or t/ha)	122	125	7.74
Average cost ($/bu or $t/ha)	3.27	3.70	137.27

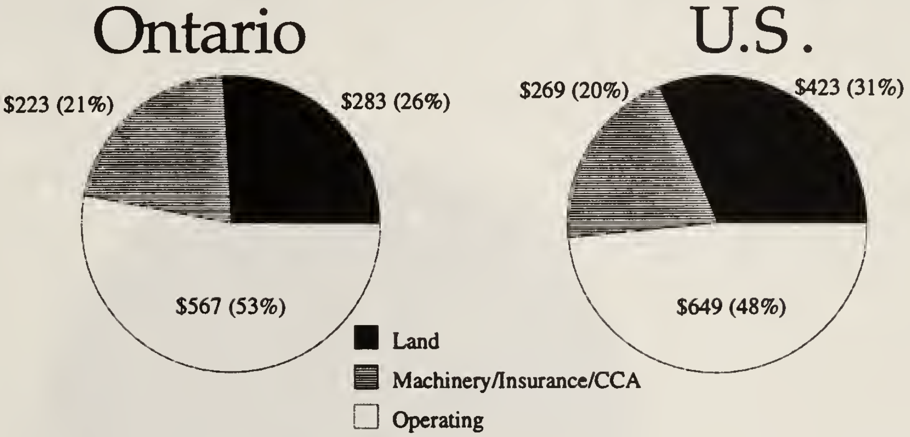


Figure 6.1. Distribution of costs of corn production in Ontario and Illinois among land, operation, and machinery/insurance/ CCA expenses.

II. ENERGY BALANCE

Corn is sometimes perceived as a crop whose production requires high inputs of fossil-fuel energy in the form of diesel fuel, fertilizers, and crop protectants. Moreover, it is often assumed that the more technologically advanced production systems, which have resulted in higher productivity, are associated with higher levels of energy input. In this analysis of energy inputs and outputs in corn production, the energy balance for a currently typical management scenario for corn production in Ontario is reviewed and past and future trends in energy inputs and outputs are considered.

The unit of energy used in this report is joules (J). Factors for the conversion of BTUs (British Thermal Units) and liters of diesel fuel equivalent (LDEF) to joules can be found in Appendix 1.

A. Energy Balance: present

Energy use for corn production, and the output/input ratio, varies significantly among growing regions, yields per ha, corn drying system utilized, etc. Coulter and Vyn (1992) estimated an energy input of 19.74 GJ (1 GJ = 10^9 J) per ha for the production of a 6.66-t/ha corn grain crop in Ontario in 1990 (i.e., average corn yield in Ontario from 1987 to 1991 was 6.66 t/ha). The three largest components in their estimate of energy input (Fig. 6.2) were fertilizers (54%), grain drying (26%), and field operations (10%). Swanton et al. (1996) estimated that the total energy input was 16.7 GJ/ha for corn grown at Elora, ON, from 1990 to 1992 with a mean yield of 8.8 t/ha. Energy-cost estimates per tonne of grain were 2.97 GJ in the Coulter and Vyn (1992) report and 1.90 GJ in the Swanton et al. (1996) study. However, the proportion of the various components of energy input were similar in both studies. Shapouri et al. (1995) reported a weighted average energy consumption per tonne of grain across the nine major corn producing states in the US of 2.29 GJ in 1991. Assuming that the heat of combustion of corn grain (@ 15.5% moisture) is 14.5 MJ/kg (Girardin, 1985) the output/input ratios were 4.9 in the Coulter and Vyn (1992) report, 7.6 in the Swanton et al. (1996) study, and 6.3 in the paper reported by Shapouri et al. (1995).

