The Energy Costs of Industrialization in Agriculture: An Application of Energy Analysis to Canadian Prairie Wheat Production 1948-1981

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A Thesis Submitted to the Faculty of Graduate Studies
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ABSTRACT

Detailed energy analysis, encompassing all essential direct and indirect inputs within appropriately defined boundaries and allowing for major technological advances in farm practice and process requirements, indicates that the energetic efficiency of Canadian wheat production has remained virtually constant over the past twenty-five years. After an initial fall in efficiencies from traditional practices rising fossil-fuel subsidies during mechanization have been largely counterbalanced by increasing grain yields. Since the mid-1970s production improvements have led to declining system intensities. By 1981 under the pressure of higher prices the collective energy cost of applied inputs fell for the first time ever in the history of industrialized farming. These findings suggest that (1) modern fossil fuel-derived practice does not suffer from endemic or progressive efficiency decay--thus invalidating secular claims to the contrary, and (2) that greater productivity and greater efficiency are not mutually exclusive events: the chance to simultaneously raise both exists. The continuation of technological and processing improvements in concert with extended farm conservation measures will in all likelihood strengthen agricultural production in the 1990s. Thus, while the data indicate that some individual farms are now operating at levels far in excess of the transitional period efficiencies, raising the national average up to at least a matching position by the turn of the century should be possible.

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I. INTRODUCTION

While only sporadically pursued before the epic turn of the 1970s, it would not be fair to say that the role of energy has gone unnoticed in human affairs. In fact its deterministic nature has been known about for quite some time. As far back as the late 1800s the anthropologists Morgan (1877) and Tylor (1881) writing at a time when steam was the power of industry and coal in England was already being depleted at a rapid rate addressed the fundamental role of energy in social development and expressed concern over its long-term supply. Pointing to the phenomenon of energetic dependency in their works it was implied that when a system based itself solely on the consumption of resources known to be finite, it would at same stage encounter structural instability, and eventually enter long-term decline. Indeed drawing on a foresight that presaged contemporary "neo-Malthusians" by almost a century Tylor spoke at what was then a critical juncture of the civilized world; it was drawing an immense supply of power from a new source, the coal burnt in the furnace of the steam engine which was being used so wastefully that economists were "uneasily calculating how long the stored up fossil fuel would last, and what must be turned to next -- tide force or the sun's heat -- to labour for us" (Tylor, pp. 204-205). In the midst of a new fuel era, our present situation appears much the same: we are again busy calculating how long the "stored up" fossil fuel will last and investigating once more the possibilities of the tides and solar energy for power. Only this time the fossil fuel being used so wastefully is not coal but crude oil, and, more importantly, it is only this time that the consequences of our excessive dependency permeate virtually all sectors of society.

Petroleum was discovered twenty years previous to the publication of Tylor's work. However it experienced then only limited application, mostly in the form of lubricating oils, and it was not until after the turn of the century that it found its greatest use. As it began to power industry this new medium quelled the earlier fear of waste and shortage of coal and greatly expanded the new industrial society's horizons. Yet the long-term contingencies of dependency remained. Writing in one of the more prestigious journals of the day a far-sighted John Ise (1925) criticized what he saw as an over reliance on a singular non-renewable resource whose reserves in the middle of booming 1920s appeared extraordinarily limited "for a nation...yet young, a nation which should look forward to hundreds of years of industrial activity" (p. 289). (At that time the no more than short-term existence of an industrialized America based on a then best estimate of 9 billion barrels of oil without a greater economy of consumption seemed imminent.)

The discovery of many of the world's giant oil fields over the next few decades: Kirkuk, 1927 (Iraq); Burgan, 1938 (Kuwait); Ghawar, 1948 (Saudi Arabia); Safaniya, 1951 (Saudi Arabia); Rumaila, 1953 (Iraq); and Ahwaz, 1958 (Iran) did much to improve the fossil-fuel position of the world (and allay a new round of attendant fears) but it neither alleviated the development of a burgeoning dependency on fossil fuels for energy, and nor did it mask the reality that shortfalls in cheaper domestic supplies were being financed by a reliance on a few countries' more costly exports.

In fact for some years prior to the end of the second world war, the U.S. regularly produced close to two-thirds of the world's crude-oil output; however, since 1946 -- about the same time as the rate of oil per meter of exploratory drilling began its historic decline (Hubbert, 1967) -- the proportion has steadily decreased. The importance of other sources meanwhile has steadily risen. In 1970, the year U.S. domestic production peaked and before its demands on foreign sources rose even more dramatically, it was producing no more than about 15 percent of world totals.

The situation that was taking shape was relatively clear to serious investigators long before the next series of events actually occurred; but with hindsight it should have been more widely apparent beforehand that while the world's greatest industrial power and user of energy was becoming increasingly dependent on foreign sources as its own production was falling its growing demands would place it in a state of unprecedented vulnerability. Late in 1973 with no energetic saviour on the horizon -- it was becoming increasingly evident by this time that even in the best scenario atomic energy would not be the panacea originally envisioned -- the OPEC nations, in response to the growing demand for their product, were to collectively triple the price of their oil exports and effectively shock North Americans into a deeper understanding of how critical energy had become to their way of life. Faced with seemingly inescapable shortages, the need for an improved efficiency of end use, and the necessity for cheap new energy sources, public interest was quickly aroused and attention focused on potential remedies.

The result was a short-term social phenomenon of dubious worth. For just as it served to publicly highlight concerns over the long-term supply and use of non-renewable fossil fuels (in an area which up until then had been the exclusive domain of a limited number of somewhat obscure academics) and to stimulate intensive research on many matters worthy of attention, it also served to eclipse the importance of systematic inquiry into the ways in which energy was being used; inquiry which in many ways was just coming on stream.

At the time, H. T. Odum (1971) had just published what remains to date perhaps the most elegant, expansive yet lucid exposition on the role of energy in human affairs. Building upon the thermodynamic principles of Lotka (1925) and Schrödinger (1944) he selected energy as the common denominator integrating biotic and physical phenomenon into functional wholes, and in developing a systems approach to energetic accounting laid down much of the groundwork influencing future energy analyses. Even though his work is one of the most scientific in its articulation and synthesis of power, nature and society it was not the first nor the only treatise on the topic. For example, in a much earlier somewhat more socially oriented dissertation, Leslie White in the 1940s had reduced all specific, concrete motive forces of cultural development to a single abstract common form, energy.

In essence this work itself could be largely interpreted as a systematic extrapolation of the ideas of Morgan and Tylor, however in one of its less theoretical passages the author posits what subsequently has survived to become one of the principal tenets of scientific energy analysis. "We can measure the amounts of energy expended; we can calculate the efficiency of the expenditure of energy in terms of measurable quantities of good and services produces. And, finally...these measurements can be expressed in mathematical terms" (White, 1943, p. 355). In addition a publication by Cottrell (1955) stands out worthy of comment by virtue of its attempt to quantify what the magnitude of several such flows would be. In fact his rudimentary approach to detailing the energetics of human-, animal- and machine-based agricultures represents one of the first.

Nonetheless, at its most feverish, the flurry of investigative activity which accompanied the energy crisis attitudes of the mid-1970s and which was oftentimes spirited by apocalyptic visions of the future lead to the publication of energy-related studies by a host of overnight experts, ranging from the patently absurd "How to recycle a cow burp" (Colligan, 1974) to the sublimely futuristic "Solar power from satellites" (Glasser, 1977).

Worry over the present standard of living has caused much effort and huge amounts of public money to be channeled towards studying ways in which the expanding of energy supplies -- in the directed attempt to exploit the frequently accredited correlation between energy consumption and GNP -- could be made possible to sustain and even promote economic development. Unfortunately in the course of such actions seemingly little attention has been paid to questioning the relative need for greater consumption, the cost effectiveness of precipitated measures, or even the potential for conservation within our economy. Instead the path of least resistance has lead to what are ostensibly political pursuits of often questionable productive value: be it in the formulation of national energy plans; the resolution of boundary disputes, ownership or revenues; the social underwriting of oil exploration and production; or the promotion of nuclear, solar, or alternative power sources. Often fashioned in a haphazard manner, such pursuits typically contain an excessively misplaced emphasis. Indeed, it is disturbing to discover once such activities have been accounted for that little research time has actually been spent on quantifying how energy is consumed by our society, let alone how it has been in the past or will be in the future.

Subsequently, in our pursuits for more we are virtually ignorant of the potential for less. Efficiencies remain largely unknown and, by extension, the degree of avoidable energy wastage undetermined. The outcome in terms of policy, of course, can be no other than a manifest lack of control over future events. An example of our oversight was the largely unforseen resiliency of the North American economy to the random stress of shortage. Both the U.S. and Canada have on several occasions not only slowed the growth of demand but even reduced overall levels of energy usage in response to higher prices, while at the same time expanding their respective economies. In Canada alone such events have occurred on three separate occasions during the past decade: 1975, 1981, 1983; indicating that in addition to there being substantial room for improvement, savings can be realized without sacrificing the industrial progress and standard of living which had been formerly thought impossible (i.e. the frequently posited GNP: energy consumption argument).

The important point for this discussion is that this development was largely unforseen. Yet not all such developments are quite so welcome by their results. For example, as opposed to the relatively innocuous effects of conservation, the unprecedented closings of schools, factories and businesses in the U.S. in the mid-1970s caused considerable hardship. It seems petty it must be emphasized that in the midst of the fervour surrounding public and professional debate over our energy futures systematic inquiry must not be forgotten. In terms of the focus of these debates it should also be stressed that living in a natural world, physical realities are paramount: they subsume all economic rhetoric. The economic rational is of course important, but it is not at the root of our dilemma, it is our physical dimensions which are, and it is the quantification and analysis of real-world systems which are essential to an understanding of the limits of economic ones. Without such investigation rational management and wise choice of conservation strategies are simply not possible. What is realistic or potentially attainable cannot remain within the realm of quantitative speculation, in an era of dwindling fossil-fuel reserves, policy directives aimed at encouraging quantitative exploration and the best use of what remains are not only expediential but imperative. In response to the need for a better understanding of energy systems, energy analysis is a technique of timely and critical importance.

Energy Analysis

The setting within which process analysis is typically performed depends almost entirely upon the basic laws of energy and matter. Although comprehensive inquiries maximizing the potential of the approach in practice are relatively few and largely of recent vintage the necessity of having at hand a repertoire of generally accepted well tested guidelines was recognized early in the 1970s. In response to rising concerns over the supply and use of non-renewable fossil fuel energies and in recognition of the discipline's long-term potential, the International Federation of Institutes for Advanced Study convened in 1974 and again in 1975 (IFIAS, 1974; 1975) to examine then existing methodologies and provide recommendations for future studies. In a comprehensive set of conventions, guidelines and procedures, the committee suggested the adoption of the title energy analysis for any endeavour which consisted of the applied empirical investigation of energy sequestered in the provision of goods, processes and services to an identified system. Such investigations should be performed within the parameters of the suggested guidelines and include as well an analysis of generated findings for purposes of policy review.

In its simplest form energy analysis consists of assembling data on the physical quantities of all fuels and electricity consumed in a studied process, and the application of corresponding enthalpies. In this form, however, the scope of the method, while it may oftentimes be adequate for the requirements of a macro-scopic interpretation, may not be sufficiently informative for purposes of decision making in those areas where the technique is particularly cogent. Therefore, in its more encompassing and, by extension, more revealing form the boundary of study is expanded to include the embodied energy of non-fuel inputs; that is, the process energy requirements (PERs) of the manufacture of intermediate requirements.

In normal use such analysis usually includes the calculation of input costs through several stages or system levels. For example: level one includes the enthalpy of fuel inputs, plus the direct requirements of electricity; level two the enthalpy of fuel inputs, the direct requirements of electricity, their associated production costs and the embodied energy cost of non-fuel inputs; level three in addition to those costs involved in levels one and two, the energy requirement of capital (i.e. the PERs of the machinery used to produce the commodities); level four the attendant costs of the first three levels plus the PERs of machine tools; and so on.

In principle the evaluation should carry on through progressively lower and lower input levels, continually developing and extending the system's universe, until each and every input has been traced back into its original components -- be they particles in the lithosphere, hydrosphere or atmosphere. But in practice significant contributions beyond the third level are only rare. In fact past the third level contributions are normally so small that the error incurred by ignoring them is typically subsumed within the inaccuracy of calculation. Analyses proceeding through level two, and in most cases level three, will capture on average 90 to 95 percent of the systems attendant requirements (IFIAS, 1974). (The Workshop recommends that whenever possible, analyses be carried back to the level of which the contributions are comparable with the uncertainties in the contributions from preceding levels.)

The goal of energy analysis is rather straightforward: that is, to give a precise physical description of the operation of real-world processes. After approximately a decade in existence, four of its more important applications have become (after Chapman, 1974):

1. The exposing of particular processes in detail and allowing the deduction of energetic efficiencies for purposes of focused conservation efforts.

2. The constructing of energy budgets in the attempt to gain a better understanding of the thermodynamics of industrial systems.

3. The determining of consumption at a macro-level for purposes of estimating aggregate demand and indicating lucrative avenues for reduction.

4. The deriving of requirements of basic technologies and the pinpointing of the consequences of sophistication, supplementation and modification on both short- and long- term usage.

The attainment of these ends has made necessary in practice a high degree of methodological rigour. For purposes of amassing a hierarchical data base such rigour allows for individual consistency and a comparability between studies. Nevertheless, because of the frequent information problems which plague many inquiries (problems which can in effect serve to limit the number of inputs and level of analysis), the application of findings and subsequent referencing between studies must be undertaken with due caution. In the attempt to ascertain the scope of analysis and establish a basis for comparison it should be clear: (1) what subsystems of the world have been analyzed, (2) what inputs have been included in the analysis, (3) what enthalpies have been assigned to primary fuels, (4) what efficiencies have been ascribed to process industries, and (5) what conventions have been employed to partition energy costs within sectors, industries, plants and so on. The neglect of any of these prerequisites introduces the potential for misleading conclusions -- regardless of their calculation accuracy. The findings, themselves, of any study which leaves room for doubt in regard to such measures must be viewed as suspect and interpreted accordingly.

The degree of error allowed by the success analysis approach to accounting is generally quite low; somewhere in the order of 10 to 15 percent. However where the quality of support data is poor, or as is true in some instances where it simply doesn't exist, or alternatively when the sensitivity of calculation doesn't require the precision and fine detail offered by the approach, a less time consuming economically-styled input-output approach can be employed.

In this approach, accounting procedures require as a first step the construction of a multi-variate input-output model incorporating either individual industries or industry-wide groupings as trading partners. Input numbers are drawn from statistical records and applied in terms of monetary exchange units. Results of exchanges are therefore recorded in terms of dollars, not physical quantities. For example, concentrating solely on the exchange or purchase of fuels and electricity gives the value of those commodities. The sum of those commodities gives the total value of consumed energies, and, when divided by the product or process in question, it gives the dollar cost of energy per unit. Equating the average selling price of fuels and electricity for the period then gives the appropriate quantities. Using the Canadian food system as an example, the production sector consumed in 1971 some 175.3 PJ of energy in total. On an energy intensity basis this consumption equals roughly 35.5 MJ per dollar's worth of output.

In downstream application derived intensities are simply compared against sales figures or the price of the commodity to yield desired results. Thus a tonne of wheat produced by an operator in 1971 and selling for $49.38 required roughly ($49.38 x 35.5 MJ/$) = 1.75 GJ to produce. Associated input-output tables and energy intensities for a number of industries and products have been compiled both for the U.S. (Herendeen & Bullard, 1974; Wright, 1974) and Canada (Deachman & Hamilton, 1978) for the years 1967 and 1971 respectively.

The attractive elegance of the models and ease of downstream application belie, however, a number of drawbacks which seriously undermine the usefulness of the once-calculated values: because of structural, technological and price changes within the economy they are restricted to use only in the year of calculation (Herendeen and Shiu, 1975); requiring an average five to seven years to process they are largely out of date when published; due to homogeneous categorization they cannot be accurately applied against end products more disaggregated than the inputs themselves, and lastly, through the use of statistical data normally designed for other purposes, and the use of money proxies for physical units, inaccuracies characteristically up to 30 and sometimes 35 percent are introduced (Berry, 1978). (It should be noted that in the case of the Canadian model some attempts have been made to overcome this final difficulty by recording inputs as much as possible in physical units of exchange. Coefficients were in several instances, however, tested against process data and found to be lacking, the energy cost of wheat production cited earlier, 1.75 GJ/tonne, was more than 50 percent below that found by the physical analysis in this study, while bakery costs on a similar basis were 20 percent above. Therefore, while the method of derivation appears to offset some of the problems associated with proxy variables the results must still be treated as highly suspect -- and of course still liable to the difficulties referred to above.)

Following the recognition of these problems, the input-output approach and the process analysis approach have been combined in the attempt to make the best of both worlds: first, by using the process technique for the most crucial requirements in the first and second levels of input (where precision is important) and second, by applying input-output intensities for those of lesser importance, the third and fourth level of inputs (wherein a process approach the calculations are time consuming) (Bullard et al., 1976). However the logic of the combination is somewhat askew, for the inherent 30 to 35 percent error probability of the input-output approach is itself far greater than the residual 10 to 15 percent of energy unaccounted for by the process analysis at these levels! Therefore it is entirely possible that greater accuracy could be had by simply ommitting those energies and the application of input-output intensities altogether.

As a result the most fitting application of the input-output technique is in the providing of gross overviews of inter-sectional energy exchanges and in the identification of large industrial consumers (Common & McPherson, 1982), while the process analysis itself remains most valuable in its application to specific production and commodity requirements. If the major complaint against the approach is the time consumed in amassing the necessary background data, then the situation can only improve as time goes on as more studies are performed.

Agriculture and Energy

Man is an animal, and above all else his first and foremost requirement is food. Such a simple reality is exceedingly distant, however, to the average North American whose primary concern is likely the upcoming evening's television schedule. Yet throughout history it has been the procurement of an adequate food supply that facilitated ecological (and of course economic) success, both for the individual and of the society as a whole. This is a fact which continues to loom large in the minds of most of the world's people -- people who don't have access to the great productivities of Western agriculture.

Essentially our present-day system of fossil-fuel subsidized farming represents the culmination of a long series of evolutionary events begun some ten to twelve thousand years ago. At that time in the Fertile Crescent where many people were stripping wild grains by hand (Harlan, 1975) the appearance of the flint-bladed sickle marked the beginning of an energetic era. Wielding this small stick-like implement (or what in Georgescu-Roegen's (1976) more eloquent phraseology is an "exosomatic extension") man effectively and significantly extended the range of applied energy beyond the hitherto existing limits of his hand only capabilities. Since that time it has been primarily through the application of progressively larger and increasingly more powerful implements: first in the form of small hand-held tools, then in the form of modest animal drawn apparatus, and finally in the form of immense mechanically driven machinery (each delivering greater and greater quantities of energy to the production process) that the practice of raising foodstuffs has come to be what it is today: economically efficient, physically productive, and energetically intensive.

Industrialized agriculture is extremely productive. For example, a primitive farmer could generally manage to grow enough food to support a family of say five to seven members with a few rudimentary implements and his own physical labour. Under semi-industrialized conditions with the addition of more sophisticated tools, draft animals and fertilizer, the more modern farmer can produce a greater surplus, enough to feed a number of families of similar size. But it is the industrialized operator, as could be largely anticipated, in command of a full complement of modern inputs ranging from diesel tractors, inorganic fertilizers, synthetic pesticides and sprinklers, who supports the greatest number, supplying literally hundreds of individuals and tens of like-numbered families. In fact the contemporary American farmworker serves as an example of one of the most productive agriculturalists on earth. In 1981 the typical farm operator could feed himself, 50 others at home, and approximately 25 more abroad with quality products (USDA, 1982). An even better example is the Prairie grain producer who in 1981 produced enough wheat to meet the annual food energy requirements of more than 675 people.

In energy terms the transition is equally as impressive. Producing subsistence crops at pre-industrialized levels yields somewhere in the range of 25 to 30 MJ of food energy per man-hour of labour input. Semi-industrialized systems can yield upwards of 35 to 50 MJ per man-hour of labour, while aggregatively under fully mechanized conditions it is not uncommon to find returns as high as 3000 MJ per unit of labour input (Leach, 1976a). Just as these increases are impressive, however, they are at the same time costly. In productive economies as in nature there is never any "free lunch" and in terms of non-renewable resources the energy price to pay for encouraging labour productivity is high. To illustrate this point the best route is to compare the extremes in production requirements; at one end of the scale primitive cropping systems and at the other end a mature food industry.

In the first example, the animate labour and organic fertilizers of traditional society are pure transformations of solar energy and, consequently the drain on non-renewable fossil energy resources is either nil or very small indeed. Assuming the energy subsidy to be zero then, the requirements of such a system are striking in contrast to those of a fully mechanized one. In the U.S. in the late 1970s the combined fossil-fuel subsidy of both direct and indirect energies sequestered in growing crops and raising livestock amounted to just over 2.0×10^{12} MJ in total or roughly 0.25 t of crude-oil equivalent per capita (USDA, 1978). Poor countries typically have not only low energy subsidies in agriculture but low overall consumption of fossil fuel for all industrial purposes. Comparing per capita consumptions in U.S. agriculture and poor country per capita energy consummation for all purposes we find the resultant figures to be almost identical. If all downstream subsidies in the food industry were added on in the form of the various energies consumed in the processing, packaging and distributing of final food products, subsequent U.S. values would grow by a factor of five, and rise to become four times as great as typical poor country total energy consumption per capita.