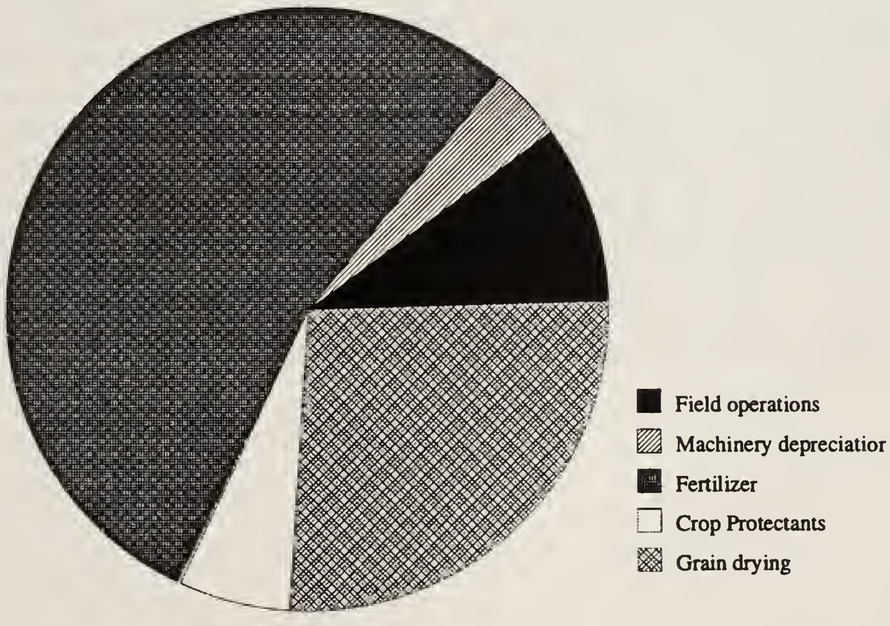


Figure 6.2. Energy input for the production of 6.66 t/ha of grain corn in Ontario in 1990; total energy input is 19.74 GJ/ha (Coulter and Vyn, 1992)

Fertilizer. The energy requirement for N fertilizer is the highest among the three major corn nutrients. The average application rate in Ontario in 1991 was estimated by Coulter and

Vyn (1992) as 115 kg N/ha, of which 47% was applied as urea, 29% as U.A.N. (a mixture of urea and ammonium nitrate), and 24% as anhydrous ammonia. Nitrogen fertilizer constitutes about 85% of the energy consumed in fertilizers for corn production (Table 6.2).

Table 6.2. Energy input for fertilizer production and transport for corn production in Ontario in 1991 (Coulter and Vyn, 1992).

Fertilizer	Frequency	Rate	Energy	Total
	%	kg/ha	GJ/t	GJ/ha
Nitrogen				
Urea	47	115	84.04	4.54
U.A.N.	29	115	80.11	2.67
Anhydrous	24	115	65.66	1.81
Total N				9.02
Phosphorus	100	47	15.29	0.72
Potassium	100	77	12.05	0.93
Total				10.67

Grain drying. Energy used in grain drying varies depending on grain moisture at harvest, desired final grain moisture, and type of drying system used. Grain moisture at harvest fluctuates with climatic conditions, i.e., heat unit accumulation during the growing season, and will tend to be higher in shorter-season than in longer-season regions. High-moisture corn is stored at moisture contents ranging from 25 to 32%, whereas storage of grain corn requires a moisture content of about 15.5%. Energy efficiency of corn drying depends on the initial moisture content of the grain and on the design of the dryers. On average, conventional cross-flow driers require 5.68 GJ to remove 1,000 kg of water, whereas batch-in-bin driers require only 4.04 GJ to remove the same amount (Table 6.3). If corn grain is harvested at 27% grain moisture, the amount of water to be removed to obtain 1 t of grain @ 15.5% moisture is 0.158 t (i.e., 0.845 t dry grain/0.73 x 0.27 - 0.155). At an average Ontario corn yield of 6.66 t/ha (@ 15.5% grain moisture), 1.05 t water will have to be removed and 5.15 GJ will be consumed (i.e., 1.05 t water x 4.91 GJ/t water).

Table 6.3. Average energy efficiency of driers and proportional use of driers in Ontario in 1991 (Coulter and Vyn, 1992).

Drier	Frequency	Energy	Total
	%	GJ/t water	
Conventional	60	5.68	3.41
Modified	25	4.04	1.01
Low temperature	10	3.36	0.34
Batch-in-bin	5	2.97	0.15
Total			4.91

Field Operations. The fall moldboard plow followed by a few passes of secondary tillage has been, traditionally, the dominant tillage system for corn production in Ontario. In 1990, about 80% of the area planted to corn was prepared with the moldboard plow, 15% with the chisel plow, 2% with a disc or cultivator in the spring, and 3% zero-till (Coulter and Vyn, 1992). Estimates of energy use in primary and secondary tillage are presented in Table 6.4. In addition, field operations include planting, crop protectant, and fertilizer applications.

Table 6.4. Energy used in primary and secondary tillage for corn production in Ontario as estimated by Coulter and Vyn (1992) and Clements et al. (1995).

Implement	Energy use estimated by:	
	Coulter and Vyn (1992)	Clements et al. (1995)
	MJ/ha	
Moldboard plow	555.2	557.1
Chisel plow	78.5	415.5
Disk	2.4	293.7
Cultivator	346.4	182.2
Interrow cultivator	80.8	161.9
Rotary hoe	—	130.8

B. Energy Balance: past and future

The output/input ratio for producing corn declined from 128.2 in primitive agriculture in Mexico, where the slash/burn technology required only the use of an axe and a hoe, to 2.47 for highly mechanized corn production, with fertilizers and crop protectants, in the US in 1975 (Pimentel and Burgess, 1980). However, estimates of the present energy efficiency of corn production range from 4.9 to 7.6, considerably higher than the estimate of 2.47 for 1975. Swanton et al. (1996) reported that the energy efficiency of corn production in Ontario doubled from 1975 to 1991 (Table 6.5). Corn yield and area of production increased during this period, but the total energy use for corn production in Ontario declined by 20%.

Table 6.5. Change in energy efficiency for grain corn production in Ontario from 1975 to 1991 (Swanton et al., 1996).

	1975	1991	% change
Energy use (GJ/ha)	19.35	11.67	-39.7
Crop area (10^6 ha)	0.575	0.766	+33.2
Total energy use (10^6 GJ)	11.13	8.94	-19.7
Total crop production (10^6 t)	3.32	5.31	+60.0
Energy efficiency (t/GJ)	0.298	0.594	+99.3
Crop yield (t/ha)	5.77	6.93	+20.1

Energy efficiency of corn production in Ontario is anticipated to increase substantially from current levels in the next decades. Increased energy efficiency will result from higher fertilizer-use efficiency, more energy-efficient grain driers, increased use of conservation practices, and higher grain yields of new corn hybrids. In addition, energy consumption for crop protectants will decline because (i) the new chemistry of crop protectants will allow for much lower application rates (Swanton et al., 1996), (ii) targeted placement of crop protectants (e.g., band application), and (iii) increased use of crop rotation and pest-resistant hybrids (e.g., biotechnology products such as hybrids with Bt genes) will reduce the need for insecticides.

Efficiencies of N-use and grain drying per unit output will increase, but the increased efficiencies per unit output will be off-set, in part, by the anticipated 15 to 20% per decade increase in grain yield per unit area. More energy-efficient grain drying systems will replace the conventional cross-flow driers (Table 6.3), but a larger volume of grain per unit land area may have to be dried. Lower N-fertilizer requirements could result from (i) more N credit given to manure and cover crops, (ii) improved soil-testing and fertilizer-application technology, and (iii) increased proportion of first-year corn. First-year corn benefits the output/input ratio by increasing yield and decreasing N-fertilization rates (Table 6.6). The average protein concentration of dry corn is 9.1% (Table 5.2). Protein consists of about 16% N; therefore, increased yields will be associated with increased N requirements by the crop, off-setting the increased N-use efficiency.

The largest reduction of energy use per unit land area will occur because of the continued expansion of conservation tillage practices. It is anticipated that conservation tillage will be used on 50% of the corn area by the year 2000, resulting in a 20% reduction in energy use for field operations.

Table 6.6. Effects of crop rotation on the energy efficiency of corn production in Ontario (Vyn, 1994).

Rotation system	Corn yield	Energy use	Energy output/input
	t/ha	GJ	GJ/GJ
Corn-corn	6.6	20.0	4.8
Soybean-corn	7.3	18.8	5.7
Alfalfa-corn	7.3	13.0	8.2

Overall, energy efficiency of corn production in Ontario has increased during the past two decades and will continue to increase in the next two decades. Although the output/input ratio will increase, energy use per ha may not change or may decrease only slightly, because of the anticipated 15 to 20% per decade increase in corn yield.