Comparing food energy outputs with production energy inputs results in the widely recognized efficiency ratio, which has been often used to gauge the performance of different agricultural systems. As production energies rise in the transition from one developmental stage to the next the measurement itself can be quite telling. Generalized for each of the above systems and in order, efficiencies ranging from 40 to 15, 10 to 5 and 0.5 to 0.1 are not uncommon (Leach, 1976b). As more and more machinery requiring fossil fuels comes into use and as synthetic fertilizers are introduced, efficiencies must decline. Thus, just as the industrialized mode of production encounters the greatest gains in productivity it also incurs the greatest losses of efficiency: in both cases change is equal to roughly two orders of magnitude over the human labour only system.

Examples of human labour only, human and draft animal labour, and machine labour corn-cropping systems comparing energy inputs, production outputs and efficiency ratios have been collected in Table 1.1. Maize farming is practiced in many areas worldwide and under methods that differ dramatically. In Africa a farmer may struggle to dissipate 400 MJ/ha of solely muscle energy in his production endeavours, grows a crop yielding 900 kg/ha, which produces an efficiency ratio of 35. His counterpart in Mexico delivers three times the animate muscle power by harnessing oxen and plow, produces a crop of 1.5 times as large, and obtains an efficiency ratio only one-half as great. In the final case, that of corn production in the Midwest, energy inputs are two orders of magnitude higher, yields five times as high and efficiency ratios only one-tenth the human labour system's.

The success of Western civilization has had at its base throughout history a highly productive system of grain agriculture. In the future it will continue to depend upon bountiful harvests to feed itself while at the same time supply a greater number of the world's people with its surplus. Yet, what is becoming increasingly clear in this era of energy restraint is that success in the future may not be determined so much by productivity alone, but by productivity in concert with energy efficiency. Awareness of the limited nature of fossil fuels and of fossil fuel-derived inputs has lead to widespread recognition of the ultimate non-sustainability of our present agricultural system. Turning tens of thousands of North American farm operations back into primitive production units is clearly unrealistic, but the wise management of our limited energy resources and a definite improvement in production efficiencies are imperative if we are to extend the usefulness of this method of food production. More importantly, however, is that if this imperative is going to be seriously embraced then we must first investigate how non-renewable resources are being used within the system in the attempt to identify where those avenues for greater efficiency lie.

Since the early 1970s a number of energy studies have been published on various aspects of western agriculture. In North America these inquiries have consisted largely of macroscopic input-output accountings of the U.S. food system (Hirst, 1974; Steinhart & Steinhart, 1974), mixed input-output and success analysis accountings of production at the state level (Lane et al., 1973; Cervinka et al., 1974; Coble & Le Pori, 1974; Lee, 1977; Patrick, 1977) and a grouping of more detailed investigations on individual crop productions (Clarke & Johnson, 1975; Allen et al., 1976; Avlani & Chancellor, 1977; Berardi, 1978; Briggle, 1980; Pimentel et al., 1983). In Canada inquiries which do exist and which follow a general input-output, mixed, or process analysis approach have pertained to food production as the national level (Downing & Feldman, 1974; Warkentin, 1976), food production at the provincial level (Stevenson & Stoskoph, 1974; Southwell & Rothwell, 1977; Stirling, 1979; Jensen, 1981) and a number of more focused single-form investigations (Jensen, 1977; Thompson & Gimby, 1979).

Unfortunately, however, virtually all these studies are limited in coverage to just a single year or two, and consequently lack temporal insight. One study conducted at the provincial level in Saskatchewan (Gayton, 1982) covers a ten-year span of inputs to Prairie small-grain production, but remains largely incomplete for it includes only two variables: fuel and fertilizer. Unfortunately also is the fact the Canadian studies stand out in particular as lacking in both methodological rigour and substance. A number contain not only inconsistencies of data, but calculation oversights, unsubstantiated and unreferenced information sources, second-hand and even third-hand quotations, and a preponderance of indirectly obtained resource coefficients -- which all serve to critically undermine the usefulness of their findings. As a result, in Canada (much more so than in the U.S.) we know precious little about the energetics of our agricultural systems, be they raising livestock, growing grain or producing vegetables.

In the case of the farm surveys there are some allowed insights, but little more: the information generated does not fulfill the proper statistical requirements to be a sample, and subsequently cannot be employed as representative data. This situation is regrettable. After surveying the literature it became embarrassingly clear that in these studies of energy, as in many other areas of empirical research, Canadians have relied far too heavily on other countries for their information; clearly, there is great room for improvement.

Compared to these general agricultural inquiries the works by Heichel (1973), Pimentel et al. (1973) and Smil et al. (1983) stand out, and out of these three, it is the last two which together represent perhaps the most dissagregated and extensive reviews of energy use in agriculture to date.

Pimentel and his colleagues in their original 1973 edition, and updated version (Pimentel & Terhune, 1977) investigated the energetics of U.S. grain corn agriculture during 30 years of continuous practice and evolution. Spanning the period 1945 to 1975, years that circumscribe both the transition from traditional to mechanized practices and subsequent intensification, the conclusion reached in both studies was that the change to mechanization involved not only a substantial drop in energy efficiencies but more importantly, that within the mode itself, the energy costs of production have been rising with time. Both suggestions are of course significant enough in themselves to warrant concern, but being issued amidst growing concerns over future energy supplies it is the latter which is particularly troubling.

Since its publication the findings have become widely publicized in professional journals and cited repeatedly as clear evidence of an industrially progressive, yet inherently specious, food system.

In an equally dissagregated and extensive inquiry of corn production in the U.S., Smil and his colleagues in a major expose published some 10 years later took issue with the earlier study's findings and pursued the topic further. The new analysis, covering approximately the same time period and including a broader base of production inputs, corrected the analytical omissions, oversights and double countings that existed in the earlier works, and incorporated as well the factors of changing technology and evolving process efficiencies. From these improvements the new data supported the original conclusion of a transitional drop in efficiency between modes, but as opposed to falling efficiencies with intensification, it was suggested that after accounting for the PERs of those inputs which had themselves improved over time, the energetic costs of corn agriculture had remained virtually constant during more than 20 years of industrial advancement. In addition it was predicted that production efficiencies would likely improve in the future, rising above what they were in the 1970s to become perhaps as much as 50 percent greater by the 1990s.

As evidenced by its greater depth and methodological rigour the later analysis is clearly an improvement over the earlier one, yet it must be stated that even with the new findings, questions of wider implication still arise. For example, can the findings be replicated across a broader range of agricultural situations and practices? Have other crops and system evolved similarly? And what of anticipated improvements; are they likely to occur? Of course, what must be realized is that for legitimate answers, more studies must be undertaken, without a foundation of empirical evidence the results from one study -- or in this instance two studies with divergent results --

cannot be unilaterally applied across all crops and practices, or assumed to be indicative of all industrialized agriculture. What is required is a modicum of restraint. Analyses must be performed across a broad range of crops, practices and different systems, and the results found to be consistent before far-reaching implications can be liberally ascribed.

One of the principal goals of this study is to supplement and broaden the existing base of knowledge and to supply the information required for more responsible generalization. Another purpose is to generate particularly Canadian data under particularly Canadian conditions on a region and activity of international importance and finally, as was discovered partway into the study, my investigations were to pull together a host of previously uncompiled resource data, and develop not only an energy analysis but a resource analysis as well as this key economic sector.

Unlike hybrid grain corn production, growing the world's most important cereal grain is a much less-demanding and less-diverse undertaking. Wheat, as it is grown under North American conditions, is one of the more frugal agricultural crops, yet despite its lower overall level of inputs, the production process itself has undergone extensive modification over its period of modernization. Occurring at approximately the same time as mechanization in the U.S., determining the performance of this dissimilar yet emminently distinguished world crop under comparable conditions makes for a relevant and compatible inquiry.

The Prairie Production System

Canada's 20 percent contribution to the world wheat trade is somewhat anomalous considering that at close to 25 million tonnes in 1981 its crop production made up no more than one-twentieth of world total. However, because of above average production and low domestic consumption the country's export to production ratio is high. Virtually all wheat produced in Canada is grown in the relatively homogenous 500,000 km^2 prairie region of the western interior. Here, in the indigenous grassland ecosystem where climatic and physical factors combine to create a natural environment favourable to its agriculture, <u>Triticum aestivum</u> is physiologically and morphologically well suited. As a sexually autogamous species of the Graminae family, the plant itself is characterized by self-pollinating and synchronistically maturing flower parts, ensuring both a minimum of genotypic variability and an extremely high fecundity rate. As a result the plant is easily propagated under a broad range of growing conditions and practices.

In addition to its fecundity one of the more beneficial attributes of the wheat crop, one which allows for its large scale success as an agricultural commodity despite the extremes of Prairie estimate, is the capacity of each plant throughout the growing season to adjust its vegetative and physiological development in response to intraseasonal variations of moisture, temperature, light, nutrient supply and various other environmental factors. Cultivars developed in Western Canada over the past 100 years have capitalized upon this ability and effectively maximized the plants ecological potential -- and economic possibility -- in all but the severest of conditions.

A crop's net primary production is conditioned by a host of climatic factors, each acting on its own, and in concert to enhance or ameliorate growth. Of course, it is impossible to discuss all affecting variables outside of a paper devoted solely to the topic, but based on climatalogical observations by Hare and Hay (1974) and agronomic data from Peterson (1965) and the University of Manitoba (1977) evidence suggests that while the wheat crops maturation period of 90-100 days is tenuously close to the frost-free maximum it is, on average, sufficiently within the bounds of seasonal limitations to provide adequate returns. The crop's heat requirement of 1100 degree days is below the average of 1200 to 1600 received; the mid-summer daily mean temperature of 20°C is near optimal for the plants C_3 photosynthetic process, and the intensity of the growing season light is above the plant's saturation threshold (i.e. the light energy of maximum photosynthesis, which for wheat (Thompson & Hill, 1949) is approximately 1800 $kJ/m^2/hr$) throughout much of the day.

Similarly the extreme latitudinal position of the Prairie region as it stretches south to north some 300 km on average from 49°N to the boreal transition zone, running in an approximate line northwest from Riverton, Manitoba to Peace River, Alberta, given the extended photoperiod (up to 16.5 hours at the summer solstice) favourable for the proper development of this 'long-day' species. Yet, with regard to all other meteorological parameters, it is undoubtedly that of moisture which is most notable. Alone moisture is the most critical limiting factor in large-scale agricultural production, occurring at irregular intervals and falling in notoriously unpredictable amounts. Fortunately, however, what does fall is normally enough. The climate is classified as humid continental and on average one-half of the yearly 250-350 mm of precipitable moisture is received during the approximate three month growing season.

In terms of pedology, the rich Prairie soils belong to the brown, dark brown, black and dark-grey groups of the chernozemic order (CDA, 1978). Built up over thousands of years of organic deposition from the native xerophytic and mesophytic grasses they originally contained a fertility that was high and a structure which was excellent from small grain production. However, like any soil resource, without proper conservation practices they have suffered progressive deterioration since first breaking; and while it is known they respond well to both organic and inorganic forms of fertilization, they have nonetheless continued to lose minerals under conventional practices.

Collectively then, on the production side the fortunate combination of these climatic, pedalogic and topographic features has been responsible for the establishment and expansion of commercial farming in the region. In fact it is the physical features of the landscape, characterized by minor relief only (typically flat to low rolling, broken only by the occasional hill, ravine or broad river valley) which manifest the continuous topography excellent for the efficient operation of a wide range of agricultural equipment -- spanning both draft animal and machine labour eras. Of the combined Manitoba-Saskatchewan-Alberta land area of some 175 million hectares close to one-quarter is considered capable of sustaining continuous production; and out of this another one-third or approximately 13 million hectares is considered prime for the growing of wheat (Action et al., 1980).

Wheat agriculture has been practiced in Western Canada and has been a key economic activity for well over 100 years. Beginning with a few meagre hectares at the Red River Settlement -- now Winnipeg -- in 1812 (Buller, 1919) the crop has been produced in ever increasing quantities over a variable but typically expanding area. As detailed in agricultural reports (Statistics Canada, 1981a) the most rapid expansion of seeded areas in the region occurred between the turn of the century and the end of WWI. Growing from a relatively restricted base of approximately 850,000 hectares in 1901, wheat areas jumped yearly to become 9 million hectares by 1921. Afterwards, expansion slowed: it increased only marginally to reach 10.5 million hectares a decade later, shrank slightly, and oscillated around the 9 million hectare mark for the next 35 years.

In fact what was true then of wheat was true of nearly all Prairie cropland: by the 1920s the majority of good quality arable land was under cultivation. Occasional expansions and contractions of planted areas after that time, of course occurred, but where they have it has been mostly related to changes in the extent of summer-fallow practices.

Specific data previous to the 1950s does not exist, but from known rotational practice, indirect references and later records, it can be reasonably estimated that at any given time, roughly one-third to one-half of Prairie cropland would have been in fallow. In 1958, the first year practices were accurately detailed, close to 80 percent of the wheat crop was sown to summer fallowed land (Statistics, 1981b). This percentage dropped on average during the 1960s, rose to record highs by the early 1970s (reaching almost 90 percent in 1971) and dropped again to lows of around 50 percent in the early 1980s. Corresponding to these variations in fallow were a rise in seeded areas: to 11 million ha in the 1960s, a fall to 5 million ha in the early 1970s and an increase to 12 million ha in the early 1980s.

New breakings of arable land in Western Canada over the past 20 years have been extremely small. Land that now remains (a small amount exists in the Peace River district) is typically of marginal quality (Simpson-Lewis et al., 1979) and so demanding of productive inputs that even under extremely favourable conditions its utilization could scarcely be justified because of prohibitive costs.

The original cropping system of the region were highly labour intensive. Early settlers with little more than their own muscles and a few rudimentary implements toiled long hours in the attempt to gain satisfactory returns from the relatively unyielding but generally responsive soils. Under comparable conditions in the Northern Plains agricultural district the USDA (1964) estimates that approximately 140 man-hours were required to farm one ha of wheat land. By 1981, the requirement had fallen to just over five hours. Animal labour which at first consisted primarily of oxen and then horses, quickly appeared on the scene and supplanted many of the heavier farm tasks. It was in turn replaced by machinery, but in essence the era of draft animal labour was relatively long, much longer in fact than is commonly recognized.

Delivering substantial quantities of energy in the 1930s and 1940s their input was important for over a century, and extended beyond the point when machinery first became available. For example, the first self-propelled steam-driven combine was built in 1887 (Nyberg, 1957), and the first gasoline tractor in 1900 (Symes, 1980), yet it would not be until the expansionary pressures of the post-WWII period were being felt that they would be decisively displaced. Only then did farmers, faced with an economic stimuli to increase production (the real price of wheat more than doubled between 1940 and 1948) and a limited land base, begin to replace their animals with tractors in substantial numbers. By the late 1950s there were some 285,000 tractors and relatively few remaining horses.

The widespread employment of tractors, marked the beginning of the mechanization period and brought with it higher grain yields, rising levels of production, greater productivity, expanding farm size and an overall reduction in the number of commercial operators. The typically Prairie wheat farm in the late 1940s averaged 1100 kg/ha. Three decades later under modern practices these yields had almost doubled, coming close to a good harvest average of 2000 kg/ha in 1981. Over this identical period production rose from 10 million to nearly 24 million tonnes; farm size grew from just over 40 to almost 120 hectares; while the actual number of farms growing wheat fell from 213,000 to 106,000. The data for these and a series of intervening periods have been assembled in Table 1.2.

For the most part the data in Table 1.2, and the diffusion history of mechanized practice in general, reflect an orderly evolution. However on several occasions, inconsistencies are evident and warrant explication. For example, in 1961 both production and yield were less than half their value five years earlier. To account for this, it was moisture (or rather the lack of it) causing one of the worst droughts on record which led to massive crop failure in virtually all districts. Ten years later it was the seeded area, the average farm size and again productions that were depressed. The causal agent in this instance however was not weather but government fiat. After receiving one of the lowest prices ever producers were literally paid not to produce and, in response, idled large tracts of land. After the event it was several years down the road before the effects wore off.

In addition to the above indicators of change, the farm population itself in absolute terms was in 1981 approximately one-half of what it was thirty years earlier. As a proportion of the total Canadian population it decreased accordingly; falling from a high of 50 percent in the mid-1940s to a low of roughly 10 percent in the early 1980s. Collectively these many industrial and structural changes had a dramatic effect. The wheat system of the 1980s had fewer operators, working on fewer farms, producing more grain, with less labour input than ever before. As was indicated earlier, however, the associated resource and energy costs of modernization have been high, and it is to quantification of these inputs that we must now turn to.

The Boundaries of Inquiry

Preceding the estimation of actual energy values, the first step in determining wheat system energetics involves a detailed accounting of the physical resources consumed in a typical one-year production cycle. In general the picture provided by economic indicators is that the consumption of major inputs has grown substantially over the past 30 years. However, when it comes to more precise quantification the detailing of these events is inordinantly time consuming.

In Canada where the manifest bias towards economic description has led to a definite absence of hard data, economic indicators and monetary detailings are oftentimes much too vague and indefinite -- falling prey to all sorts of mitigating circumstances and qualifying factors -- to be of great value in physical analysis. And this is in addition to 'normal' problems (for an enlightening exposé on the inaccuracies contained within common economic observations see Morgenstern, 1963). In fact in a number of instances where the reconstruction of past events was possible while those of the present were not, it could be reasonably concluded that things have gotten worse with time. A favourite example of this is the Statistics Canada series entitled "Detailed Energy Supply and Demand in Canada" whereby in amalgamating a number of more dissagregated reports the organization has obtained results which are anything but "detailed".

This is not to imply that the required information cannot be obtained, in most cases it eventually can; but the situation is extremely unfortunate, for so little is at hand when needed. The necessary data for this study invariably lay scattered across a broad array of public and private, functioning and defunct agencies. Compounding the collection problem were inherent discontinuities in statistical series, changes in survey design, and variances in statistical technique. This introduced the requirement of a time consuming search for definitional explanation and the necessity of extensive cross-referencing for data verification. Empirically such difficulties are bound to introduce unavoidable error. Yet the simplicity of the wheat production process itself, the aggregate level of investigation, and the reliability of several of the key indicators did much to mitigate the inconsistency of the written record, and reduce the probability of significant error from occurring. Taking all these considerations into account an implicit degree of error of 15 percent would appear reasonable.

Studies reflecting the true energy cost of secondary goods, processes and services which are indigenous to specific Canadian conditions have rarely been performed. Thus the second step in determination of the energy budget for wheat production involved the undertaking of process analyses for several of the intermediate input themselves. This requirement became especially important where foreign values were found to be too far removed to be representative of actual conditions. For example, the PER of nitrogen fertilizer as it is often used in Canadian agricultural studies was calculated by British researchers for that country's specific manufacturing and farming conditions, and is roughly one-third higher than the average value under comparable Canadian conditions. If the British value were to be used in this study it would have led to an inaccuracy greater than the requirements of transportation, herbicide, phosphorus and potassium combined! In cases where foreign values were considered appropriate they were subsequently employed.

Lastly, as a final step, the PERs of major production inputs were, where it was at all possible, adjusted historically to reflect the technological advances which have transpired in the efficiency of their fabrication over time. Surprisingly the effect of these calculations has a substantial impact on results. Using nitrogen fertilizer again as an example, the energy cost of its manufacture has declined by approximately one-third since the beginning of the study period. Not accounting for this improvement, in fact not even accounting for industrial improvement in any of the inputs, regardless of their being manufactured off the farm, would have led to deflated production values for earlier years and substantially skewed findings throughout. In a wider perspective, this inclusion is doubly important for its omission would virtually deny the fact that the wheat system and mechanized agriculture depend upon an integrated industrial superstructure for their existence. Western agriculture has a huge and necessary industrial support base -- advancement or change in any of the constituent sectors will have a corresponding effect on the system itself.

In summary by developing a comprehensive approach to accounting, data as it presented in this study allow for the measurement of three distinct variables; each contributing in its own way to the energetics of production. They are: (1) the actual level of inputs, (2) the constituent mix of inputs, and (3) the PERs of those inputs over time.

Of primary importance to the design of this study was the consumption of energy in its equivalent non-renewable forms. The time span of coverage was chosen to encompass both the transition from earlier traditional practices and mechanization in its intensifying stages. Information was assembled into eight specific time slots and recorded both as physical inputs in terms of natural units and as energy inputs in terms of either enthalpies or embodied energy equivalents. The interval of the last two entries was shortened in the attempt to capture any adjustments which might have occurred in the system over time as a result of rapidly rising fossil fuel, electricity and fertilizer prices during the 1970s.

System boundaries were set to include only those direct and indirect energies consumed in the production activity proper: beginning in typical sequence with seedbed preparation, fertilization, crop planting, spraying; and finishing with the final harvest and delivery of ripe grain to its initial market. Direct inputs to the system included the various fuels consumed by on-farm machinery and the vehicles transporting major commodities to the farm gate, as well as the business portion of electricity utilized by services contributing to on-farm operations.

Indirect inputs consisted of machinery, nitrogen, phosphorus, potassium, herbicides, seeds and in the early years animal feeds. All values were summed to totals, prorated on a cropped hectare basis, and compared to yields of wheat in corresponding years. Where particular data were not available, information gathered at the level of all field crops was considered to be suitably representative of actual wheat grain requirements, and utilized accordingly. In the cases where this was made necessary, the similarity of agronomy between the predominant grains prevents any significant discrepancies from occurring.