III. CARBON BALANCE

Global carbon balance. Plants absorb atmospheric carbon dioxide (CO_2) in the process of photosynthesis and sequester it as organic carbon. The organic carbon may be converted back into CO_2 relatively quickly, such as in the digestion of food or feed, and in the burning of the raw product or its derivatives (e.g., fuel ethanol made from corn). Long-term conservation of organic carbon can occur when the carbon is used in the production of paper and lumber. Another important sink of plant organic carbon is soil organic matter, although the conservation of organic carbon in this form is highly dependent on soil management. The importance of organic carbon in the global atmospheric carbon budget is indicated in a recent report that suggested that some 30% of the increase in atmospheric CO_2 due to fossil fuel burning and deforestation may be subsequently stored in soils and vegetation (i.e., discrepancy of global sources and sinks, Table 6.7). Plant growth increases when atmospheric CO_2 levels increase. A comprehensive review of the scientific literature showed that plant growth under optimal conditions increased about 40% with a doubling of atmospheric CO_2 (Idso and Idso, 1994). Plant growth is even more stimulated by doubling of atmospheric CO_2 when plants are grown under suboptimal conditions (i.e., plant growth increased by 80%). Consequently, the importance of plants as a sink of carbon increases as atmospheric CO_2 levels rise.

Table 6.7 Global carbon balance (Gifford, 1994).

	Billion tonnes C/year
Global sources	
Fossil fuel burning	5.8 - 6.2
Tropical deforestation	1.5 - 3.0
Total	7.3 - 9.2
Global sinks	
Atmospheric increase (1.8 ppm/year)	3.6 - 4.0
Ocean uptake	1.3 - 2.9
Total	4.9 - 6.9
Discrepancy of sources and sinks:	0.4 - 4.3

Carbon balance of corn. Few crop plants match the productivity of corn and, therefore, corn is potentially an important sink for atmospheric CO_2. A corn crop that yields 6.66 t/ha at a grain-moisture content of 15.5% produces 5.63 t/ha grain dry matter. A typical corn plant at maturity consist of 50% grain and 50% stover (leaves, stem, cob, and husks) and, consequently, the total above-ground dry biomass at maturity is 11.26 t/ha. Root biomass of a typical corn plant at maturity is about 10% of the total above-ground biomass (i.e., 1.13 t/ha). In addition, organic compounds are released by the roots during the growing season, which are added to the soil organic carbon pool. Although little quantitative information is available on the root exudate, total root exudate is estimated herein as 10% of above-ground dry matter (i.e., 1.13 t/ha). Hence, the corn crop that yields 6.66 t/ha grain produces approximately 13.5 t/ha dry matter during the growing season. The carbon content of corn dry matter is approximately 0.46 (Rajcan, 1996) and that of CO_2 is 0.27, consequently, 1.704 g CO_2 is absorbed in the production of 1 g of corn dry matter. A 6.66 t/ha grain corn crop absorbs annually approximately 23 t of carbon dioxide per ha (Table 6.8).

Carbon dioxide is also released into the atmosphere in the production of corn. For instance, fossil fuels are consumed in field operations and in the manufacturing of fertilizer, crop protectants, and machinery. If we assume that 50% of the energy in corn production is derived from natural gas, with a combustion value of 50.53 kg CO_2/GJ, and 50% is derived from petroleum liquids, with a combustion value of 81.73 kg CO_2/GJ and upstream releases (production, refining, transportation, etc.) of 8.62 CO_2/GJ (Marland and Turhollow, 1991), then the average CO_2 release per GJ of energy input in corn production would be 70.44 kg CO_2/GJ. Energy expenditure in the production of a 6.66 t/ha grain crop is 19.74 GJ (Fig. 6.2) and, consequently, total CO_2 release is 1390 kg CO_2/ha or 6% of CO_2 absorbed by the crop. In addition, a large part of the CO_2 that is absorbed to produce corn grain is converted back into atmospheric CO_2 relatively quickly by digestion of food or feed and the burning of fuel ethanol made of corn. Approximately 65% of the Ontario grain corn crop is used as animal feed, of which 20% is not digested and returned to the soil as livestock manure. Byproducts of industrial utilization of corn are used as livestock feed (see 5.II) and, consequently, are also partly returned to the soil as livestock manure (i.e., about 10% of the remaining 35%). Hence, approximately 80% of the grain used as animal feed and 90% of the grain used in industrial uses are converted relatively quickly back to atmospheric CO_2, i.e., 0.8 x 0.65 + 0.9 x 0.35 = 84%. In balance, the 6.66 t/ha grain corn crop will absorb 13.57 t/ha carbon dioxide from the atmosphere and deposit the organic carbon to the soil in the form of crop residue and manure (Table 6.8). Approximately 10 to 20% of the crop residue and manure may be sequestered into soil organic matter, which would increase soil organic matter in the top 30-cm soil layer by 0.06 to 0.12% per year.

Table 6.8 Carbon balance of a 6.66 t/ha grain corn crop.

	t dry matter/ha	t CO_2/ha
Input		
Grain (6.66 t/ha @ 15.5% moisture)	5.63	9.59
Leaves, stems, cobs	5.63	9.59
Roots	1.13	1.92
Root exudate	1.13	1.92
Total	13.52	22.75
Output		
Energy input (fertilizer, crop protectants, etc.)		1.39
Grain uses (@84%)		8.06
Total		9.45
Net Input: 13.57 t CO_2/ha		

Deposition of soil organic matter. The question whether agriculture, in general, and corn production, in particular, is a source or sink of atmospheric carbon hinges to a large extent on the fate of the organic carbon which is returned to the soil. Soil organic carbon increases with the addition of crop residue and manure and decreases due to the decomposition of soil organic matter and erosion. The average carbon concentration in the soil is influenced by soil texture, temperature, soil moisture, soil N, and tillage practice. Traditional intensive tillage methods maximize the availability of oxygen which enhances the decomposition of stable soil organic matter, thereby mining the soil of organic matter and nitrogen. Conventional tillage is the major reason for the initial loss of the soil organic matter in the years that soils in North America have been cultivated. The loss of soil organic matter can be reversed, however, with the use of conservation tillage practices.

It was estimated in a recent report (CAST, 1992) that soil carbon levels in the US would be increased by 1 to 3 t/ha in the next 40 years if high yielding crop cultivars were used and minimum-tillage practices were adapted. This estimate appears to be low. Soil carbon levels increased by up to 0.2 t C/ha per year in a 8-year crop-rotation study in Nebraska (Varvel, 1994). A study conducted in Quebec (Liang and MacKenzie, 1982) reported that soil organic carbon increased by 1.2 t C/ha per year in the top 20-cm layer after 6 years of continuous corn, with conventional moldboard plowing and the addition of 1.6 t/ha manure per year. In Ontario, Gregorich et al. (1995) reported that no-till plots had on average 11.5 t/ha more organic carbon in the top 15-cm layer than moldboard-plowed plots, in soil seeded to corn and soybeans for 18 years (Table 6.9). The difference in soil organic carbon between no-till and conventional tillage was 0.64 t C/ha per year, which is equivalent to 1.1 t/ha per year soil organic matter or 2.3 t CO_2/ha per year. The reduction or elimination of soil tillage will increase the rate at which carbon is sequestered in the soil, but the organic content in no-tilled soils will reach an equilibrium after 10 to 25 years.

Table 6.9 Soil organic carbon levels after 18 years of various tillage systems on a silt loam soil near Elora on October 1993 (Gregorich et al., 1995).

Tillage	0-15 cm depth	15-30 cm depth
	Soil organic carbon (t/ha)	
Zero-tillage	50.0	37.7
Fall chisel plow	42.2	30.4
Offset disc	43.1	33.9
Spring moldboard plow	43.4	32.9
Fall moldboard plow	38.5	37.0
Least significant difference (0.05)	8.0	11.5

Corn-derived fuel ethanol. Utilization of corn grain in the production of fuel ethanol improves the carbon balance of corn production. A detailed analysis of CO_2 emission resulting from both production and combustion of fuel ethanol and gasoline in the US was reported by Marland and Turhollow (1991). Their analysis showed a reduction in CO_2 emissions associated with the replacement of gasoline by fuel ethanol from corn of 20 to 40%. Their estimate of CO_2 emission of fuel ethanol accounted for the amount of energy required to produce soybean protein that equated with the ethanol protein-by-products gluten feed and gluten meal (i.e., the CO_2 emitted to produce the equivalent amount of soybean protein was subtracted from the fuel ethanol CO_2 emission).