The incorporation of productive factors was limited only to those activities which were attributable directly to the farming operation as a functioning business enterprise. This approach excluded consumption of fuel by automobiles in personal use as well as those energies associated with the general maintenance of farmhouse and family. Presumably, these fixed expenditures would occur regardless of one's particular occupation. Along this same line of reasoning, the human labour input, (which at best is only minor in mechanized systems), was also considered a given and subsequently assigned no energy cost. Again it must be stressed that fundamental importance was placed on the societal use of a single non-renewable resource, energy, and following this emphasis was placed on the depletion of it and only its finite reserves.

TABLE 1.1

HUMAN, ANIMAL AND MACHINE LABOUR GRAIN CORN PRODUCTION SYSTEMS

Farming System	Energy Input (MJ/ha)	Production (kg/ha)	Energy Ratio (output/input)
Human labour only Africa*	400	900	35
Human and animal labour Mexico**	1,350	1,500	17
Machine labour United States***	19,000	5,000	4

*Clark, C. and Haswell, M. (1970). The Economics of Subsistence Agriculture, 4th ed. Macmillan, London.

**Lewis, O. (1951). Life In A Mexican Village: Tepostlan Revisited. University of Illinois Press, Urbana, IL.

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

TABLE 1.2

WHEAT PRODUCTION INDICATORS 1946-1981*

Year	Seeded Area (10^3 ha)	Production (10^3 tonnes)	Yield (kg/ha)	Wheat Farms	Average Farm Size (ha)
1946	9,170	10,696	1115	213,370	43
1951	9,603	14,424	1462	192,310	50
1956	8,928	15,000	1679	170,460	49
1961	9,975	7,076	710	165,990	60
1966	11,812	21,963	1861	151,220	78
1971	7,643	13,880	1816	117,070	65
1976	10,949	22,664	2070	112,870	97
1981	12,145	23,840	1967	106,020	114

*Derived from Statistics Canada, 1946-1981. Census of Agriculture, five and ten year series, Minister of Supply and Serivces, Ottawa.

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II. LABOUR

Levels of Demand In Wheat Production

One of the most distinguishing characteristics of North American agriculture over the past 200 years has been the dramatic fall in its productive labour requirements. In the field steel plows which replaced wooden ones, cultivators first drawn by horses then by tractors, grain drills of evolving design, pressers, mowers, reapers, binders, threshers, swathers and combines have, alone and in combination, served to reduce the time spent by workers performing farm tasks. A good example of this is manifest in the wheat-harvesting operation over time. Under the primitive conditions of cutting with a sythe, and the subsequent requirements of binding, shocking, threshing and bagging, the entire harvesting operation may have consumed upwards of 100 hours of labour per hectare of wheat. The use of a horse-drawn binder and stationary thresher accomplished the same task in roughly seven hours (Peterson, 1965), while today's direct combining uses up no more than 30 minutes (Reed, 1980). On a broader scale, the United States Department of Agriculture estimates that in the early 1800s the full cycle of wheat production would need close to 140 hours of concentrated physical labour (USDA, 1964). By the mid-1960s the associated demand would bottom out at about five and one-half hours.

Data on the history of labour demand in wheat production are presented graphically in Figure 2.1. Separating the fall of requirements into three 50 year blocks, we find a reduction of 70 hrs/ha between 1800 and 1850, 35 hrs/ha between 1850 and 1900, and 18 hrs/ha between 1900 and 1950 (the approximate beginning of mechanization in wheat agriculture). Reductions continued during the mechanization period and by 1975 requirements had fallen by an additional 10 hrs/ha. In total, the cumulative decrease is impressive: roughly 135 hrs/ha in 175 years. However, as is evidenced by Figure 2.1, the line of decrease is not linear. If we break the 175 years into two distinct periods -- one spanning the traditional mode of production, 1800-1900, and the other mechanization between 1950 and 1981 -- we get two uneven declines of, respectively, 128 and 5 hours. On a percentage basis, the delines are equal to 93 percent and 4 percent of the original input of 138 hr/ha.

Implications are clear: at the time of the onset of mechanization the majority of labour-saving devices were already in place and labour requirements were already at very low levels. Although this may be somewhat of a revelation, it is of course, no more than the natural outcome of preceding events (i.e. the labour demand curve is reverse logistic). Mechanization did reduce labour requirements substantially (by about 50 percent) and accomplished it in a relatively short time (a dozen years), but by virtue of the approaching asymptotic limit, reductions could be no more than minor in comparison to past declines. In fact since the early 1960s, during more than two decades of ongoing industrial improvement, there has been no significant change in requirements. Apparently at roughly five to six man-hours per hectare the bare minimum of physical necessity has been reached. And of course with such low levels already in place, it is highly improbable they could fall any further in the forseeable future.

Compared to the per hectare labour requirements of other crops; for example, rice (31), corn (17), buckwheat (15), hay (14), sorghum (11), oats (10) and barley (9), wheat is lower in virtually all respects (USDA, 1964). This reality stems from the fact the system is extremely frugal in its production requirements. The basic agronomic inputs of, for example, fertilizer, pesticides and irrigation are significantly lower than for say corn or rice and as a result time spent in application is less and, moreover, the crop itself requires only minimal care while growing, with the result that out of total labour requirements the majority is spent in preparing soil and harvesting grain.

So far we have been using aggregate U.S. data for the purposes of general description. However, the averaging of values disguises the many regional differences stemming from topography, soil and climate. For example, in one of the prime wheat growing regions of the U.S. (South Dakota, North Dakota, Kansas and Nebraska) operators have the lowest requirements in the nation with a labour input almost 20 percent below the national average, and 10 percent better than their closest rivals. Here land is flat, fields are free from obstacles and the farms expansive. As a result, scales of operation are correspondingly large, equipment is above average in size and field machinery can be operated at high speeds. Straight combining in this region for example takes only half the time it requires in Appalachia, where uneven topography and small irregularly shaped fields offer obstacles to large efficient machinery.

Because of the virtual absence of applicable labour data for Canadian agriculture, data from the Northern Great Plains district in the U.S. were employed to represent Western Canada wheat farming. Differences which do exist between the two systems will be no more than minor owing to the contiguous nature of the regions and comparable agronomic practices.

Accounting For The Energy Cost Of Labour

All industrial processes, be they agricultural or otherwise, involve physical labour and, by extension, energy which can be apportioned on a human basis in one of three ways: (1) on the basis of the energy content of food consumed by an individual while going about his daily activities, (2) by estimating the power delivery of an individual's muscles to the task at hand, and (3) through a calculation of the energy cost of goods, processes and services upon which the workers depends for a comfortable existence. Yet despite its obvious contribution to production activities (and regardless of calculation method) labour is typically ignored in industrial energy analysis

(Boustead and Hancock, 1979). As the quietly celebrated and universally honoured mainstay of traditional agriculture, however, labour is virtually synonymous with the practice itself. Nevertheless, industrialization has brought with it great changes, and it was decided that this inquiry would follow the lead taken by other industrial studies and disregard the energy costs of labour. However, the contributing conceptual and logistical reasons for doing so give rise to some engaging questions of principle.

Deriving costs through the first approach (i.e. food consumption) is accomplished by the direct apportioning of the farm operator's food intake on a 24-hour basis to the time he is actually involved in production related tasks. The average farm worker in Western Canada (Duckham and Masefield, 1970) between the age of 20 and 39 and weighing 65 kg, has a nutritional energy requirement of about 12.5 MJ per day (FAO/WHO, 1974). Labouring an average of seven hours per day the energy cost attributable to each working hour is 1.8 MJ. This value can then be applied against yearly wheat production inputs to yield total requirements (Table 2.1). On this basis, it was found that the average energy cost, like the input of labour itself, fell close to one-half between 1948 and 1981.

This simple approach to labour energy costs capitalizes upon the homogeneity of human dietary intake, which can be easily standardized across the normal farm population, but there are clearly problems with the procedure. Such averaging cannot take into account the particular nature of the production tasks involved, and cannot distinguish the changes that have occurred in those tasks over time; which include, for example, the historic reduction in requirements that have accompanied the release of energy intensive hand labour, and the replacement of many tasks by machines. The second approach already mentioned does, however, take this into account and as a result is much more revealing. Focussing on the muscular energy expenditure of the task it measures the actual work performance.

The assimilation of power machinery into commercial wheat production was especially rapid. Yet even in the mid-1940s, nearly one-quarter of the man-hours needed to produce a crop were still in the form of labouring performed by the hands or with hand-held tools (USDA, 1947). Great physical effort was required for the heavy tasks of shocking, hauling and threshing of grain. However with the diffusion of intensive practices which followed, tractors and combines soon displaced what was left of the traditional inputs, so much so that by the late 1950s the corresponding requirements of hand labour had been halved. Extrapolation from these early figures suggests that hand labour was all but non-existent by the late 1960s; however, it was assumed (after Smil et al., 1983) that the variety of miscellaneous activities, such as shovelling grain, connecting or disconnecting implements and cleaning clogged machinery would always require some effort, so a minimal requirement of five percent hand labour was considered appropriate for the wheat system even under complete mechanization.

The other 95 percent of work not performed by the hands alone now consists of activities which do little more than direct large flows of mechanical energy by the means of operating switches, levers and wheels. The energy expenditures associated with such efforts are predictably minimal, falling somewhere between 8 and 21 kJ/min, with the average taken as 15 kJ/min (Passmore and Durnin, 1955). To put it another way, the present physiological costs of every day farming tasks vary between two and four times the resting or basal metabolic rate, which for the 65 kg reference man is just over 4.2 kJ/min. In comparison to such light activities performing a physiologically moderate task, could raise the multiplier to six, while in some cases performing extremely difficult tasks could raise outputs to as much as ten times the basal metabolic rate. However such heavy requirements are rarely ever encountered in modern wheat agriculture.

In fact, it is the lowering of activities from the categories of heavy and moderate to light, which characterize the transition to mechanized practice. For example, comparing the replacement of walking with a horse-drawn plow by the seated driving of a tractor, Hettinger and Writh's (1953) found that the attendant energy expenditure of the operator fell by an estimated one-third, which in effect served to downgrade the activity from the moderate to the light category. In this study, values of 23 kJ/min (1.4 MJ/hr) and 15 kJ/min (0.9 MJ/hr) were used for moderate and light categories and were applied against the proportional contributions of hand and non-hand labour to calculate the requirements of muscular energy shown in Table 2.2

The third approach to computing energy requirements involves the calculating of what Slesser (1973) termed the energy subsidy or life support cost of labour. In the method one attempts to establish the sum of all energies sequestered in goods, processes and services consumed by the individual in his society. The basic approach entails the dividing of a country's energy consumption by the hours its population worked to derive an intensity which can then be multipled by the particular system's labour input to yield a final cost. Variations on the approach have been presented by several authors (Jones, 1975; Hawthorn, 1975; Fluck, 1976; 1981), but in all cases they have been unable to avoid the obvious double counting.

As noted at the beginning of this chapter, no energy cost has been assigned to human labour: none of the approaches proposed above was considered logically satisfactory. Reviewing each in order, it should be noted that in the initial approach the calculations involved no partitioning of operator food intake between farm related and non-farm related tasks. Instead, all intake was assigned solely to the performance of production duties. The underlying assumption here can be only that all the farmer's daily requirements, waking or non-waking, work or leisure related were required for the growing of a crop. But such rationalization is obviously questionable; for to suggest that an individual eats only to work is clearly false. People eat to live, and work is only one part of life. No society employs its members solely as food converters, consuming foods to liberate economically productive energy; regardless, even if it did, such energy would account for only a small proportion of total intake. Assuming the typical North American spend eight hours each in bed, work and non-occupational activity, then one-half of a moderately active person's consumption would go towards maintaining basic bodily processes and functions, another one-quarter to the supporting of recreational pursuits, and only the remaining one-quarter would go towards meeting labour-related expenditures. Ultimately, from the sedentary lifestyle exhibited by most North Americans, it might make more sense to gauge requirements by choice of recreation rather than by occupation. People would likely consume more if less time were spent working!

Alternatively, of course, food consumption could be divided amongst its various constituents, and only the appropriate fraction charged to the growing of the crop. Costs could then be apportioned on basal metabolism plus a performance mutliplier, or simply the multiplier itself. However, regardless of method, neither overcomes the fact that food consumption for the most part is given and largely independent of occupation. Moreover, they do not overcome the fact that even if we were to accept the approach, it would not be the energy content of the food that is important. The overiding concern of this study is to quantify non-renewable fossil fuel and fossil-fuel derived energy consumption, if anything then it would be the energy costs of producing, processing and distributing the food that are critical.

Where the initial approach suffers from an inability to distinguish between activity-related costs, the second offers an improvement by better detailing task and effort, and in this sense is a better measure of labour's true thermodynamic input. In reality, though, such improvement may only be minor. Tasks can only rarely be measured in great detail (categories may contain up to a 50 percent range within their own boundaries) and again, as with the minimum that exists for food, there is a minimum of muscular expenditure which must be considered necessary in order just to live. As agricultural tasks can now be categorized as light (15 kJ/min) energy expenditure will rarely be raised above this level. Fifteen kJ will be spent whether one is gainfully employed or not, and therefore, must be taken as a given cost.

Finally, in the so-called life support energy approach to accounting -- while it may serve as a convenient yardstick by which to roughly measure a society's energetic performance -- in much the same way GNP accounting broadly defines a society's economic performance, its employment at the level of description required by process analysis is inappropriate. Gross measures are highly inaccurate indicators of underlying realities: we simply cannot define the energy cost to society of maintaining an agricultural worker with intensity values that allow for no differentiation between occupations. These values as they are normally derived show no more than a homogeneous breakdown of national totals, where every member in society is allotted an identical proportion of the whole. As a consequence, the subsidy ultimately shows little.

But there is a more fundamental argument which limits the usefulness of this approach; that is, the presence of the double counting which cannot be expelled regardless of the calculating procedure. What this amounts to, is that as long as a worker consumes a product, process or service, created and distributed within the society of which he is part, he is in effect supporting himself (insofar as he himself contributes in a productive manner) by his own labours. In principle, of course, it is conceivable that the countless goods and services consumed by an individual in work-related activities could be separated and accounted for -- albeit on an arbitrary basis amounting to a task of monumental proportions -- and subsequently assigned to him as a subsidy cost, but the double counting would still remain: it may be now somewhat more refined, but by virtue of the circular nature of the problem (and the circuitry of social interrelationships) it still exists.

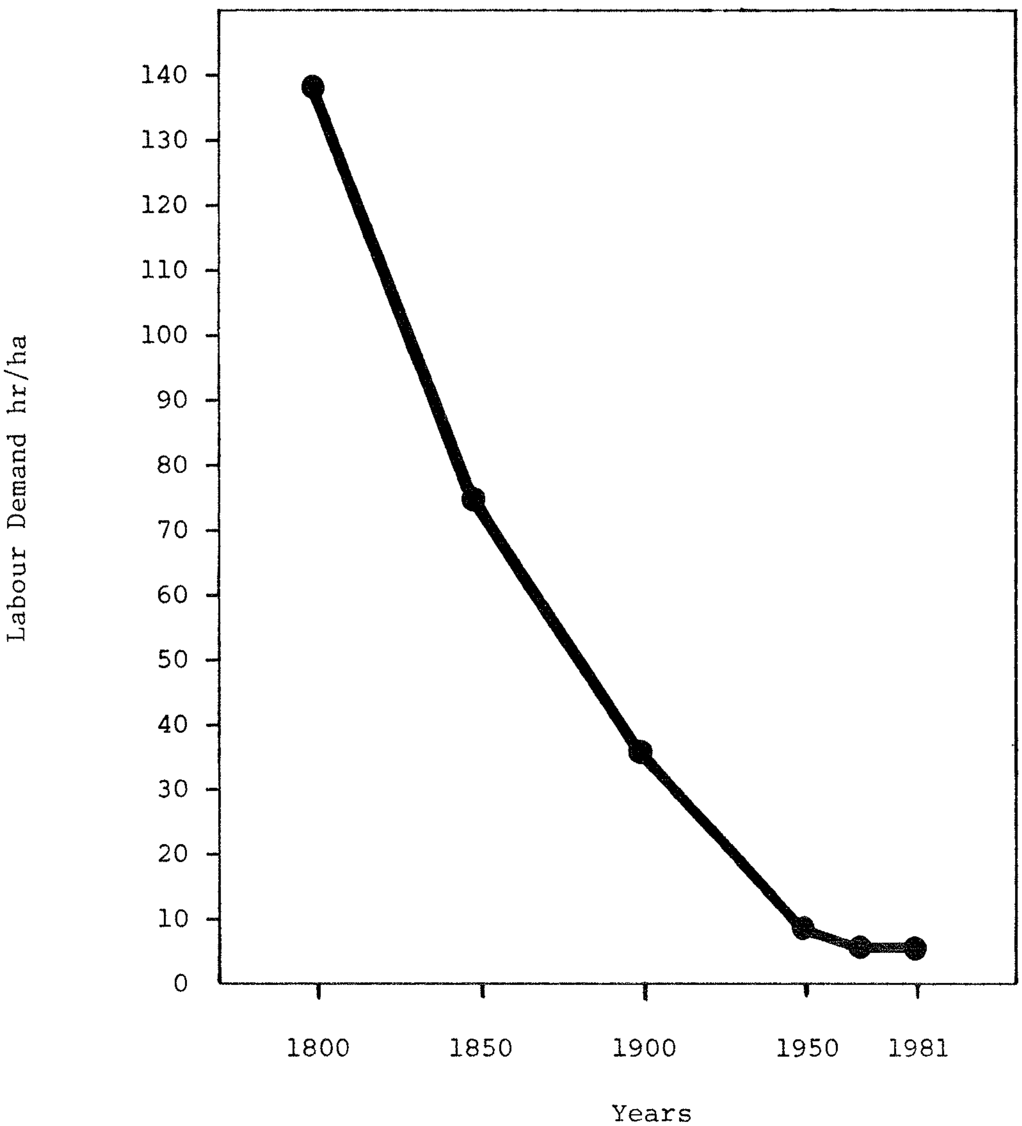
Life-support energies can also be seen in the same light as the two previous cost-of-living arguments: that is, regardless of one's particular occupation a fixed cost will be incurred. Only in this instance the basic prerequisites are socially not physically defined. In accordance with cultural norms an individual will on average own a home and furnish it, drive a car and clothe himself in spite of the type of job he or she has, and, ultimately, there will be little quantitative difference between the banker, broker or tradesman. Assigning such cost to a farm operator would again show little.

Human labour presents itself as a production input unique among farm requirements. As an agent of power delivery it is categorically similar to the inputs of draft animals and machinery, yet at the same time it is fundamentally different. Animals and tractors are maintained expressly for the purpose of performing work, and can be pastured or turned off when not in use, but human labour is not and cannot be. Work is an activity, one amongst many, which in essence makes up only one part of the day, and one segment of existence; and, moreover, individuals do not reduce their food intake or store their thermodynamic potential while unemployed.

Labour, of course, plays a pivotal role in agricultural production, but in modern farm practice its function is largely as a switch rather than a source of power. The energy input of labour is undeniably small, and, essentially, has changed little over the 1958-1981 period. As a result its exclusion from the system's energy budget will have little practical effect on total requirements. The central idea in this study of Prairie wheat agriculture is, ultimately, not human labour but rather determining how much society must draw upon its depletable sources of energy to produce wheat. Human labour is renewable, it is not depletable: it will exist whether or not wheat is produced. This, of course, is not the case for draft animals and machinery, and it is to a quantification of these two inputs that we now turn.

FIGURE 2.1

LABOUR INPUT TO WHEAT PRODUCTION
1800-1981



SOURCES: USDA, 1964. Labour Used To Produce Field Crops. Statistical Bulletin No. 346, U.S. Department of Agriculture, Washington, DC, and USDA, 1982 Economic Indicators of The Farm Sector: Production and Efficiency Statistics 1980, Statistical Bulletin No. 679, U.S. Department of Agriculture, Washington, DC.

TABLE 2.1

FOOD ENERGY REQUIREMENTS OF LABOUR IN WHEAT PRODUCTION

Year	Labour Input* (hr/ha)	Energy Cost** (MJ/ha)
1948	10.0	18.2
1953	8.1	14.8
1958	7.2	13.1
1963	5.4	9.8
1968	5.6	10.2
1973	6.0	10.9
1977	5.7	10.4
1981	5.5	10.0

*Labour input calculated for Northern Plains Agricultural District from USDA, 1982. Economic Indicators of the Farm Sector: Production and Efficiency Statistics 1980. Statistical Bulletin No. 679. U.S. Department of Agriculture, Washington, DC.

**Adult male; 65 kg; 20-39 years of age; with daily food intake of 12.5 MJ; working 7 hr/day; consuming 1.8 MJ/hr.

TABLE 2.2

MUSCULAR ENERGY EXPENDITURE OF HUMAN EFFORT

Year	Labour Input* hr/ha	Hand Labour** hr	Percent	Energy Expenditure*** MJ/ha
1948	10.0	23	(2.3)	10.1
1953	8.1	16	(1.3)	7.9
1958	7.2	11	(0.8)	6.8
1963	5.4	8	(0.4)	5.1
1968	5.6	6	(0.3)	5.2
1973	6.0	5	(0.3)	5.5
1977	5.7	5	(0.3)	5.3
1981	5.5	5	(0.3)	5.1

*From Table 2.1

**Calculated for wheat farming from USDA, 1947, Progress of Farm Mechanization. Misc. Publ. NO. 630. U.S. Department of Agriculture, Washington, DC up to 1953 with extrapolation of linear decrease to minimum of five percent.

***Derived by multiplying hand labour by 1.48 MJ/hr and the remainder by 0.9 MJ/hr.

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III. DRAFT ANIMALS

No fewer than 30 years ago animal power was still the "modus operandi" of agricultural practice. At that time, before mechanization was well under way, fully three-quarters of commercial farms in Western Canada owned and maintained draft animals. Not until the early 1960s were those animals which remained finally pastured. For the first few intervals of the study period, then, animal power was a significant component of wheat-production energy requirements.

The type of animal employed in Prairie agriculture changed with time and underwent at least one major transition before the diffusion of tractor power. During the early years of Western settlement it was the powerful slow moving ox which supplied the primary energy needed to break the new land and work the soils into a fertile seed bed. Data on the precise number of animals existing during this period are not generally available, but in 1886 the Canadian Dominion Bureau of Statistics recorded the presence of some 14,000 oxen, which at the time made up just one-third of the estimated work force (DBS, 1886). Their prominence was relatively short lived (numbers had been already falling for some time) and with the spread of farming throughout the region over the next decade the more agile faster-moving horse soon replaced those that remained. Horses were well suited to prairie farming conditions, and their numbers quickly swelled to reach close to 2.5 million by the mid-1920s.

Canadian Department of Agriculture records indicate that the draft animal work force never exceeded the level it attained in this prosperous era, and it soon entered a historic decline from which it never recovered (Statistics Canada, 1981). Within 20 years it was one-half its former level. The initial cause for the demise, one which preceded the widespread displacing effects of "tractorization" was the economic depression and the severe droughts experienced during the 1930s. Both events did much to depress agricultural activity throughout the region, and while tractors were available during this period, endemic high costs, heavy fuel consumption and frequent repairs made their operation only marginally economic. The ultimate doom of the animal work force, however, came with the period of rapid post-war agricultural expansion and the intensification of modern practices. An example of the speed with which this took place is shown by the drop in numbers over the initial five years of the study period. Between 1948 and 1953 more than 500,000 animals disappeared from service. By the late 1950s the transition into mechanized production was virtually complete, and by the early 1960s few if any animals were functioning in a productive capacity. Estimates for the 1948-1963 period are shown in Table 3.1.

Calculations of the energy input of draft animals is based entirely upon the embodied energy costs food consumed while in service. According to data complied by Grest (1936) an average horse in Western Canada between the ages of three and 20 years would consume roughly 1900 kg of feed annually under typical working conditions. Out of this total mass approximately 1430 kg would consist of hay, 350 kg of oats and 120 kg of mixed small grains. During the phase-out of draft animals in the late 1940s and 1950s horses which entered service most likely worked fewer hours at less strenuous tasks as tractors became more prevalent. Data compiled by the U.S. Department of Agriculture (USDA, 1964) indicate that this indeed was the case for animals in the U.S., and it also indicates that under these conditions less feed would be consumed. Comparable Canadian figures do not exist, but considering the magnitude of the accompanying decrease (ten percent in the U.S. between 1945 and 1960) the exclusion of this variable will have only a minor effect. As a result the constant feed value of 1900 kg per annum was used in calculations for each interval.

Before deriving energy input costs, the feed requirements per animal must be multiplied by the total number of working animals, and divided by the area of principle crops to obtain consumption values on a per hectare basic. The results of these calculations for the years in question are shown in Table 3.2. To arrive at the corresponding production costs of feed, each contributing type was computed on the basis of wheat equivalents; that is, the total mass of 1900 kg was treated as if it consisted wholly of wheat. The method, while it is general in its approach, was considered legitimate even though wheat itself makes up only a small proportion of the overall quantity, for its costs of production are in essence not much different from those of the other small grain and forage inputs. Small discrepancies where they do occur will be in all likelihood subsumed within the error of calculation.

Of paramount importance to process analysis is, of course, that energy which is consumed in the growing of the wheat crop, not the energy content of the grain itself. Such values are important to studies of biomass production and metabolic conversion efficiencies but not to the requirements of commercial production. Therefore, in constructing the final energy costs of animal feed, we must wait until all production input have been summed to total in a later section and the energy intensities of wheat production calculated.

TABLE 3.1

DRAFT ANIMALS ON PRAIRIE FARMS
1948-1981

Year	Total Animal Population*	Idled Population** Percent	Working Population
1948	1,289,013	20	1,031,210
1953	577,723	20	462,178
1958	343,173	20	274,538
1963	246,767	25	185,075
1968	Not appl.	-	-
1973	Not appl.	-	-
1977	Not appl.	-	-
1981	Not appl.	-	-

*Statistics Canada, 1948-1981. Census of Agriculture, five and ten year series, Minister of Supply and Services, Ottawa.

**Idled population consists of horses and mules younger than 3 years and older than 20 which were considered incapable of achieving full working capacity. The last recorded value is an estimate based on annual attrition.

Table 3.2

ANNUAL FEED CONSUMPTION OF PRAIRIE DRAFT ANIMALS

Year	Annual Feed Consumption* kg/horse	Horses per 100 ha**	Feed Consumption kg/ha/year
1948	1900	5.9	112
1953	1900	2.5	47
1958	1900	1.5	29
1963	1900	1.0	19
1968	Not appl.	-	-
1973	Not appl.	-	-
1977	Not appl.	-	-
1981	Not appl.	-	-

*Grest, E. G. (1936). An Economic Analysis of Farm Power in Alberta and Saskatchewan. Canadian Department of Agriculture, Ottawa, Ontario.

**Product equals working population divided by total area sown to principle grains in Western Canada.

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IV. MACHINERY

The determination of machinery's input to the wheat-production system is an involved task which is somewhat circuitous in nature. The problems involved in its accounting are many, there are great disparities in cultural practices, in the form and scale of operations, in the type, size and age of mechanical equipment and, of course, between the different periods of study. Disaggregated information is rare and both farm and regional inventories are few. Because of these difficulties there was little chance of calculating directly how much machinery was being used during the study period to produce wheat. As a result machinery is perhaps the least certain among all production inputs, and results should be interpreted accordingly, as indicative -- not definitive -- estimates of actual on-farm requirements.

The approach taken in this study (after Smil et al., 1983) was to compute the equivalent energy input of the average mass of farm machinery depreciated or worn out in servicing one hectare of wheat during a one-year production cycle. The common denominator in all calculations was the typical Prairie tractor and its proportional contribution to overall equipment manifests. After a process of scaling to derive mass values for each interval, embodied energy costs (which were themselves historically adjusted to reflect efficiency improvements over time) where applied to hectare requirements to arrive at the equivalent energy expenditure.

Field Operations

During the nineteenth century people of predominantly European stock brought the cultural practices of Eastern Canada, the U.S. and Europe to Western Canada (Buller, 1919). Working the fertile land, farmers originally practiced continuous cropping broken only by the occasional year of summer fallow to control weeds or restore depleted soil moisture. In this manner the native Prairie ecosystem supported "intensive" cropping for many years (with little or no fertilizer inputs and very few soil conservation measures), until about the turn of the century, when cultivated areas rapidly expanded and fallowing became more widely practiced. After years of what in essence were longer rotations, the two-year wheat-fallow cycle became the most common cropping sequence in the drier southwest and southcentral areas of the region, while the three-year wheat-wheat-fallow cycle became popular in the surrounding areas where the soil moisture regimes would permit (Peterson, 1965).

The pace of early farming was geared to the use of draft animals as traction power and, for the most part, equipment was designed accordingly. Standard tillage implements included the mouldboard plow, the disc and spike-toothed harrow, and the ordinary cultivator. The size of the equipment was typically limited by the number of animals that could be harnessed in one team and was generally less than five metres in width (Anderson, 1967). With the advent of tractor power the use of much larger equipment became widespread. As the negative side effects of this equipment became recognizable in turn, the use of lighter, less destructive types replaced these early varieties. The new equipment included subsurface implements such as the Noble blade, heavy duty cultivators, rod weeders, and a broad array of surface implements collectively known as disk-tillers (Symes, 1980). The mouldboard plow by this time had fallen into disuse on all but the wettest soils. Equipment sizes continued to grow over the next 25 years and had peaked by the early 1970s. In 1973 it was not uncommon to find a 150 hp tractor pulling a ten metre span of tillage implements in one unit. Throughout the period of mechanization many tillage implements incorporated fertilizer and seed boxes as standard equipment, effectively replacing operations that were well done in two or three passes with one.

Actual field operations have not changed radically since wheat farming was first established; they include seedbed separation, crop seeding, fertilizer application, herbicide spraying and combining in the fall. A typical sequence consists of primary tillage with a heavy-duty cultivator and a harrowing implement in the fall (with the possible addition of fertilizer and herbicide application), and secondary tillage in the spring with a discer or seed drill preceded by a heavy-duty cultivator with attached harrows and equipped with mounted seed and fertilizer hoppers. A subsequent operation might include soil packing in either the same or a separate operation, or harrowing with a spike-tooth or tyne harrow.

After seeding is complete herbicides are normally applied by a tractor-drawn or tractor-mounted sprayer when the crop is in early stem extension stage. Dusting by plane is not a common practice in Western Canada and is usually economic only for extremely large-scaled operations. Following spraying the wheat requires little in the way of care during the growing season, except for perhaps the periodic application of insecticides where localized infestations occur. The only other operation of significance is the harvesting operation, which is either performed in one pass by direct combining or in two by swathing and threshing separately. Threshed grain is then simply augured out of the combine into an accompanying truck and driven directly to the nearest elevator for shipment to market, or alternatively to on-site bins for storage.

Machinery on Prairie Farms

In the estimation of machinery inputs what must be relied on are gross averages of what could be expected to be found on a typical wheat farm. The normalizing of data ultimately has the effect of concealing great variations between individual operators, but at the same time the level of description allowed by the approach is sufficient to reveal the magnitude and change of machinery over time. The first step in the calculation procedures involves the identification and quantification of equipment typically employed for each period in the time series.

A broad-based compilation of equipment complements on four model farms in Western Canada serves as a convenient starting point (Table 4.1). Data from the physical manifests shown in the table were drawn primarily from two Canadian Department of Agriculture studies (Johnson, 1971a; 1971b) which reflect the number, size and distribution of major items found on farms during the late 1960s. Minor items such as tools, augers, gas tanks, small motors and so on, were excluded because of their insignificant mass. Estimates of the weights of individual pieces were based on averages computed from a number of sources. Farm implement weights were obtained from Prairie Agricultural Institute evaluations, Implement and Tractor Redbook listings and company literature. Tractor weights were calculated from Nebraska Tractor Test reports, while truck weights were drawn from current dealer sales quotations. The mass listings of Table 4.1 consist either of the mean of selected manufacturer's makes and models within a specific size range (as in the case of tractors where five categories are listed) or values prorated on a mass unit basis (as in the case of drag harrows at 112 kg per meter of width). The most elusive items in the manifests were the self-propelled combines, with weights displaying great variation nominal descriptors of small, medium and large based loosely on grain cylinder size had to be used. Tillage equipment included the mass of fertilizer and seed-box attachments, while larger truck weights were recorded with steel grain boxes as standard equipment.

Predictably, as the size of an operation increases so too does the size, power and mass of machinery used to farm it. Tractors are more powerful and more numerous, combines become bigger, implements wider and trucks heavier. However when machinery complements are prorated on an areal basis, the reverse is true; both power and mass become less. For example, from Table 4.1, the 1000 ha model has twice the total mass of tractors, trucks, combines and implements, and twice the tractor horsepower of the 100 ha farm, but only one-quarter the mass and one-quarter the horsepower per hectare. What this implies, of course, is that the larger the farm the greater the efficiency of machinery use. The underlying causes of such improvement are many, but aside from inherent scales of efficiency, an important causal variable is the falling mass to power ratio of larger machinery. Data in the table also indicate that there is a surprising regularity in the ratio of tractor to total equipment mass: tractor mass alone accounts for an average one-fifth of all equipment by weight in each instance. As a result of this apparent consistency, from a knowledge of tractor values alone we make rough estimates of total complements for a range of other farm sizes.

How does this all relate to actual farms and their machinery requirements? The average-sized Prairie wheat farm in 1968 covered close to 94 ha. Drawn from agricultural census data (Statistics Canada, 1981a) and seeded area reports (Statistics Canada, 1981b) this average size lies very close to that of the first model farm listed in Table 4.1. However, the average size must be weighted to account for the predominance of larger farms in the region. Combining the values for Saskatchewan (67 percent of the wheat area at 118 ha/farm), Alberta (22 percent of the wheat are at 74 ha/farm) and Manitoba (11 percent of the wheat area at 56 ha/farm) we get a weighted average of 101 ha, a value so close to that of the model that it can be considered identical.

Assuming the ratio of tractor mass to inventory mass has remained constant over time, machinery and implement totals for other years in the time series can now be estimated by using 1968 as the base year, and scaling accordingly. Before doing this, however, we must derive tractor-mass values for each year in the time series. A number of calculations are required in this process, for which the first set of input data are assembled in Table 4.2.

The total number of tractors in service in Western Canada almost doubled during the study period, rising from approximately 180,000 machines in 1948 to just under 340,000 by 1981. The most rapid increase came during the decade of transition into mechanized practice; between 1948 and 1958 the number of tractors on farms rose by more than 50 percent. By 1958, in fact, there were more tractors per hectare than at any other time during the entire study period. Accompanying their increase in numbers was, of course, the dramatic use of horsepower ratings. Information drawn primarily from equipment sales records (Statistics Canada, 1977) indicates that the horsepower of the average Prairie tractor more than tripled, from a low of 25 in the earliest period, 1948, to a high of 83 in the latest, 1981.

For the calculation of tractor mass in each period it is important that an allowance be made for the fall in unit weights which has occurred since 1948. The result of lighter construction materials and improved mass to horsepower ratios, average unit weights declined from about 62 kg/hp in 1948 to around 48 kg/hp in 1977 (Table 4.2). As a result, the average tractor in service in the late 1970s was developing identical power with only three-quarters the mass of the comparable type 30 years earlier. All indications were that this trend should have continued into the last interval of the study period, yet in an interesting turn of events between 1977 and 1981 unit weight rose. Attempting to discover the underlying causes for this reversal data on some 400 tractors of various manufacturers makes and models sold in Canada between the years 1971 and 1981 were collected. The units were grouped into six categories, each based on horsepower ratings, and the weights calculated. Mass to power ratios fell between most of the categories, declining from 59 kg/hp in the 17-29 hp range to approximately 50 kg/hp in the 74-164 hp range (Table 4.3), though, in the category of highest ratings, the 165-387 hp range, the ratio went up appreciably, to 54 kg/hp -- an increase that is the direct result of these tractors four-wheel-drive capabilities.

At this stage of the calculations it is possible to verify the earlier estimate of inventory mass. Using the total number of tractors in service in 1968 from Table 4.2, 317,110, the figure is multiplied by the mass of the average tractor in the same year, 3016 kg, and by five again to account for the tractor to equipment ratio to result in a regional aggregate of roughly 4,782 X 10^3 tonnes of assorted tractors, trucks and implements. Dividing this total by the number of hectares sown to all crops in the Prairie region, 20,926 X 10^3 (Statistics Canada, 1981b) yields a product of approximately 228 kg/ha; a value just six percent higher than the originally calculated mass of 215 kg/ha listed for the 100 ha farm manifest in Table 4.1. Considering the inherent uncertainty in calculations of this kind the results are surprisingly close. The value of 215 kg/ha was used for the 1968 reference year in subsequent computations.

To complete machinery mass estimates, tractor power was derived by simply multiplying the number of tractors per hectare by average horsepower; tractor mass was calculated as the product of tractor power and unit weight; scaling factors were obtained by dividing tractor masses into the 1968 reference value; and machinery mass for each year computed by multiplying the 215 kg/ha index value by the appropriate scaling factor. Results for the 1948-1981 period are shown in Table 4.4.

The majority of improved agricultural land in the Prairies has always been sown to cereal grains, of which wheat accounts for by far the largest proportion. Considering most cereal grains in Western Canada are produced under similar agronomic conditions and comparable agricultures, the requirements for one will be much like the requirements for any other. Assuming this to be the case, the tractor mass and tractor power data for years other than 1968 and calculated across all Prairie cropland will be good indicators of what is needed for wheat in particular. The combined mass of machinery used on wheat farms then has risen dramatically over time, from 75 to 275 kg/ha between 1948 and 1981. As could largely be expected quantities rose most over the decade 1948-1958, and least during the years which followed. In fact the evidence suggests that by 1973 some type of saturation point has been reached. Remaining unchanged for each of the last three intervals, the mass of 275 kg/ha may be all that is needed to produce a wheat crop efficiently. Indeed if the future changes outlined in Chapter XIII are correct, it may be more than what is necessary for efficient production.

Energy Cost Calculations

Calculating the energy cost of machinery requires as a first step the derivation of an appropriate factor from the conversion of mass values into corresponding energy equivalents. Embodied energy costs arrived at by a number of investigators show substantial variation. Ranging from a low of 64 MJ/kg for combines and tractors to a high of 116 MJ/kg for tractors alone these estimates display a variance of close to 100 percent (Table 4.5). Notwithstanding each study's claim to legitimacy, I simply took an average of the energy costs from each study and employed it as a representative value in downstream calculation.

The product of averaging, 87 MJ/kg, is typical of late 1960s process technology and can be compared to a carefully calculated study of North American automobiles performed at about the same time (Berry and Fels, 1973). Having production requirements not unlike that of most farm machinery it is indeed surprising to find that the value calculated by Berry and Fels is identical to the one already arrived at. A further comparison reveals that this value is very close to the 85 MJ/kg used by Smil et al. (1983) in their study of corn production in the U.S.

As with the majority of industrial energy analyses, studies pertaining to the energy requirements of machinery are of relatively recent vintage, with little information being available prior to 1970. However, historical data on the energy costs of farm machinery's major construction material, steel, are available as far back as the early 1940s, and indications are that its attendant requirements have fallen significantly since that time in virtually all producing countries (Decker, 1976). Using historical data for the U.S. iron and steel industry (the majority of farm machinery in use in Western Canada is manufactured with U.S. Steel) compiled by Batelle Columbus Laboratories (1975), the reference value for farm machinery was adjusted to incorporate the changes in efficiency which occurred between 1948 and 1973 (Table 4.6). Over this period the average energy cost per kilogram of finished steel fell from 56 to 40 MJ, and reflected in the embodied energy cost of farm machinery, the result was a drop from 106 to 87 MJ/kg.

Efficiency increases in modern steelmaking have come about through progressive improvements in process technology (for example, better blast furnace and open-hearth operation, plant design and systems control) and through standard good 'housekeeping' practices (Leckie et al., 1982). Since 1973--the date of the last Batelle Columbus entry -- the closing of older facilities, the increasingly widespread use of scrap metal and the intensified shift towards continuous casting have extended efficiency gains into the present (AISI, 1982). According to U.S. Department of Energy estimates (DOE, 1983) there was a 15 percent improvement in the U.S. iron and steel industry between 1973 and 1981, a reduction which when incorporated into the last two intervals of study translates into farm machinery intensities of 82 MJ/kg for 1977 and 75 MJ/kg for 1981. Thus in a full sequence of energy savings spanning just over 30 years of industrial advancement requirements have dropped 31 MJ/kg, or an impressive 30 percent.

With the establishment of machinery's embodied energy costs, the only remaining step in estimating the full cost of farm machinery inputs is the addition of an energy factor for equipment repair and maintenance. The procedure itself involves a rather straightforward multiplication based on the physical weight of replacement parts necessary to keep an operator's trucks, tractors and implements in good running order. Replacement parts, as they consist mostly of steel, can be simply assigned the same manufacturing energy cost per kilogram as the original machinery and added on as a percentage to total costs. However, the quantity of replacement parts clearly depends upon the serviceable life of the equipment in question.

The estimated wear-out life of farm machinery in Western Canada ranges from a low of 13 years for combines to a high of approximately 25 years for soil packers (Johnson, 1971a). Tractors, the backbone of any grain operation, have been estimated to last approximately 15 years with average upkeep. Such values are, of course, generalized across a broad array of disparate farm practice and maintenance schedules. Excellent maintenance could extend equipment service life by up to 10 years, while poor maintenance could equally reduce it. (On one 1000 ha grain farm surveyed in central Saskatchewan a Massey Ferguson 88 tractor purchased in 1960 was still engaged in active field work at the time of writing.) An average of 15 years was chosen as a representative value for all items in the equipment manifest. Compared to American Society of Agricultural Engineers standards (ASAE, 1981) such an estimate is not out of line.

Maintenance and repair estimates are equally applicable to Canada as they are to the United States. Computing an energy cost for replacement parts, Berry and Fels (1973) estimated that just under two percent of the total free energy cost of manufacturing an automobile could be added. Pimentel et al. (1973) in estimating a comparable cost for farm machinery applied a six percent figure to their calculations, and used a machinery service life of 10 years. Smil et al. (1983) after consultation with a number of farm implement and tractor dealers assigned a value of eight percent, and used a machinery service life of 12 years. Total accumulated repair costs according to the ASAE (1982) are exponential in nature and therefore lead to an increased repair rate over the lifetime of the equipment. Following this, the 15 year service life of machinery used in this study required the slightly higher energy cost for repairs of ten percent.