The reduction in CO_2 emission when gasoline is replaced by fuel ethanol from corn can be estimated. The ethanol yield from 1 kg of corn is 0.394 L (Table 5.3), but the more conservative estimate of 0.372 L/kg employed by Marland and Turhollow (1991) will be used. Total ethanol production per ha of corn (6.66 t/ha) is, therefore, 5628 kg/ha x 0.372 L/kg = 2094 L/ha. The energy content per litre is 1.48 times larger for gasoline than for ethanol. However, extensive experience throughout North America with blended gasoline suggests that the performance of ethanol in blends is equal to the performance of pure gasoline on a volume basis. The CO_2 emission from gasoline is 2.76 kg CO_2/L and Marland and Turhollow (1991) reported that CO_2 emission from the combustion of ethanol is 80 to 60% of that of gasoline. Marland and Turhollow (1991) estimated that 22% of the CO_2 emission from fuel ethanol was from corn production, however, the carbon balance of corn production does not show a net CO_2 emission (Table 6.8). Hence, the CO_2 emission of corn-derived ethanol could be estimated as 0.78 times 80 to 60% (i.e., 62 to 47%) of the CO_2 emission from gasoline. A conservative estimate of the reduction in CO_2 emission due to the replacement of gasoline by corn-derived fuel ethanol is 2.20 t CO_2/ha (Table 6.10).

Conclusion. Corn production can make a significant contribution to the deceleration of the increase in atmospheric CO_2, a major "greenhouse" gas. Although fossil fuels are consumed in corn production, the CO_2 emission from combustion (1.39 t CO_2/ha) is small relative to the carbon absorbed by the crop in photosynthesis (22.75 t CO_2 /ha). Approximately 10 to 20% of the carbon returned to the soil as crop residue (1.36 to 2.71 t CO_2/ha) may be sequestered into soil organic matter. The carbon balance for corn production improves when the corn is used for fuel ethanol production (i.e., 2.20 t CO_2/ha for replacement of gasoline by fuel ethanol). It can be anticipated that increased yields (1.5% per year), the reduction in and elimination of soil tillage, increased efficiency of nitrogen fertilizer usage through fertilizer application technology, and improvements in ethanol-manufacturing technology will substantially improve the carbon balance for corn production in the next decades.

Table 6.10. Reduction in CO_2 emission due to the replacement of gasoline by ethanol derived from corn grain produced on 1 ha.

Grain (6.66 t/ha @ 15.5% moisture)	5628 kg/ha
	x
Ethanol yield	0.372 L/kg
	x
Performance (ethanol/gasoline)	1
	x
CO_2 emission from gasoline	2.76 kg CO_2/L
	x
Reduction in CO_2 emission due to replacement of 1 L gasoline by 1 L ethanol	38 - 54%
	=
Total reduction	2.20 - 3.12 t CO_2/ha

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Appendix 1. Conversion factors

To convert from:	To:	multiply by:
Acres	Hectares (ha)	0.405
Pounds	Kilograms (kg)	0.454
Tonnes (t)	Megagrams (Mg; 1 Mg = 10^3 kg)	1
Pounds/acre	kg/ha	1.12
Bushels/acre	kg/ha (corn @ 15.5% moisture)	62.7
Bushels/acre	kg/ha (dry corn)	53.0
Gallons (US)/bushel	Liters (L)/kg	0.1488
Calories (cal)	Joules (J)	4.186
Kilo Watt hours (kWh)	Kilojoules (1 kJ = 10^3 J)	3600
British Thermal Units (BTU)	Kilojoules (kJ)	1.055
BTU per pound of water	KJ per kg of water	2.324
Liters Diesel-Fuel Equivalent (LDFE)	Megajoules (1 MJ = 10^6 J)	38.13
Carbon dioxide (CO_2)	Carbon (C)	0.273
*Soil organic matter	Carbon (C)	0.58
*Corn biomass	Carbon (C)	0.46
*1% soil organic matter (top 30-cm soil layer)	t CO_2/ha	23.2

* conversion factor used in this report