Somewhat surprisingly the issue of energy costs for farm machinery repair and maintenance has recently been the focus of some debate, and on at least two occasions has led to the publishing of extraordinary results. In one paper Fluck (1982) applies an ASAE business costing formula (EP, 391) which puts total accumulated repair costs at 129 percent of the equipment's original list price. Taking this as a direct correlate of energy costs he concludes that the energy requirement for repairs and maintenance should be 129 percent of the initial manufacturing input. While replacement energies and mass values are equivalent, this means that 129 percent of original machinery mass will be replaced during a machine's lifetime. Yet, putting this in physical terms, a 3000 kg tractor will consume an average of roughly 4000 kg of replacement parts during its useful life! This is obviously an incredibly high figure.

Aside from the relative magnitude of such a value the calculation process is itself flawed. By basing his derivation on ASAE standards Fluck inadvertently included the remuneration of labour as a physical commodity. Doering (1980) foresaw this error in an early publication and corrected for it by assigned two-thirds of the 129 percent value to labour. In subsequent calculations the procedure was again, to equate monetary and energy costs, with the result that the repair cost was estimated to be one-third of equipment original energy requirements, or following the same energy to mass relationship as before, the 3000 kg average tractor would now require about 1300 kg of replacement parts during its life-time. This value is less than Fluck's 4000 kg, but it is nevertheless extremely high; prorated over a ten year machine life, it would require an annual input of 130 kg!

Despite lower levels, Doering's calculation is flawed again in exactly the same way as was Fluck's: on both accounts error lies in the use of monetary costs as a proxy for energy requirements. Such an approach is consistent with standard input-output accounting, but it is not consistent with the process analysis approach the authors assumed. As can be seen from the foregoing calculations, the results of such comparison lead to grossly distorted values. There is simply no inherent relationship between monetary inputs and physical mass; and any correlation based on this is categorically invalid. The proper approach is to estimate specifically the mass of replacement parts and assign to such mass the equivalent energy cost.

The energy equivalent of farm machinery depreciated or worn out in servicing one hectare of wheat for each period in the time series are shown in Table 4.7. Final values were obtained by multiplying mass per hectare machinery outputs by corresponding energy intensities and by 1.10 to account for repairs and maintenance requirements, and by dividing the product by 15, the average number of years a machine would be in service. Results for each year indicate that over the study period energy costs grew from a low of 583 MJ/ha in 1948 to a high of 1755 MJ/ha in 1973. After 1973 inputs surprisingly fell; to 1654 in 1977 and again to just over 1500 in 1981. Equal to machinery energy costs more characteristic of the late 1960s, the value of 1981 is in fact 15 percent lower than the all time high recorded in 1973. Considering that between 1973 and 1981 production itself grew by 50 percent, the reduction is impressive indeed. During this period farmers held machinery inputs constant, reductions came solely from a lowering of unit energy requirements as a result of improvements in industrial efficiency. In the future with further technological advancement and more efficient machinery use it is entirely likely that the minor improvements of the past can be extended.

TABLE 4.1

WHEAT FARM EQUIPMENT MANIFESTS

		Farm Size (ha)							
		100		250		450		1000	
Item	Equipment Size**	No.	Wt. (kg)	No.	Wt. (kg)	No.	Wt. (kg)	No.	Wt. (kg)
Tractor	< 30 hp	1	1470	-	----	1	1470	-	----
	30-36 hp	-	----	1	2040	-	----	1	2040
	37-49 hp	1	2400	-	----	1	2400	-	2400
	50-74 hp	-	----	1	3450	1	3450	-	----
	> 74 hp	-	----	-	----	-	----	1	5880
Combine	Small	1	6560	1	6560	-	----	-	----
	Medium	-	----	-	----	1	7700	-	----
	Large	-	----	-	----	-	----	1	8840
Swather	3.7 m	1	920	-	----	-	----	-	----
	4.3 m	-	----	1	1070	-	----	-	----
	4.9 m	-	----	-	----	1	1220	1	1220
	5.5 m	-	----	-	----	-	----	1	2130
Cultivator	3.7 m	1	1270	-	----	-	----	-	----
	4.3 m	-	----	1	1470	-	----	-	----
	4.9 m	-	----	-	----	1	1700	-	----
	7.0 m	-	----	-	----	-	----	1	2440
Discer	Double disc	1	2190	-	----	-	----	-	----
	4.9 m	-	----	1	2190	1	2190	1	2190
	6.4 m	-	----	-	----	-	----	1	2880
Drill	3.7 m	1	1630	-	----	-	----	-	----
	4.3 m	-	----	1	1902	1	1902	2	3800
Drag harrow	5.5 m	1	620	-	----	-	----	-	----
	9.1 m	-	----	1	1020	-	----	-	----
	11.0 m	-	----	-	----	1	1230	1	1230

TABLE 4.1 (continued)

		Farm Size (ha)							
		100		250		450		1000	
Item	Equipment Size**	No.	Wt. (kg)	No.	Wt. (kg)	No.	Wt. (kg)	No.	Wt. (kg)
Packer	3.7 m	1	1660	-	----	-	----	-	----
	4.3 m	-	----	1	1940	-	----	-	----
	4.9 m	-	----	-	----	1	2210	-	----
	6.1 m	-	----	-	----	-	----	1	2770
Sprayer	9.8 m	1	370	-	----	-	----	-	----
	13.1 m	-	----	1	500	1	500	-	----
	16.5 m	-	----	-	----	-	----	1	630
Truck	½ - 3/4 t	1	1725	1	1725	1	1725	1	1725
	1 - 1½ t	-	----	1	2725	-	----	1	2725
	2 - 3 t	-	----	-	----	1	4760	1	4760
Total weight (kg)			21,505		27,620		34,105		50,305
Tractors only			3,870		5,490		7,320		10,320
Machinery only			12,155		16,500		21,505		28,955
Implements only			9,350		11,120		12,600		21,350
Mass intensity (kg/ha)			215		110		76		50
Power intensity (hp/100 ha)			68		38		28		18

*Manifests based on Johnson, L. M. 1971. Machinery Costs on Prairie Wheat Farms in Central Saskatchewan, and Johnson, L. M. 1971. Machinery Costs in Central Alberta, Economics Branch Publications 71/10 and 71/16, Canadian Department of Agriculture, Ottawa.

**Both equipment size and weights averaged from Implement and Tractor Redbook (various editions), Nebraska Tractor Test listings in Agricultural Engineers Yearbook (various editions), and the Prairie Agricultural Machinery Institute (various publications).

TABLE 4.2

TRACTORS IN PRAIRIE AGRICULTURE

Year	Number of Tractors*	Average Pto Horsepower**	Average Unit Weight (kg/hp)***	Tractors per 100 ha[t]
1981	336,920	83	50	1.41
1977	328,660	80	48	1.52
1973	315,720	74	51	1.55
1968	317,100	58	52	1.52
1963	299,500	42	54	1.59
1958	288,340	33	57	1.61
1953	247,520	28	58	1.33
1948	182,430	25	62	1.05

*Interpolated from Statistics Canada 1946-1981. Census of Agriculture, five and ten year series, Minister of Supply and Services, Ottawa.

**Calculated on a power take-off basis. Assuming a typicaly 15 year service life, the average tractor in use in any given year was sold roughly 7 years early. Horsepowers were derived from Statistics Canada, 1942-1977. Farm Implement and Equipment Sales, Catalogue 63-203, annual, Minister of Supply and Services, Ottawa.

***Typical weights averaged from Nebraska Board of Tractor Test Engineers, 1940-1977. The Nebraska Tractor Tests. Department of Agriculture Engineering, University of Nebraska, Lincoln, NE.

[t]Values equal the number of tractors divided by the area seeded to principle field crops from Statistics Canada, 1948-1981, Field Crop Responding Series, Catalogue 22-002, seasonal, Minister of Supply and Services, Ottawa.

TABLE 4.3

WEIGHT TO POWER RATIOS FOR DIFFERENTLY SIZED TRACTORS*

Tractor Size Ranking	Hp. Range	Number in Sample	Maximum Mean hp	Average Machine Weight (kg)	Weight to Power Ratio (kg/hp)
Small	17 - 29	45	22.7	1342	59.1
	30 - 36	29	33.9	1947	57.4
Medium	37 - 49	50	42.5	2230	52.5
	50 - 74	91	60.3	3156	52.3
Large	75 - 164	134	113.0	5694	50.4
	165 - 387**	53	226.6	12069	53.5

*Tractor data drawn from Nebraska Tractor Tests, 1971-1981. In The Agricultural Engineers Yearbook, annual, American Society of Agricultural Engineers, St. Joseph, MI.

**Four-wheel-drive models.

TABLE 4.4

MACHINERY EMPLOYED TO WORK ONE HECTARE OF WHEAT
1948 - 1981

Year	Tractor Power (hp/100 ha)	Tractor Mass (kg/100 ha)	Mass Index 1968 = 100	Machinery Mass (kg/ha)
1981	117	5850	1.28	275
1977	122	5856	1.28	275
1973	115	5865	1.28	275
1968	88	4576	1.00	215
1963	67	3618	0.79	170
1958	53	3021	0.66	142
1953	37	2146	0.47	101
1948	26	1612	0.35	75

TABLE 4.5

EMBODIED ENERGY COSTS OF FARM MACHINERY

Source	Item	Energy Cost (MJ/kg)
Doering	Tractors, combine	64
Makhijani and Lichtenberg	Trucks	71
	Farm Implements	79
Herendeen	Farm Implements	104
Clark and Johnson	Tractors	116

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TABLE 4.6

ADJUSTED FARM MACHINERY ENERGY COSTS

Year	Energy Cost per Unit Mass (MJ/kg)
1981	75
1977	82
1973	87**
1968	88
1963	92
1958	97
1953	103
1948	106

*Adjusted figures represent the energy cost of machinery, in service during the year listed.

**Average of values listed in Table 4.5.

TABLE 4.7

ENERGY EQUIVALENTS OF MACHINERY USED IN PRAIRIE WHEAT FARMING 1948-1981

Year	Input Cost* (MJ/ha)
1981	1513
1977	1654
1973	1755
1968	1387
1963	1147
1958	1110
1953	763
1948	583

$$\text{*Input cost} = \frac{\text{(Mass per ha)} \cdot \text{(energy cost per unit mass)} \cdot \text{(repair cost)}}{\text{(estimated service life)}}$$

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V. FUEL

Factors Affecting Relative Consumption

As in the preceding chapter where it was the farm operator who was personally responsible for the maintenance and repair of his equipment, it is again the operator in this section who is ultimately responsible for how much fuel that machinery will consume in the performance of a given task. To reduce running costs efficient operation and efficient use of fuel can be obtained by having all equipment in good running order, by timing operations properly (to reduce the distance of travel and idling requirements), by using the right machine for the job and, in general, by simply pursuing sound business practice. However, there is a limit to the savings these measures can bring about and regardless of the attention paid to detail, an operator must produce under a given set of environmental variables which vary greatly from farm to farm and over which he has little control. Variables include local soil type and soil conditions, topography, climate, field size and shape, as well as the presence of obstacles on the land such as windbreaks, ponds, ditches, and so on, and each has an impact on potential fuel consumption. For example, tilling fine-textured soil such as clay will require more fuel per hectare than a comparable coarse-textured soil such as sandy loam.

Moisture content will affect fuel requirements, as will working depth. Wet sticky clays use far greater amounts than dry loose loams -- in some cases as much as soils with a hard and dehydrated consistency -- and it has been estimated that increasing the depth of cultivation under typical Prairie conditions will double horsepower-hour and fuel requirements (Ridley, 1961).

The presence of hills, ridges, valleys, pot-holes and the area of land worked will also affect fuel consumption. In Nebraska it was found that fuel use was higher on smaller than on larger fields (Shelton & Von Bargen, 1980).

Differences were not necessarily due to improvement in field efficiencies, but rather were the result of less road travel between holdings. Field speeds themselves are an additional factor. The faster the pace of the operation the higher the rate of fuel consumption. This is not true in all instances however, for some implements such as discs tend to penetrate less at higher speeds and demand lower draft requirements. In addition to environmental variables, the variety of wheat being grown and the yield of the crop will affect requirements. For example both solid stems and heavier stands require more power to combine (Bigsby, 1959).

The machine which is responsible for by far the largest proportion of on-farm fuel consumption is, of course, the common tractor. Yet, while accounting for its consumption of fuel is typically a straightforward process, it must be pointed out that in terms of work per unit of fuel consumed the actual size of tractor has little bearing on field efficiencies. Butterworth and Nix (1983) report from OECD tests that all classes of diesel and gasoline tractors consume approximately equal quantities of fuel per horsepower-hour of energy delivered. Of course, within each class there are great differences amongst the various makes and models, but on average results should be expected to be similar. For example, larger tractors pulling wider implements may spend less time tilling the field, but they invariably consume fuel at a much higher rate. To further this point one U.S. report indicated that large- and small-sized tractors used roughly the same amounts of fuel on a per hectare basis when given identical tasks, whereas intermediate sizes burned slightly less (Tompkins & Carpenter, 1977). (These findings apply specifically to gasoline-gasoline and diesel-diesel comparisons, not to gasoline-diesel tests, in such cases the diesel engine by virtue of its greater mechanical efficiency is categorically superior.)

Specific fuel requirements for a number of common wheat farming operations have been collected in Table 5.1. The assembled data were drawn from estimates for North Dakota, which has similar conditions to those of Western Canada, and were collapsed into categories of low, average and high consumption. Data of this type (and indeed as has already been pointed out for farm practices themselves) are highly variable and defy precise quantification. Non-fallow land fuel requirements for primary tillage range from a low of 5.0 l/ha to a high of 75 l/ha: a fifteen-fold difference in values! Moreover, after summer-fallow, with a low fuel consumption, one pass with a field cultivator may constitute only one-fifth of total requirements, while under the high use category the same pass may constitute more than 50 percent. What is also worthy of mention is that somewhat surprisingly as much fuel may be consumed in summer-fallow and after-fallow practices as in continuous cropping. This in fact has been found to be the case in Western Canada, the proportion of cropland left in fallow from year to year has little effect on overall fuel use (Canada Grain News, 1984). Given such variability, compiling fuel-use statistics on a task-by-task basis could only lead to grossly inaccurate results. However, it is possible to gauge farm consumption totals on the basis of regional aggregates, and this was the approach taken.

Estimating Prairie Fuel Use

Historically the input of fuel has always constituted the foremost energy requirement of producing wheat in Western Canada, yet, there has been little systematic coverage of its use. Nonetheless by selectively extracting from a broad array of published statistics on the major contributing types (gasoline, diesel fuel, fuel oils, tractor fuel, stove oil, kerosene, lubricating oils and greases), a reasonably accurate picture of consumption was obtained. Major fuel types were collapsed into three categories, and their total consumption for each period between 1948 and 1981 is recorded in Table 5.2.

In this study, farm consumption included all farm activities in their capacity to use of refined petroleum products (lubricating oils and greases are not fuels per se but as they do constitute a refined product their inclusion within the group is logical) and not just field operations alone. Totals include fuels burned by tractors, trucks, combines and any other fuel-consuming machinery which can be assigned to the farming operation as a functioning business enterprise. However, private automobile use is excluded from totals as are the heating costs of farm housing. Following the energy cost of living argument (see Chapter II for details) such uses were considered to be basic costs quite unrelated to the requirements of Prairie production. Aviation fuel for aerial spraying was ignored because of its negligible contribution, while custom work involving activities, such as primary tillage, seeding and harvesting, has been included as a cost for which farm operators are considered responsible. The transporting of production inputs, such as fertilizer, seed and pesticides, from the dealership to the farm gate are also included as is the movement of harvested grain to its primary distribution point.

As could be anticipated, consumption of liquid fuels increased in proportion to the diffusion and intensifying use of power machinery. For example, between the years 1948 and 1958, when the mass of machinery employed on wheat farms doubled, fuel used doubled as well. Up until the mid-1970s quantities continued to rise. As long as petroleum prices rose little in constant dollars -- they had the least of all inputs or farm services between 1948 and 1973 (Statistics Canada, 1984) -- consumption of aggregate fuels increased, rising from approximately 900×10^6 l to 2600×10^6 l. After the

1973 petroleum price hikes the indexed price of farm fuel began an upward swing which brought it to a level even with other inputs by 1977. In that year the quantities consumed on the Prairies peaked at roughly 3000 X 10^6 l, or 15 percent above what it had been four years earlier. However at precisely the same time as fuel prices began to escalate more rapidly than the price of any other input, levels of consumption dropped, and dropped dramatically; by 1981 consumption had fallen 20 percent. This reduction in fuel use combined with the fact machinery inputs remained stable over the same period, indicates that farmers had become much more efficient in their use of fuel, and it suggests also by extension that in 1981 there was excess machine capacity.

In the short history of Prairie fuel use initial varieties quickly gave way to the preferred use of gasoline. Early model tractors burnt an assortment of petroleum products; including virtually all grades of fuel oil, tractor fuel, distillate, stove oil and kerosene. In fact as a major industrial consumer of petroleum products tractor engines are unique in that they are the only large class of engine designed to run on such a broad array. By the late 1940s, however, the use of these models was waning and with mechanized practice came gasoline tractors. By 1953 gasoline was the number one Prairie fuel and by 1958 it was virtually the only fuel of significance, capturing then close to 85 percent of the farm market.

In high-powered tractors diesel engines are preferred to gasoline and subsequently, as the average horsepower of Prairie tractors rose, so to did the use of diesel fuel. Diesel-fuel consumption had been steadily growing since the late 1950s yet the most rapid increases came about during the 1970s and early 1980s when its consumption almost doubled from 735 X 10^6 l to 1325 X 10^6 l. During the same period the average rating of tractors sold in Canada passed the 100 hp mark. The diesel engine is durable, gives good performance and with a compression-ignition design it is inherently more efficient than the comparable spark ignition gasoline engine. Under top-working conditions mechanical efficiencies should reach 35 percent for diesel and 28 percent for gasoline models. Contributing as well to its widespread use is the fact that the fuel itself contains 12 percent more energy per volume, 38.6 MJ/l versus 34.6 MJ/l for gasoline. In the effort to reduce costs a diesel tractor delivering on average 1.4 times as much power from a given litre of fuel (a litre which itself costs less originally) would be the logical choice. Over the last interval of the time series diesel became the most widely used fuel and it did so largely at the expense of gasoline.

In absolute term the 20 percent drop in fuel consumption between 1977 and 1981 is almost entirely accounted for by gasoline. Data collected by Statistics Canada (1983) indicates that over this period: tractors in the less than 60 hp range saw less working time; machinery in general was engaged more productively; and many cultural operations were either combined or eliminated. As well, reductions accrued from better vehicle maintenance, travel at slower speeds, use of the most appropriate vehicle for purposes of general transportation (i.e., restricting the use of pickups to related farm tasks) and combining business trips away from home.

Of the six principal field crops which normally occupy more than 90 percent of the cultivated land in Western Canada, no one stands out as being unique in its typical pre- and post-harvest requirements (University of Manitoba, 1977). Cultural practices involving primary tillage in the fall, secondary tillage in the spring and the seeding process itself for wheat, oats, barley, rye, flax and canola are all basically similar. Harvesting operations as well differ little; requiring in most instances no more than a change of combine header. Thus, it was considered reasonable under normal conditions that the quantities of fuel consumed on a Prairie-wide basis would serve as an indicator of fuel consumed in wheat farming alone. An alternative way to state this is that in general the amount of fuel consumed in the production of a given crop will match its regional importance (Shelton & Von Bargen, 1980). Therefore the wheat sown to roughly 60 percent of Prairie cropland would be expected to account for 60 percent of the region's fuel use. Calculations of fuel use were further simplified by the relatively minor presence of non-grain related agricultural activities. As a result, to derive the proportional fuel consumption of wheat production alone, total fuel use is simply divided by the seeded area of all principal field crops to arrive at per hectare requirements.

In calculating the fuel use energy equivalent inputs were multiplied by their corresponding enthalpies (according to standard Canadian values, shown in Table 5.3) and summed to totals. For prorated usage totals were divided by the area of all crops. The results of these calculations have been assembled for each year in Table 5.4.

On an areal basis the intensity of fuel use is much the same as it was for total consumption: it increased dramatically until the late 1970s and then fell back (to levels more characteristic of the late 1960s). The most rapid increase occurred during the diffusion of machinery between 1948 and 1958. Over this decade consumption nearly doubled, from just over 50 l/ha to just under 95 l/ha. Energy costs, of course, followed suit, rising from a low of 1900 MJ/ha at the beginning of the study period, to around 3300 MJ/ha by 1958 and to a high of just over 5000 MJ/ha by 1977 before it too fell by the early 1980s.

One variable which was not included in the estimation of farm-fuel costs is the so-called energy cost of energy (i.e. the energies expended in the extraction, transportation, refining and distribution of petroleum resources).

Published values range from roughly 2 to 20 percent of the farming fuel's heat of combustion (Boustead & Hancock, 1979), and if they were to be included, it would have been a process of simply multiplying the totals in Table 5.4 by the appropriate factor, be it 1.02, 1.05 or 1.10. However, several considerations reduce the usefulness of this variable. First, specific costs for the fuel in question and its initial origin are rarely known: the multipliers that are used are typically no more than nation-wide aggregates, averaged for the sake of simplicity. Secondly, since efforts are continually being made to improve production efficiencies by both the introduction of new technologies and the installation of sophisticated machinery, process requirements are constantly changing. Thirdly, and most importantly, however, is that the additional cost is so small that its omission will have very little impact on overall farm requirements. (This is, however, not the case for the energy costs of electricity where associated production requirements will triple the actual value of fossil-fueled generation.) A caveat is required here though, this variable will gain greater significance in the future as the energy costs of exploration and extraction of increasingly scarce oil reserves rise, and it will then be of importance greatly out of proportion with today's.

TABLE 5.1

SPECIFIC GASOLINE REQUIREMENTS FOR FIELD OPERATIONS

Crop	Machine	Number of times Over Field	Consumption (l/ha) Low	Average	High
Summer fallow	Chisel Plow	1	3.7	15.6	32.1
	Field Cultivator	2	5.6	25.2	52.5
	Total		9.3	40.8	84.3
Small grain after fallow	Field Cultivator	1	2.8	12.6	26.1
	Grain Drill	1	0.6	2.2	4.3
	Drag	1	0.4	1.2	2.4
	Sprayer	1	0.6	0.8	1.0
	Swather	1	2.2	3.2	4.0
	Combine	1	6.6	10.0	13.6
	Total		13.2	30.0	51.4
Small grain or non-fallow	Moldboard plow, packer, grain drill	1	5.1	34.2	75.4
	Sprayer	1	0.6	0.8	1.0
	Swather	1	2.2	3.2	4.0
	Combine	1	6.6	10.0	13.6
	Total		14.5	48.2	94.0

Source: Frith, R. R. and Promersberger, W. J. 1974. Estimates of Fuel Consumption for Farming and Ranching Operations Under Typical North Dakota Conditions. Bull. No. 493, Dept. of Agricultural Engineering, North Dakota State University, Fargo, ND.

*To convert into diesel-fuel requirements multiply by 0.73.

TABLE 5.2

FUELS CONSUMED IN PRAIRIE AGRICULTURE
1948-1981

Year	Diesel	Fuel Type (10^6 l) Gasoline	Other*	Percentage Distribution	Total (10^6 l)
1981	1324.50	1129.92	66.33	53/44/3	2521.78
1977	969.60	2019.73	49.03	32/66/2	3038.31
1973	735.72	1828.44	47.10	28/70/2	2611.22
1968	655.58	1601.31	39.95	28/70/2	2296.83
1963	378.30	1375.76	38.05	21/77/2	1792.14
1958	226.13	1401.62	37.24	13/84/3	1665.00
1953	200.45	1072.60	100.76	14/78/8	1373.82
1948	65.15	65.61	207.84	7/71/22	929.08

*Consists of light-and heavy-fuel oils, tractor fuel, stove oil, kerosene, lubricating oils, and grease. Liquid petroleum gas is not consumed in significant quantities.

Sources:

1948 - Fuel oils, furnace oils, tractor fuel, stove oil, and kerosene, were taken from Statistics Canada, Consumption of Petroleum Fuels In Canada, Cat. 45-206, annual, 1945-1966, Minister of Supply and Services, Ottawa. Each fuel type was listed for tractors and other motor vehicles. In the Prairies the middle distillates were considered to be consumed solely on farms. Diesel fuel consumption was calculated as the difference between the listed total and other vehicles. Other vehicle use was calculated from Statistics Canada, Motor Carriers Freight-Passenger, Cat. 53-0-20, annual, 1941-1956. In 1948 no diesel fuel use was reported by motor carriers in Western Canada. The Motor Vehicle, Cat. 53-203, annual 1945-1959, listings of taxed gasoline subtracted from the 'domestic consumption' category in Statistics Canada. Refined Petroleum Products, Cat. 45-204, annual 1945-1971. The result, less 15 percent to account for other untaxed uses (as listed in Cat. 53-203), is equal to the quantities consumed by farm equipment. Lubricating oils and greases were a best estimate derived from Statistics Canada, Sales of Lubricating Oils and Grease, annual 1948-1954.

1953 - Ibid, 1948.

1958 - Fuel oils and furnace oils subsumed under tractor fuel. Tractor fuel, stove oil, and kerosene; ibid, 1948. Diesel fuel, gasoline, lubricating oils and grease shown from detailed listings in Statistics Canada, 1958 Farm Survey Report No. 3: Motor Vehicles and Machinery on Farms, Cat. 21-510, occasional. Automobile use assigned to farm operations was excluded from calculations.

1963 - Tractor fuel, stove oil, and kerosene in steady decline after 1958 were deleted from calculations. Diesel fuel, gasoline, lubricating oils and greases taken from Statistics Canada, Refined Petroleum Products Vol. II: Consumption of Petroleum Products, Cat. 45-208, annual, 1963-1977. Diesel fuel defined includes all grades of distillate fuel sold for diesel engine use.

1968 - Ibid, 1963.

1973 - Ibid, 1963.

1977 - Ibid, 1963.

1981 - Diesel fuel and motor gasoline calculated from Statistics Canada 1983. Farm Energy Use Survey, 1981, Cat. 21-519, occasional. Both sets adjusted upward ten percent to account for farm sizes not included, and adjusted upward again by varying amounts to account for custom work listed elsewhere in the publication. Lubricating oils and greases estimated from past performance at approximately 2.5 percent of total fuel consumption.

TABLE 5.3

CANADIAN FUEL CONVERSION FACTORS

Fuel Type	Enthalpy (MJ/l)
Motor gasoline	34.62
Diesel fuel	38.64
Kerosene*	37.64
Light fuel oil	38.64
Heavy fuel oil	41.69
Lubricating oils and greases	39.12

Source: EMR 1984. Energy Statistics Handbook. Canada Department of Energy, Mines, and Resources. Minister of Supply and Services, Ottawa.

*The heating value of kerosene was applied uniformly to tractor fuel and stove oil.

TABLE 5.4

LIQUID FUEL INPUTS TO PRAIRIE WHEAT FARMING
1948-1981

Year	Area Sown To Field Crops (10^3 ha)	Fuel Use** (l/ha)	Total Energy In Fuels (PJ)	Equivalent Energy Input (MJ/ha)
1981	23,854	105.7	92.934	3896.0
1977	21,665	140.2	109.321	5045.9
1973	20,351	128.3	93.583	4598.4
1968	20,926	109.8	82.344	3935.0
1963	18,814	95.2	63.739	3387.8
1958	17,967	92.7	58.712	3267.8
1953	18,585	73.9	48.735	2622.3
1948	17,463	53.2	33.086	1894.6

*From Statistics Canada 1948-1981. Field Crop Reporting Series. Cat. 22-002, seasonal, Minister of Supply and Services, Ottawa.

*Quantities of all fuels (in varying proportions) from Table 5.2, divided by area sown to field crops.

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VI. ELECTRICITY

Although a much smaller component of direct energy use when compared to fuels, the input of electricity to Prairie wheat production is significant. Ranking fourth in the energy budget behind machinery, its increased usage has been dramatic -- especially in the earliest years of the study period. The approach taken in calculating energy equivalents was to first simply gather from central distribution statistics data on the overall quantities of electricity consumed by agricultural operations. Effectively this served to bring together all production activities under one heading. The advantage of this approach (as opposed to one based on an activity by activity accounting) are twofold: first it obviates the possibility of double counting (which is easily done in complex studies, for example, Pimentel et al. (1973) recorded electricity and irrigation as separate inputs even though the majority of U.S. agriculture's irrigation energy requirement is met by electricity), and secondly it allows the consolidation of a range of electricity consuming operations, services and devices which might otherwise escape detection. In downstream accounting calculation adjustments were made for the energy costs of fossil-fuel generation.

There is, of course, one major drawback to the approach, by aggregating activities into one consuming category there is a substantial loss of process detail. Inputs which contribute to overall consumption include irrigation, drying, seed cleaning, grading and treating, augering, the heating and lighting of buildings, as well everyday shop tasks that require power tools such as saws, drills, lathes, planers, welding units, compressors, and so on. Yet, in reality, the lack of detail does not take away from the objectives of this study. In electricity we have captured a systems component, and while exploring deeper we could potentially identify a whole range of contributing "sub-system" components, such an undertaking would be in essence, more closely related to a farm survey study, and the identifications of specific conservation opportunities, rather than to the regional investigation of an industry.

Indirect evidence gives us a rough indication of where the electrical energy is going and how it is being used in Western Canada. A Statistics Canada survey of farming operations in 1958 recorded the presence of some 90,000 grain cleaners, 700 portable driers, 190,000 electric motors and more than 14 million dollars worth of assorted power tools (Statistics Canada, 1967). A more-detailed record of the number of independent electric motors (typically portable and used in the capacity of power-take-off engines) gives some idea of the diffusion and importance of electrical equipment over the past four decades of Prairie farming. Throughout this period the number of electric motors in service increased substantially, rising from just over 5,000 in 1941 to 115,000 in 1981. Responsible for much of this increase have been the two production activities of irrigation and crop drying.

Irrigation

While irrigation may be a significant consumer of electrical energy in Western Canada it is so largely because of its high energy requirements -- not as a result of its widespread usage. Irrigated areas have expanded since the late 1940s, but only at a very slow rate. At an all time high of roughly 450,000 ha in 1981 irrigated cropland accounted for only two percent of all crops sown in the region. Data on the extent of irrigation and the extent of irrigated wheat have been assembled in Table 6.2. Wheat until the mid-1960s was by far the single-most irrigated crop on the Prairies. In 1950 its 65,000 irrigated hectares constituted one-third of all cropland receiving water. The reasons for irrigating wheat,and for that matter any other field crop in a climatic region where extreme moisture deficits are common, are straightforward and economic. Irrigation can lead to as much as a 50 percent increase in yields (Russel and Sonntag, 1978). Yet despite the potential for returns the area of irrigated wheat over the past three decades has been declining, both in absolute terms, and as a proportion of total irrigation.

Reflected in the overall increase of irrigation throughout the region between 1950 and 1980 are the "other" cereals and forage crops which have largely taken the place of wheat. Correlated with a rise in the use of sprinkler systems expanding areas have presumably reflected an adequate return on equipment investment, in spite of the fact that both the economic and energy costs of sprinkler systems are high. Table 6.3 shows the estimated energy costs of nine common irrigation systems. Included in the data are the energies consumed in the fabrication of structural materials, the installation of equipment and the operation of each type of system, and between them they show a wide variation in total cost. Assuming the average southern Saskatchewan irrigation requirement is 45 cm (Korven and Randall, 1975), the cost of supplying water by surface irrigation (without a runoff recovery system) would be roughly 700 MJ/ha. Meeting the same requirement with a travelling sprinkler system would raise the energy input per hectare to approximately 9500 MJ on average. Accounting for the fact that the efficiency of simple surface systems are on average no more than 50 percent and that of sprinkler systems 70 percent, more realistic energy requirements would be, respectively, 1,400 and 13,570 MJ/ha.

Taking this last figure as an example of modern irrigating requirements, it is readily apparent why -- even with a 50 percent increase in yields -- wheat could rarely justify the investment in a sprinkler system. At lower cost, surface irrigation offers a much better return on investment, but here too installation may be inappropriate: the climatic conditions of the region are just too severe to guarantee returns. Evaporation throughout the region is high, the fertility of the soil is low and the growing season is short.

Together such conditions can limit yields even when moisture is no longer a critical variable.

What is true for wheat one would think should be true for all Prairie crops, yet the most energy intensive systems underwent rapid diffusion at precisely the time the cost of energy underwent its most rapid increase ever in the history of modern fossil-fueled agriculture. Over the ten-year period 1970-1980, sprinkler irrigation grew from 1100 to 3800 units, and from 55,000 to 300,000 ha. The reasons for expansion are not clear, but as one report suggested causes were largely non-market oriented, and probably short-sighted. The Environmental Council of Alberta (in the provice where most of the increases took place) commented in 1982 that "current heavy government subsidization of the capital costs of irrigation encourages decisions to expand without full cognizance of the costs of that irrigation" (Environmental Council of Alberta, 1982, p. 50).

There are of course much cheaper ways of bringing water to the field. As one researcher indicates, manipulation of the snow cover offers great economic potential (Nicholaichuk, 1980). Data on the extent of irrigated wheat are not available after 1970, but indications are that it probably increased during the expansionary 1970-1980 period. However, while areas are likely less than they were in the 1950s, the use of high-cost systems has undoubtedly increased the energy cost of that which is now being irrigated. Powering approximately 1300 units, electricity accounted for approximately one-fifth of all systems operating in Western Canada in 1981 (Statistics Canada, 1983).

Drying

Grain drying with heated air under the prevailing semi-arid conditions of the Prairie environment is not extensive. Data from a Statistics Canada survey (1983) indicate that no more than two percent of the 1981 wheat crop was dried by this method. Wheat is typically harvested at or below 18 percent moisture content and as such requires little more than ambient air to bring it down the several points necessary for shipment. Where the prevailing weather conditions permit one of the cheapest methods of drying the crop is to simply leave the cut grain lie in the field several days and dry under the clear Prairie skies. The most common form of drying is, however, with fan-forced unheated air, and in 1981 an estimated 25,000 electric motors were used for that purpose.

The energy requirements of drying wheat with ambient air clearly depends on both the moisture content of the air and the moisture content of the grain. Each of these factors varies widely with time and location, and estimates of the associated energy requirements can serve as no more than broad indicators of what could be expected. Fraser and Muir (1980) estimate that the energy requirements of reducing the moisture content of wheat from 19.5 to 14.5 percent with unheated air ranges from a low of 95 MJ/t in Swift Current, Saskatchewan (one of the driest areas in the region) to a high of 150 MJ/t in Winnipeg, Manitoba (one of the most humid areas). Taking the figure for Winnipeg, the average 2000 kg/ha wheat crop in southern Manitoba would need roughly 300 MJ/ha to dry if harvested under these conditions. Extending this requirement across the whole region indicates that drying costs when incurred can be substantial.

The Consumption of Electric Energy

Electric-power statistics since the mid-1940s, recording provincial farm consumption in categories separate from industrial and domestic service, do not give a breakdown on specific crop or production requirements. However in keeping with earlier considerations it is assumed that the majority of Prairie electricity consumption goes towards the region's primary activity, the production of wheat, and that average consumption will be relatively uneffected by the presence of other crops (which in any event have similar input requirements), or by the existence of livestock operations (which utlimately have their major energy consumption in the form of liquid and gaseous fuels). Naturally such enterprises will have some effect, but when averaged across the great expanse of Práirie cropland their contribution to prorated results can be no more than minimal.

Around the turn of the century, with the presence of thermal-generating plants in urban centres and only a few small hydro-electric stations in Alberta and Manitoba, the generation, distribution and consumption of electricity in rural areas was extremely limited. Problems of low population and undeveloped uses combined to present formidable economic and technical problems to electrification. In the late 1940s only five percent of farms in Western Canada had central service.

The absence of electrical service from central generating stations before 1950 should not, however, leave the impression that electricity went unused. For as one author recently pointed out the use of windmills was widespread; fifty years ago nearly all farms in the U.S. had at least one operating unit (Klueter, 1980). In Western Canada during the 1940s wind electric systems were at least as popular as central servicing. Saskatchewan at the time had close to 10,000 operating wind systems. Nevertheless, in response to the growing availability of central servicing and for obvious reasons of convenience the use of windmills fell off, and by the mid-1950s fewer than half remained.

Late 1940s - early 1950s rural electrification allowed roughly 50 percent of Prairie farms to be reached with electricity by 1953. In that year close to 125,000 km of rural pole line extending across Manitoba, Saskatchewan and Alberta -- up from 40,000 km five years earlier. In 1958 lengths had risen to 250,000 km, and by the early 1960s 300,000 km of line was deliveryіng power to more than three-quarters of the farm population. Approaching the point of complete service expansion slowed thereafter and within 10 years electrification was complete. Since that time there has been a marked trend towards double servicing of farm customers.

To separate production requirements from household usage, consumption figures were calculated as the business proportion of farm service. Data for the three prairie provinces were extracted from detailed annual reports for each interval (Statistics Canada, 1981), and specific business allotments taken as the average of an almost exact agreement (62 and 63 percent) between studies conducted in Western Canada in 1958 and 1981 (Statistics Canada, 1967; 1983). The breakdown of actual contributions of each of the thermal- and hydro-electric generating modes to overall generation was available from the Prairie Provinces Water Board (1982) and has been employed for the calculation of energy intensities. Capturing the energetic difference of the two modes, hydro-electric generation was calculated at its direct kWh_e equivalent, 3.6 MJ, while the thermal-electric generation was calculated at a 34 percent conversion efficiency (i.e. one kWh equals 10.6 MJ) to yield generation energy intensities for each year in the time series. The results of these calculations are presented in Table 6.4.

Regional consumption of electricity understandably displayed its greatest increase at the time rural electrification was just getting underway. During this early period between 1948 and 1953 which coincides perfectly with the beginning of mechanization, consumption rose dramatically from 11.6×10^6 to 108.7×10^6 kWh. In later years increases were much less (although still substantial) and quite uniform. Between 1953 and 1973 consumption virtually doubled every five years, and by the early 1970s total farm business use was one order of magnitude larger than what it had been 20 years previous. During the decade which followed, even though percentage increases were falling, levels of consumption continued to rise, and surprisingly so, for the price of electricity had more than doubled. However, with increases past the point of inflection now evident (and rural electrification, of course, complete) consumption should level off in the near future. Accompanying the rise in consumption over the time period of study was an increase in the energy intensity of generation. Reflected in a regional shift towards thermal power, electrical energy intensities rose from approximately 4.6 MJ/kWh in 1948 to 7.5 MJ/kWh in 1981.

Over the past three decades the total energy cost of electricity consumed in Prairie agriculture has increased tremendously, rising from a low of 53.8 PJ to a high of more than 15,250 PJ between 1948 and 1981. The final set of figures collected in Table 6.5 gives a detailed breakdown of on-site consumption and areal costs. Annual electricity consumption per farm service rose from 1,120 to 10,316 kWh -- an increase equal to a full two orders of magnitude. Combining this information with total use indicates that both regional and customer use have increase simultaneously; that is, both the diffusion of service throughout the region and the intensification of use by those farms serviced occurred hand in hand. Starting in 1948 farm customers virtually doubled their consumption of electricity every 10 years. However, over the past decade annual rates of increase have fallen, from a high of 20 percent in 1971 to a significantly smaller eight percent in 1981.

An interesting comparison can be made between rural and urban levels of customer consumption. On a relative basis farm service total requirements (consisting of both business and household uses) remained lower than annual domestic consumption rates until the early 1960s. Rural consumption continued to increase thereafter and by 1981 the ratio of farm service to domestic service was roughly 2:1. However, when business proportions are subtracted from farm totals the situation is somewhat different: the resultant farm household requirements have always been lower, though by a margin which has been steadily shrinking since 1948. By 1981 the two household services were basically equal.

Dividing farm business consumption totals by the area of field crops sown in each year yields the associated input of electricity per hectare. Results show that the consumption of electrical energy increased from less than one to more than 85 kWh/ha over the study period. Multiplying consumption by the corresponding energy intensities gives final figures, which indicate that on a percentage basis electricity has been the fastest rising energy input in modern wheat production. On an relative basis though, its increase of 637 MJ/ha is far behind the input of greatest absolute increase, nitrogen fertilizer.

TABLE 6.1

ELECTRIC MOTORS ON THE PRAIRIES
1941-1981

Year	No. of Motors	No. per 100 cropped ha
1941	5,232	0.04
1951	52,486	0.28
1961	201,978	1.06
1971	75,861	0.34
1981	115,000	0.48

*Includes all independent units greater than 1 hp operated in listed year.

Sources: Statistics Canada 1941-1971. Census of Agriculture, ten year series, Minister of Supply and Services, Ottawa.

Statistics Canada 1983. Farm Energy Use Survey 1981. Cat. 21-519, occasional, Minister of Supply and Services, Ottawa,

TABLE 6.2

IRRIGATED PRAIRIE CROPLAND

Year	Total Irrigated Area (ha)	Irrigated Wheat Area (ha)	Irrigated Wheat Farms (No.)	Irrigated Wheat to Total Irr. Area %	Irrigated Wheat to Total Wheat Area %
1950	196,086	64,985	2842	33	0.7
1960	239,564	37.784	2113	16	0.5
1970	251,775	25,180	1214	10	0.4
1980	456,817	n.a.	n.a.	n.a.	n.a.

n.a. = not available

Source: Statistics Canada 1951-1981. Census of Agriculture, ten year series, Minister of Supply and Services, Ottawa.

TABLE 6.3

TOTAL ENERGY INPUTS FOR COMMON IRRIGATION SYSTEMS

(All energy costs in MJ/ha)*

System	Installation Energy	Pumping Energy	Labour Energy	Total Cost
Surface without Runoff Recovery	11.67	3.98	0.05	15.70
Surface with Runoff Recovery	20.33	5.43	0.03	25.79
Solid-set Sprinkler	69.41	87.04	0.04	156.49
Hand-move Sprinkler	18.05	90.89	0.50	109.44
Side-role Sprinkler	22.61	90.89	0.25	113.75
Centre-pivot Sprinkler	43.9	97.67	0.01	141.58
Travelling Sprinkler	32.66	177.36	0.04	210.06
Trickle	59.97	54.94	0.01	114.92

*Based on a one cm net irrigation requirement, 75 percent pumping efficiency and zero pumping lift.

Source: Batty, C. J., Hamad, S. N., and Keller, J. 1975. Energy Inputs To Irrigation. J. of the Irrigation and Drainage Division (ASCE), 101: 293-307.

TABLE 6.4

AGRICULTURAL CONSUMPTION OF ELECTRICITY
IN WESTERN CANADA

Year	Farm Business Use (kWh X 10^6)*	Percentage Service By Hydro	Energy Intensity MJ/kWh**	Equivalent Cost (TJ)
1948	11.558	85	4.65	53.806
1953	108.711	80	4.96	539.514
1958	286.725	58	6.55	1,878.101
1963	528.961	50	7.01	3,710.750
1968	865.923	47	7.26	6,289.375
1973	1,294.162	46	7.39	9,570.625
1977	1,718.512	41	7.70	13,233,125
1981	2,034,792	43	7.50	15,258.750

*Calculated as 62.5 percent of farm service total as listed in Statistics Canada 1948-1981 Electric Power Statistics, Vol. II. Cat. 57-202, annual, Minister of Supply and Services, Ottawa.

**Hydro-electric contributions calculated at 3.6 MJ/kWh and the remainder at 10.58 MJ/kWh.

TABLE 6.5

CONSUMPTION OF ELECTRICAL ENERGY IN PRAIRIE WHEAT PRODUCTION 1948-1981

Year	Annual Business Use (kWh/farm customer)*	Consumption kWh/ha	Intensity MJ/kWh**	Equivalent Energy Cost MJ/ha
1948	1,120	0.66	4.65	3.08
1953	1,645	5.85	4.96	29.03
1958	2,200	15.96	6.55	104.53
1963	3,346	28.12	7.01	197.73
1968	5,145	41.38	7.26	300.54
1973	7,468	63.59	7.39	470.26
1977	9,336	79.32	7.70	610.78
1981	10,316	85.30	7.50	639.68

*Farm business use from column one, Table 6.4, divided by the number of farm customers in each year.

**From Table 6.4.

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VII. FERTILIZERS

The Soil Environment

Among the most important environmental factors known to influence plant growth: temperature, moisture supply, radiant energy, composition of atmosphere, gas content of the soil, soil reactions, biotic factors and the supply of mineral nutrient elements (Tisdale and Nelson, 1975), it is the supply of mineral nutrients which is the most easily altered and significantly conditioned by man's agricultural efforts. Traditional Prairie practices have always relied heavily on the nutrient reserves of the native grassland soils to support field production, and while some fertilizers in organic form have historically been applied in the attempt to maintain fertility and build good soil tilth, it was not until the late 1940s that the need for synthetic supplements became widespread. Since that time application of inorganic fertilizers has been responsible for much of the production increases in Western Canada.

The history of fertilizer use in Western Canada can be best described with reference to the fundamental principles of general ecosystem development. Composed of fresh litter, plant material, soil biomass, the microbial byproducts of decomposition, enzymes and material in various stages of humification, soil organic matter is the major storehouse and supplier of more than one-half the essential nutrients of plant growth, and by extension is particularly important in providing the nitrogen, phosphorus, sulfur and micronutrients necessary or commercial crop production (Campbell and Biederbeck, 1980). Mature ecosystems (i.e. grassland climax) compared to younger or developing ones (i.e. anthropogenic sub-climax) possess a far greater capacity to entrap and hold nutrients for cycling within the plant-soil environment and support a much greater biomass than the comparative monoculture (Odum, 1969). Nitrogen fixation of natural grassland at 1 kg/N/year is approximately double that of typical cultivated soils (Vlassak et al., 1973; Paul et al., 1971), while biomass production can be expected to be almost four times as great (Coupland and Dyne, 1979).

In the evolutionary sense of seral development, the practice of intensive agriculture reduces the volume of both above ground and below ground vegetation (e.g. shoots, roots and litter) and affects a regression to the younger successional state. In a sub-climax soil the setback will be accompanied by a gradual depletion of the nutrient pool through the process of harvest removal, erosion, leaching, volatilization and denitrification, and eventually lead to a situation where the antecedent high productivity of the younger system can be maintained only with a compensating input of nutrients from external sources. This is only a small part of the story, for in addition to fertilization the inputs of irrigation, insect and weed control, genetic selection and machinery are also required, but for purpose of clarity fertilization can be focused upon as a constituent in isolation.

When the majority of Prairie cropland was first broken around the turn of the century there was a wealth of primary elements stored in the native grassland soils following thousands of years of continuous deposition. With the beginnings of systematic crop production large and initially rapid decreases in soil organic matter occurred. The process was especially rapid during the early years of cultivation (Campbell et al., 1976) and by the 1930s the situation had become serious. (As one report noted, the rise of fertilizer sales experienced at this time was in direct response to the fact that "ingredients necessary for healthy growth had been taken from the soil" (Dominion Bureau of Statistics, 1932, p. 4.)). By 1981, only an estimated 40 to 60 percent of original nutrient reserves on average remained (Rennie, 1979), while on badly-eroded sites lows of as little as 10 and 20 percent have been recorded (Paul and Rennie, 1979). In the same year rates of fertilizer application reached an all time high with a combined input of just over 40 kg per cropped hectare. In the wider perspective of ecosystem development, it can be said that man, in his agricultural pursuits, maximizes for net primary production; that is, for the quantity of phytomass available for harvest at the year's end. However the agronomic costs pursuing the strategy are high, and in terms of fertilizer use alone costs will rise in the future.

Where nutrient inputs are not of a level sufficient to compensate for loss, the depletion of soil reserves under intensive cultivation (where erosion is not controlled) will lead to eventual soil sterility. If erosion is controlled, however, it is estimated that under conventional practices a steady state may be attained around the year 2000. At this point nutrient levels will be expected to stabilize at approximately 20 to 25 percent of the native grassland content (Voroney et al., 1981). Yet the removal of nutrients in harvested grain still exceeds those which are applied annually, and with present rates of removal being three times higher than harvest losses (Laverty et al., 1976) the use of fertilizer in Western Canada must increase significantly before any equilibrium is reached. That is, of course, if the present levels of production are to be maintained.

There are in total approximately 20 elements which may be categorized either as micro- or macronutrients essential to plant growth. Out of this group it is the nitrogen (N), phosphorus (P) and potassium (K) which are required in the largest amounts (hence macronutrients) and which constitute the three fundamental building blocks of conventional crop production.

Nitrogen, the most important of the three and required in the largest amounts, fulfills both a structural and metabolic role in living plant matter. Structurally it serves as an integral part of the chlorophyll molecule (which captures the sun's energy for photosynthesis), and metabolically is a fundamental constituent of plant protein synthesis. Adequate supply is associated with vigorous vegatative development and deep green colour. Phosphorus functions as a secondary but critical element in the energy transfer reaction, phosphorylation. Through its operation the phosphorylation process lowers the activation energy level of chemical exchange, overcomes a set of otherwise unfavourable thermodynamic conditions and effectively increases the number of chemical reactions vital to the plant's life processes. Phosphorus is considered essential to good seed formation and is associated with early plant maturity and full root development. Potassium is not, as both nitrogen and phosphorus are, an integral part of the plant's molecular make-up, but acts rather as the critical catalyst in more than half a dozen independent physiological processes (Tisdale and Nelson, 1975). A deficiency in this nutrient greatly reduces potential yield.

Fertilizer Applications

In Canada, surprisingly, data on the actual quantities of fertilizer applied in agriculture do not exist. However, owing to the fact that costs of storage and difficulties of winter carryover to the producer are prohibitive, detailed records of domestic sales will be considered reflective of actual use. The total quantities of N, P and K supplied by chemical fertilizers in Prairie agriculture between 1948 and 1981 have been calculated in Table 7.1. (Prior to 1948, the use of fertilizers was minimal; that which did exist was composed primarily of manures and conditioned animal byproducts. In 1941 sales of ammonium phosphates were approximately 7,500 t). Inputs were calculated on the basis of the nutrient content of direct forms only; mixed fertilizers while they are, of course, applied, are used in amounts so small that their exclusion from the total consumption of nutrients will be negligible. Manures and other organics were excluded on the same basis; however, it should be noted that even if their quantities were substantial such use would be excluded on energetic grounds alone -- they are the non-assignable byproducts of a different industry. The general trend of fertilizer use in Western Canada is one of constantly increasing use. Several periods show especially rapid increases; for example between 1948 and 1953 and between 1958 and 1963 where consumptions doubled and tripled respectively. Overall usage increased from roughly 14,000 to over 800,000 t between 1949 and 1981. In terms of a constituent breakdown, P was the most heavily applied nutrient until the early 1960s. Potassium had its first usage recorded in 1963 and has increased marginally since then. In 1963 as well N became the most widely used fertilizer and by 1981 comprised virtually four-fifths of overall use.

Deriving the quantity of primary nutrients applied to the Prairie wheat crop required the assumption that all fertilizer be allocated to and prorated across each of the five principal field crops grown in the region. Methodologically the assumption may appear somewhat simplistic, but in reality it is all that is actually required. Five crops: namely, wheat, oats, barley, flax and canola, occupy the vast majority of seeded and fertilized land in the Prairies. Of these five, four have identical rates of recommended application. Only canola displays a departure from the norm with slightly greater inputs of N, but it covers too small an area to be important. The use of chemical fertilizers in Prairie wheat production for each year in the time series are presented in Table 7.2.

No distinction was made in application rates between wheat sown to stubble or wheat sown to summer-fallow land. The quantity of each primary nutrient applied to the wheat crop is simply the product of total quantities consumed (from Table 7.1) and the proportion of wheat to total field-crop area, divided by the number of wheat hectares in each of the corresponding years. Clearly applications differ between stubble and summer-fallow seeding (especially in terms of N), but for the purposes of this study such a distinction would disclose no additional information or serve any instructive purpose -- what it would require is a set of cumulative and increasingly speculative assumptions. As many hectares receive no fertilizer at all, average rates are typically less than actual field rates.

Inputs of chemical fertilizer to wheat agriculture have risen dramatically over the past three decades. Over the first decade of study increases were moderate, doubling from just under one kg/ha to just under two kg/ha. However after mechanized practices were in place by the late 1950s increases were much more rapid, rising more than an order of magnitude between 1958 and 1968, and almost tripling again by the final year of study 1981. Fertilizer consumption has shown one of the greatest percentage increases of all inputs to modern wheat production. This growth is shown in Figure 7.1. As can be seen from the compound line graph, applications of each N, P and K have followed a similar pattern of increase. In absolute terms -- much as in the case of regional consumption -- quantities of N applied were initially lower than P, but by the early 1960s the two had risen to equal levels. The situation changed dramatically thereafter with N being applied in even greater amounts. By 1981 it was being supplied at roughly 3.5 times the rate of P by weight. This development of course had its foundation in the pre-existing and evolving conditions of the soil environment: an early emphasis on P was consistent with the characteristically low levels of availability in Prairie soils (Beaton, 1980); while the increasing dependence on N can be directly related to the ongoing depletion of natives reserves.

As stated earlier, increases in the use of fertilizer have followed a more or less constant pattern over time. Yet several breaks in what otherwise would have been a straight-line linear increase after the early 1960s are worthy of mention. The first and foremost anomaly in fertilizer use happened in 1969, and its occurrence was the direct response to falling grain prices. In a market which had been declining for a number of years world wheat prices fell to record breaking lows in 1968. In Canada, the nominal price of wheat which had been $65 per tonne in the mid-1960s fell to $49. Calculated in constant dollars the real price of wheat was lower than it had ever been since the Great Depression. In response the federal government instituted its "Less Inventory For Tomorrow" (LIFT) program which essentially encouraged producers not to plant wheat in the attempt to buoy up prices and so avoid overproduction. Areas sown to wheat were halved and the idling of productive land became widespread. In 1969 alone summer-fallow plantings rose to capture over 90 percent of seeded areas. Fertilizer use fell accordingly. Applications which had reached close to 16 kg/ha in 1968 dropped to roughly 9 kg/ha one year later. World prices recovered quickly thereafter -- Western Canada spring wheat selling for $68 per tonne in 1972 leaped to $165 in 1973 -- and the LIFT program was discontinued. Plantings increased, the proportion of summer fallow in the Prairies decreased and fertilizer applications regained their earlier rate of increase.

Two anomalies occured in the trend line after 1969; one in 1974-1975, and another in 1979-1980, and both are best explained by fertilizer price increases. Fertilizers show one of the lowest indexed price increases between 1948 and 1973 (Statistics Canada, 1984). The cost of fertilizer was slightly lower in 1970 than what it had been in 1960, and only marginally higher than what it was in 1948. Not until 1974, in response to the rapidly rising price of its major feedstock, fossil fuel, did the price of fertilizer increase significantly. Prices rose one-third by 1975, one-third by 1979 and another one-third by 1981. The result of these increases was a complete turn-around in farm input pricing: by 1981 fertilizer had become the commodity with one of the highest indexed increases of all inputs. The shock of these prices increases can be seen in the temporary leveling, decreasing and increasing of fertilizer use throughout the 1970s (Figure 7.1).

From the developments of the past decade it is clear that price has an appreciable and immediate impact on fertilizer consumption. However, what is also clear is that after such shocks have been internalized, consumption has shown a tendency to regain its former rate of increase. In fact if one extends the major trend line of the 1960s into the late 1970s, actual application rates were only marginally lower than what could have been predicted from extrapolation (Figure 7.1). Yet in the face of such input cost increases, the price of wheat has not kept pace. In real prices producers were receiving in 1981 about one-half what they were getting for a tonne of wheat in 1973! Of course, in the near future the price of wheat might increase, but as evidenced by increasing production in several of Canada's major export customers (e.g. China and India) the chances of this coming about are slim. In this price scenario fertilizer inputs cannot continue to increase indefinitely. To remain economic future production practices must reduce the cost of this input by (1) improving the efficiency of use, and by (2) using less expensive and less energy intensive forms.

Energies of Fertilizer Synthesis and Use

Nitrogen

Early in the era of chemical fertilizer application the majority of N supplied to the Prairie wheat crop was mostly as a component of commonly used phosphatic materials. On a nutrient basis by weight N comprised anywhere between 11 and 18 percent of these materials by weight. However as the native N reserves of the grassland soils diminished under intensifying agriculture practice, the need for direct applications and higher grades became widespread. Ammonium nitrate (34-0-0) became commercially available in Western Canada in 1945, and was followed by urea (46-0-0) 15 years later. Not gaining widespread acceptance until the mid-1970s, anhydrous ammonia (82-0-0) was first marketed in the mid-1950s. Nitrogen solutions were introduced to the Prairie market in 1965, and a broad array of other nitrogenous materials, including ammonium sulfate, ammonium nitrate phosphate and urea combinations were developed and became available in the late 1960s and early 1970s. Table 7.3 lists the various materials contributing to the consumption of fertilizer N in wheat production over time. The calculations incorporate assumptions identified under the preceding subsection and, as in Tables 7.1 and 7.2, include the input of direct applications only. All commonly used varieties have been collapsed into five categories and listed accordingly (as calculations were made on a more disaggregated basis such aggregating does not affect totals). Ammonium phosphate was including in the listing -- even though it is more commonly referred to as a phosphatic fertilizer -- because of its significant N content.

As the percentage of total N supplied by urea and anhydrous ammonia increased and surpassed the percentages of N supplied by each of the ammonium sulfates, nitrates and phosphates in the mid-1970s, the shipping ratio (defined as the quantity of material divided by the quantity of nutrients) dropped, falling from approximately 6.7 in 1958 to about 3.0 in 1981. Anhydrous ammonia, with an N fraction of 82 percent, by 1977 was the largest single supplier of N, constituting roughly one-third of total applications to the wheat crop. In 1981 urea was the second largest supplier of N and, with a 46 percent N fraction, was most heavily applied material.

The drift towards greater utilization of anhydrous ammonia in a era of rising energy and fertilizer prices is a natural development. Anhydrous ammonia, utilizing hydrocarbons for both fuel and feedstock purposes, is the source and starting point for virtually all nitrogenous fertilizers produced in Western Canada, which when applied directly the single most inexpensive source of inorganic N. Major expansion in Western Canada's N production took place in the 1970s, with the new facilities increasing both ammonia and urea capacity by 150 and 450 percent respectively (Rennie et al., 1979).

Virtually all ammonia and downstream nitrogenous fertilizers consumed in Western Canada are produced locally. The abundance and availability of low-cost fossil fuels has directed the location of the industry to Alberta, and has made the use of natural gas the feedstock for ammonia synthesis. The first petrochemical plant in North America to utilize natural gas in the steam reforming process was in fact constructed in Alberta in 1941. Ammonia itself is produced commercially by the Haber-Bösch process in the catalytic reaction of pure hydrogen and atmospheric nitrogen (Blouin and Davis, 1975). Several sources of hydrogen other than natural gas can serve as the feedstock for the process; for example, naptha (from steam reforming), fuel oil (from partial oxidation), and coal (from gasification), however, the ease of handling and the lower production costs of the accompanying process have made natural gas the feedstock of greatest importance worldwide. (It is important to recognize that although costs differ between each method of production all are energy intensive processes, regardless of the hydrogen source. As a general rule, the energy cost of production increases as the C:H ratio of the feedstock increases.)

Focusing on the manufacture of anhydrous ammonia, changes in the GER of its production over time serve as an excellent example of the effects improvements in technology can have in historical energy accounting. Data on the energy costs of its synthesis were collected for a period spanning 50 years of continuous processing advancement, beginning with 1930 and ending with the requirements of the most modern techniques in 1980. They are presented in Figure 7.2. The actual drop in the energy consumed per unit of product over this time period has been dramatic, falling from 365 to approximately 30 MJ/kg, an order of magnitude difference. Such advances have been facilitated by the utilization of preferred fuels and feedstocks, improvements in unit operations, increased scales of production and overall engineering design integration. Advances in several of the processing steps as well as the integration of heating and power requirements (for example, high pressure byproduct steam produced in larger plants provides the power required by major compressors (Ennis and Lesur, 1977)) have given more efficient operation, and since the late 1940s plants have increased in size from 150t/day to 1500t/day capacities.

Further efficiency gains in ammonia synthesis are, of course, entirely possible, but as evidenced by the approaching asymptotic and thermodynamic limits in Figure 7.2, improvements of any significance are highly unlikely. The two best claims for efficiency today are a world scale plant in Fort Saskatchewan, Alberta with a cost of roughly 31 MJ/kg ammonia (Chemical Engineering, 1980) and an operation in Ohio with an estimated requirement of 29 MJ/kg (Ricci, 1979).

Urea, the second largest supplier of fertilizer N to wheat production, incorporates anhydrous ammonia and its production byproduct CO_2. As a result, the urea manufacturing plant is typically part of the ammonia production complex, and on a nutrient basis the product is more energy expensive than ammonia itself. So expensive is it, that it is one of the most energy intensive suppliers of inorganic N. Disaggregating energy requirements from the bottom up, ammonia constitutes the largest single input cost at approximately 27 MJ/kg of product. Conversion of the ammonia to urea solution requires 5.5 MJ/kg, and further processing another 4.1 or 2.5 MJ/kg depending on its form. Summing each cost, the total will be either 36.6 or 35.0 MJ/kg of prilled or granular product, or 79.5 and 76.1 MJ/kg of N.

The average North American energy requirements for anhydrous ammonia, urea and a number of other commonly used nitrogenous fertilizers have been collected in Table 7.4. Included in the list are values for a number of additional P and K based materials which are applied regularly in Prairie grain agriculture. Costs were drawn largely from surveys conducted throughout Canada and the U.S. by the International Fertilizer Development Center (Mudahar and Hignett, 1982) and represent the actual consumption ratios for plants operating in 1979. Data in the study were calculated across all production technologies, ranging from those of the oldest least efficient plants to those of the most modern and efficient design, and subsequently display little resemblance to often cited single plant or battery-limit estimates. In production requirements, N is by far the most energy intensive chemical fertilizer; on average it is three to four times more expensive than P and ten times as expensive as K.

Before computing the equivalent energies of N in Prairie production, two importants sets of calculations are required. First, in the attempt to develop a truer picture of actual requirements for the 33 year period of this study, and basing calculations on the fact that the technological efficiency gains of ammonia synthesis can be transferred directly onto the associated production costs of all downstream products, the energy costs of the major N suppliers were adjusted for each interval in the time series. These values have been collected in Table 7.5. Between 1948 and 1981 the drop in the GERs for anhydrous ammonia (98.4 to 57.2 MJ/kg), urea (119.0 to

77.8 MJ/kg) and ammonium nitrate (113.8 to 72.6 MJ/kg) have all been significant.

Second, in the attempt to capture changing application habits (i.e. the fractional contribution of each type of N fertilizer to total use) the approximate energy intensities of N by weight as applied was calculated for each year in the time series. The example of 1981 is shown in Table 7.6. In that year the energy cost of one kg of N was 65.9 MJ/kg. By including this calculation and technological adjustments, the resultant energy intensities of N in each period will encompass and reflect the results of both improved manufacturing efficiency and a shift towards the use of higher analysis products. The final calculations of N supplied to the Prairie wheat crop are the product of the mass of N applied and the energy intensity of the material. Energy equivalents for each year in the time series are shown in Table 7.7.

The total increase in the cost of fertilizer N consumed in Prairie wheat production has been dramatic. Rising from a negligible 17 MJ/ha in 1948 to just over 2000 MJ/ha in 1981 the change is equal to two orders of magnitude. In 1981 N was the second highest energy cost in wheat production (only a few points behind fuel) and the fastest rising input of all.

Phosphorus

Since the beginning of modern agriculture in Western Canada, phosphatic materials have always made up the largest mass of chemical fertilizers applied, and until the early 1960s it was in fact the supply of phosphorus -- not N -- which was of greatest concern to producers. Yet while it was recognized early on that native soil alkalinity could be overcome by annual applications of P, the actual biogeochemical condition of Prairie soils has not improved with time. Conventional cropping practices have exacerbated the situation where since cultivation began removal has continually exceeded inputs (Racz, 1981).

In simple form, the manufacture of phosphatic fertilizers which comprise the overall P input involves a process which starts with the solubilization of various phosphate ores derived from a number of dissimilar beneficiation and mixing operations. The ores,originating in deposits which have evolved from various natural processes, can be divided into five categories: marine phosphorite, apatite of igneous origin, residual deposits, phosphatized rock and dried avian excrement (guano). Some four-fifths of world production comes from the phosphates of sedimentary marine origin, of which the U.S. is the largest producer (Cathcart, 1980).

There are few suitable phosphate deposits in Canada with any real economic potential. Therefore, where the finished phosphate products are not imported directly, the Canadian fertilizer industry obtains its primary requirement from rock mined chiefly in Florida and to a lesser degree in the western states of Idaho, Montana and Utah. Such imports require transport by rail of distances margins anywhere from a few hundred to several thousand kilometers. Supplies up until now have come from high-quality ores low in gangue; however, in the future it is expected that such materials will soon be depleted and replaced by poorer quality or more expensive grades (Lehr, 1980). Average grades of ore now being mined in Florida are about five to six percent P.

Phosphate rock in the U.S. in mined principally in open-pit operations where recovery methods -- and energy costs -- differ widely according to overburden thickness, and the structure and stratigraphic sequences of ore beds. Concentrating is performed in downstream crushing operations followed by hydro-separation or flotation to remove impurities. Rock at this stage is reacted with sulfuric or phosphoric acid in a chemical process to convert the phosphate into a form readily usable by crops. The important products of sulfur-acidulation are ordinary or single superphosphate (at about nine percent P by weight) -- and, of course, phosphoric acid itself -- and from the phosphorous-acidulation concentrated on triple superphosphate (at approximately 20 percent P by weight). The two superphosphate products can be applied directly to the crop, while the byproduct phosphoric acid is either routed back for use in further phosphorus-acidulation operations or used directly in a subsequent manufacturing process, with ammonia, to produce ammonium phosphate. In Canada it is the ammonium phosphates in concentrations of 11-48-0, 11-55-0 and 18-46-0, which are used most widely in supplying P to the Prairie wheat crop.

In terms of the energy costs of phosphate production, the mining of the sulfur input is by far the largest requirement. Consuming on average 9.3 MJ/kg of S, sulfur production alone accounts for close to one-third the costs of ammonium phosphate fertilizers -- that is of course excluding the associated energy costs of ammonia. Energies consumed in the production of diammonium phosphate (DAP) -- which are basically the same as those consumed in monoammonium phosphate (MAP), the most popular variety of phosphatic fertilizer in Western Canada -- are presented in Table 7.8. Included in the table are the energy requirements associated with using recovered S, which in Western Canada (with one of the largest supplies in the world) is the primary source of all production requirements. Meeting virtually all its manufacturing needs with S recovered from sour and refinery gas (Rennie et al., 1979) the production of ammonium phosphates in the Prairies shows a 25 percent saving in energy requirements over the Frasch sulfur route more commonly used in the U.S.

The major phosphatic fertilizers consumed in Prairie wheat production in selected years are shown in Table 7.9. By a large margin the ammonium phosphates are the major carriers of inorganic P; in fact, they were the only suppliers until the late 1960s. Within this group itself there has been a slight shift towards higher analysis varieties, reflected in a minor improvement in the shipping ratio between 1977 and 1981. Ammonium nitrate phosphate inputs have fallen off since first use in 1968, while applications of both urea phosphate and ammonium phosphate solution became appreciable in 1981.

Phosphatic fertilizers were not adjusted to incorporate efficiency improvements in their synthesis over time. Considering the relative magnitude of the input and its cost (in comparison to N for example) such calculations would have had only a minor effect. Moreover, as there has been only a slight change in the constituents of overall use, it was not considered necessary to adjust for proportional contributions. Therefore the GER of P from fertilizer DAP at 9.3 MJ/kg was employed as a constant value throughout the study period and used in the construction of Table 7.10, the energy equivalents of phosphatic fertilizers consumed in Prairie wheat production. Quantities of applied P and the associated energy costs have shown a substantial increase between 1948 and 1981, and although used in lesser quantities and energetically cheaper to produce than fertilizer N, the seventeen-fold rise from 4.7 MJ/ha to 78.1 MJ/ha and the levels themselves are both significant.

<u>Potassium</u>

Potassium, although it represents agriculture's third most important fertilizer nutrient, is used in Western Canada in quantities far less than those of either N or P. Having its first widespread usage recorded no more than two decades ago its consumption is only just now becoming appreciable: in 1981 application rates for the first time surpassed one kg/ha. Potassic fertilizers have been given a variety of informal and interchangeable names, most notably amongst them are potash, muriate of potash and sylvinite. However, all are synonymous with various chloride salts and sulfates which serve as the principal carriers and out of this group it is the mineral potassium chloride (KCl) which is of greatest economic importance. The word potassium originates from the New Latin potassa, a term which denotes the original source of the element "pot ash", a white coloured lye-like residue of the wood ash evaportated in cast iron pots by early agriculturalists.

Potassium, as the lithosphere's seventh most common element, is found in large deposits in several areas through the world. Western Canada's deposits at an estimated 50 billion tonnes are the largest and one of the richest, supplying on average close to 25 percent of world demand. The Prairie ore body stretching some 750 km across central Saskatchewan and western Manitoba was initially discovered in 1943, but it was another 20 years before production became continuous. Ten mines, all in Saskatchewan, now work the deposits: nine by conventional room and pillar techniques and one by a solution mining in a process where underground ores are dissolved by a reducing agent in site and brought to the surface in solution form. Through both methods the refined produce granular KCl with an average 50 percent K analysis by weight is the finished material.

The manufacturing of K-fertilizer, unlike that of either N or P, is a rather straightforward process, involving production of a single product by one industry, performing both production and refinement at a single location. Because of this, analysis of the industry's energy requirements requires little more than a comparison of fuels and electricity consumed with quantities produced.

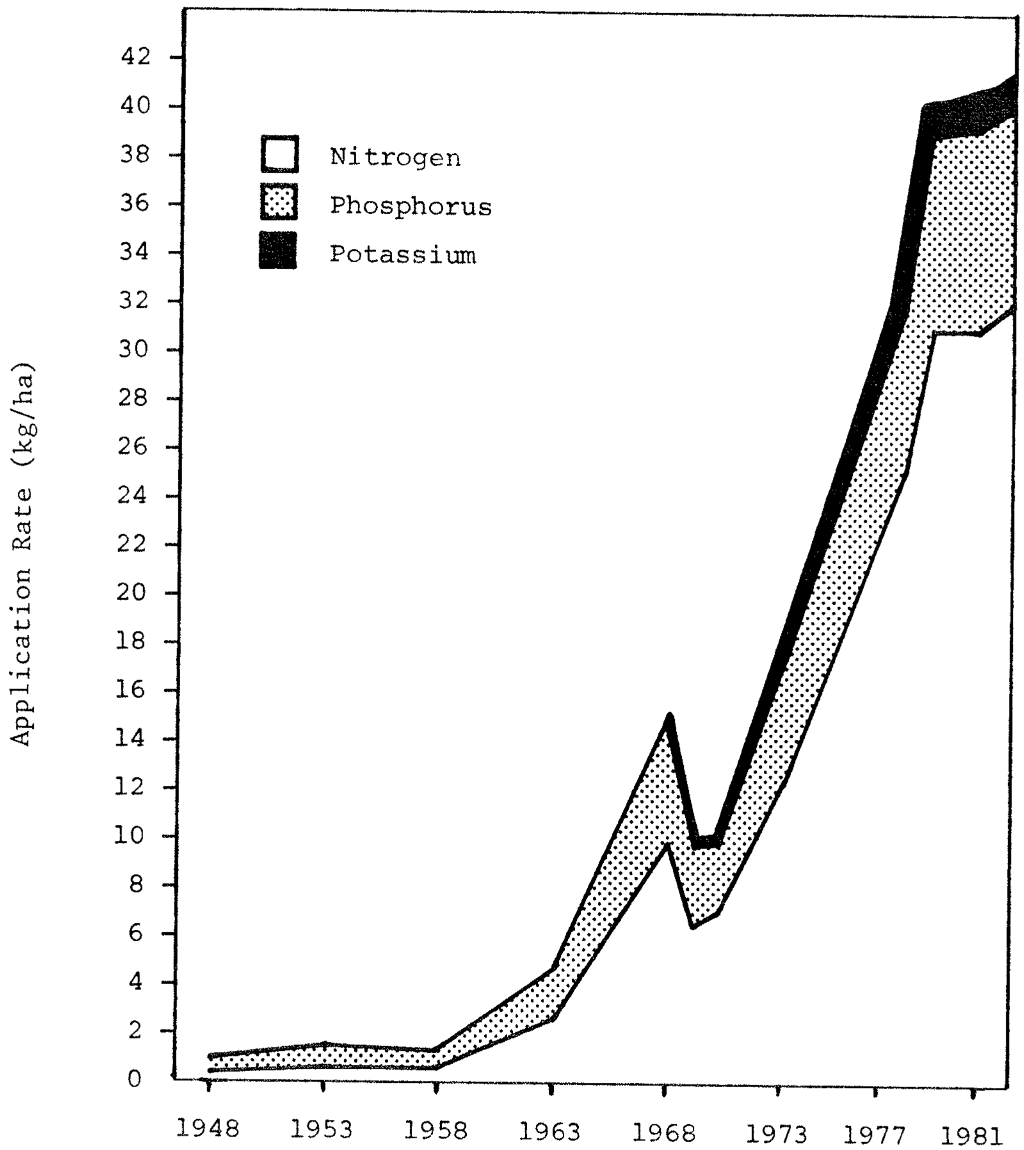
The Western Canada potash industry had existed roughly 10 years before the data on its operations became publicly available. After 1973 statistical sources began recording rudimentary data on various aspects of the industry's performance (Statistics Canada, 1974a; 1974b; 1978a; 1978b; 1983). In 1973 the industry consumed 23.287 PJ (415.12 X 10^6 m^3 natural gas, 3,425 X 10^3 l diesel fuel, 806.97 X 10^3 l gasoline, 673.49 X 10^3 l heavy fuel oil, 655.42 X 10^3 l light fuel oil, 311.87 X 10^3 l L.P.G. and 687.78 X 10^6 kWh electricity) in the production of 3.700 X 10^6 t of K. Simply dividing overall consumption by total production yields an average energy intensity of 6.3 MJ/kg of K. Comparable intensities for 1977 and 1981 are, respectively, 6.0 and 5.7 MJ/kg of K. The fuel and electricity figures from which these values were derived include not only extraction and milling requirements but the requirements of building, heating and lighting, and business-related transport. Intensities were the calculated average of both shaft-and solution-mining techniques.

Energy intensities were also calculated from data collected in an industry-wide survey conducted in Western Canada in 1982. Comparing energy consumption to production output, an intensity of 3.8 MJ/kg was calculated from the information I received, although in this instance computed intensities reflect only the requirement of the extraction and milling of ore in shaft mines: solution-mining energy requirements would not be disclosed by the company involved. Estimates in the U.S., however, put the cost per unit of production at approximately four times the cost of shaft-mining methods (Blouin, 1974), which in the case of this study would be roughly 15 MJ/kg of K. The suggestion is that the original investment for solution mines in terms of capital energy costs are low, low enough in fact to offset its substantially higher operating requirements. However no data exist to support this contention. In the only other solution mine in North America (located in the southern U.S.) concentration of the extracted solution is performed in above ground open-air lagoons by solar evaporation in the attempt to reduce drying costs.

The energy intensities calculated from statistical sources were believed to offer the fullest description of actual conditions, and were therefore employed in computing application energy costs. The quantities of potassic fertilizer applied in Prairie wheat production between 1948 and 1981 and the corresponding energy intensities have been assembled in Table 7.11. The value of 6.3 MJ/kg for 1973 was applied where intensities were unavailable for earlier years. From the data it is clear that the energy equivalent of fertilizer K consumption has always been small, in part owing to the fact that positioned above one of the most extensive ore bodies in the world the soils originally had an adequate K content and low fertilizer requirement. However, increases in both application rate and energy cost over the last interval in the time series has brought the input to a position of a little more significance.

FIGURE 7.1

CHEMICAL FERTILIZERS CONSUMED IN
PRAIRIE WHEAT PRODUCTION
1948-1981*



*Application rates from Table 7.2

FIGURE 7.2

ENERGY COSTS FOR THE SYNTHESIS
OF AMMONIA OVER TIME

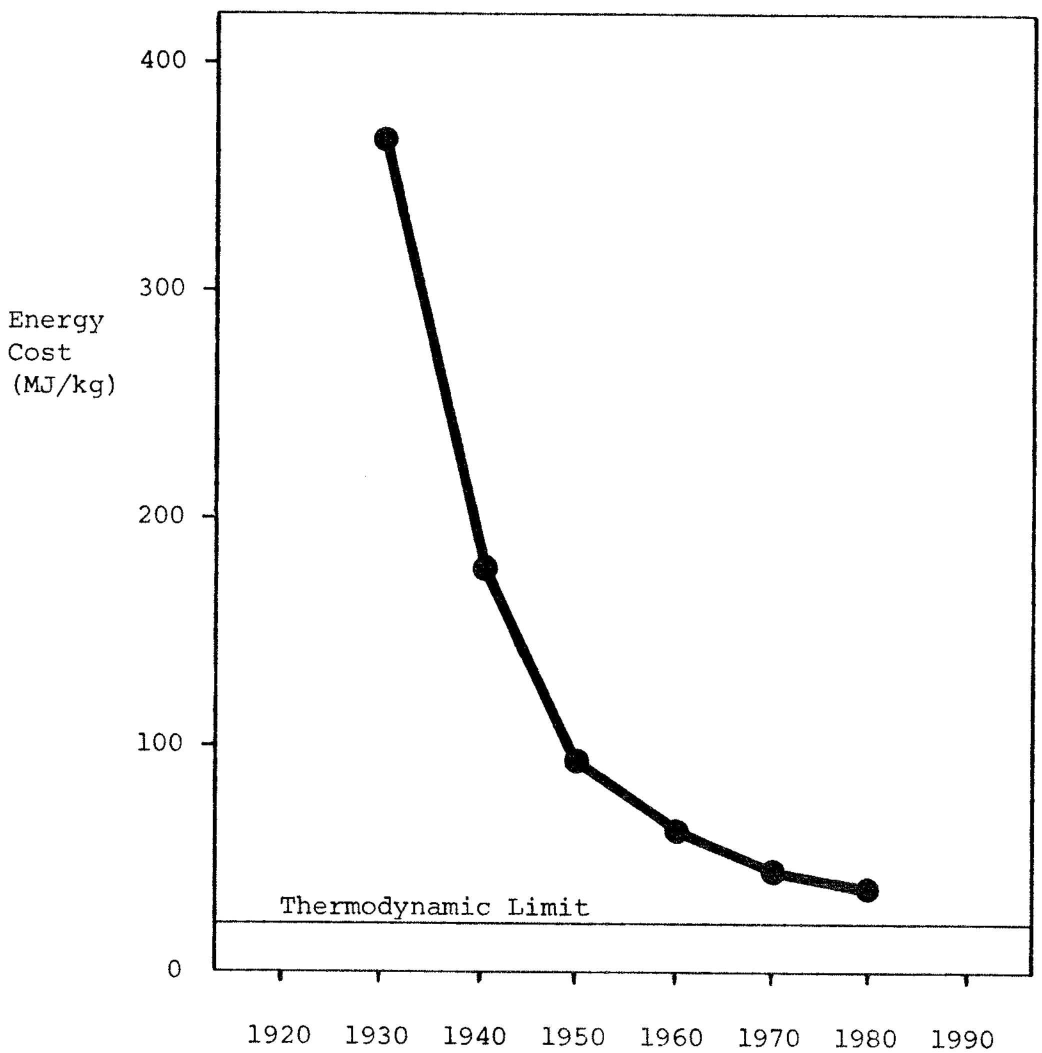


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TABLE 7.1

PRIMARY NUTRIENTS IN COMMON FERTILIZERS CONSUMED IN WESTERN CANADA AGRICULTURE

(All quantities in '000 tonnes)

Year	Nitrogen (N)	Phosphorus (P)*	Potassium (K)**	Total
1948	5.29	8.90	--	14.19
1953	11.07	16.52	--	27.59
1958	10.75	11.34	--	22.09
1963	42.67	39.38	0.05	82.09
1968	179.73	103.04	1.89	284.66
1973	228.62	89.07	1.86	319.56
1977	369.50	111.50	2.00	483.00
1981	617.11	168.81	30.83	816.72

*Conversion: P_2O_5 X 0.4364 = P

**Conversion: K_2O X 0.8302 = K

Derived from: Statistics Canada 1948-1977. Fertilizer Trade. Cat 46-207, annual, Minister of Supply and Services, Ottawa, and WFCA 1981. Annual Retail Fertilizer Sales Survey, Western Canada Fertilizer Association, Calgary, AB.

TABLE 7.2

APPLICATIONS OF NITROGEN, PHOSPHORUS AND POTASSIUM TO PRAIRIE WHEAT

Year	Area Sown To Wheat* 10^3 ha	Area Sown To Wheat* As a proportion of principal grains (percent)	Application Rates N (kg/ha)**	Application Rates P (kg/ha)**	Application Rates K (kg/ha)**	Total
1948	9,452	(57)	0.3	0.5	--	0.9
1953	10,268	(60)	0.7	1.0	--	1.7
1958	8,450	(50)	0.7	0.7	--	1.4
1963	10,618	(65)	2.5	2.4	--	4.9
1968	11,967	(64)	9.9	5.6	0.1	15.6
1973	8,418	(53)	12.5	4.9	0.1	17.5
1977	9,794	(55)	20.5	6.2	0.1	26.8
1981	12,120	(60)	30.7	8.4	1.5	40.6

*Areas from Statistics Canada 1948-1981. Field Crop Reporting Series. Cat. 22-002, seasonal, Minister of Supply and Services, Ottawa.

**Quantities calculated by equating percentage wheat area of principal grains with consumption figures from Table 7.1, and dividing the result by hectares sown to wheat.

TABLE 7.3

MAJOR NITROGENOUS FERTILIZERS SUPPLIED TO THE PRAIRIE WHEAT CROP IN SELECTED YEARS

('000 tonnes)

Fertilizer Material	Nitrogen Fraction	1958 Material	1958 N content	1968 Material	1968 N content	1977 Material	1977 N content	1981 Material	1981 N Content
Anhydrous Ammonia	0.82	0.23	0.19	5.19	4.26	77.67	63.69	160.10	131.28
Ammonium Nitrate*	0.34	3.11	1.06	233.02	61.26	218.75	64.45	224.84	69.68
Urea**	0.46	--	--	28.20	8.37	75.20	34.59	232.11	103.84
Ammonium Sulphate	0.21	1.07	0.22	16.77	3.50	29.93	6.28	25.35	5.32
N-solution	0.28	--	--	5.73	1.60	17.58	4.92	42.55	11.91
Ammonium Phosphate***	0.12	32.77	3.90	254.69	36.20	244.00	29.28	404.39	48.24
Total N			5.38		115.21		203.21		370.27
Shipping Ratio: Quantity Material / Quantity N =			6.73		4.54		3.26		2.94

*Includes ammonium nitrate phosphate in 27-14-0 and 28-23-0 analyses
**Combined with urea phosphate in 29-29-0 analysis
***Made up of MAP (11-48-0 to 11-55-0), DAP (18-46-0), and ammonium phosphate sulphate (16-20-0 (14)).

TABLE 7.4

AVERAGE GROSS ENERGY REQUIREMENTS FOR NORTH AMERICAN MANUFACTURE OF SELECTED NITROGENOUS, PHOSPHATIC AND POTASSIC FERTILIZERS

Product	Nutrient Fraction (%)	Average GER MJ/kg Product	MJ/kg Nutrient
Nitrogen Fertilizers (N)			
Anhydrous Ammonia	82	46.9	57.2
Urea: prilled	46	36.6	79.5
granular	46	35.0	76.1
Ammonium Nitrate			
prilled	34	24.9	73.4
granular	34	24.4	71.8
Ammonium Sulphate			
synthetic	21	12.6	60.0
byproduct[b]	21	4.7	22.4
N-solution	22	12.6	57.2
Phosphorus Fertilizers (P)			
Phosphate Rock[c]	14	1.2	9.2
Single Superphosphate			
granular	8.7	1.7	19.5
non-granular	8.7	1.0	11.5
Triple Superphosphate			
granular	20	4.3	21.5
recovered sulphur[d]	20	1.7	8.3
Diammonium Phosphate[e]			
Frasch sulphur	20	14.6	28.5
recovered sulphur	20	10.8	9.3
Potassium Fertilizers (K)			
Potash[f]	50	3.0	6.0
Sulphur (S)[g]			
Frasch process	100	9.3	9.3
Recovered	100	0.4	0.4

Sources:

[a] all data from Mudahar, M. S. and Hignett, J. P. 1982. Energy and Fertilizer. Technical Bull. IFDC-T-20, International Fertilizer Development Center, Muscle Shoals, AL. 241 pp.; except where indicated.

[b] Ammonium sulphate as a byproduct of coke-making in the steel industry.

TABLE 7.4 Continued

[c] For direct application purposes; dried and finely ground.

[d] Value from Blouin, G. M. and Davis, C. H. 1975. Energy Requirements For The Production And Distribution Of Chemical Fertilizers In The United States. In Proceedings of the Energy in Agriculture Conference-Workshop, Southern Regional Education Board, Atlanta, GA. pp. 51-67.

[e] Costs derived from Blouin, G. M. 1974. Effects Of Increased Energy Costs On Fertilizer Production Costs And Technology. TVA Bull. Y-84, National Fertilizer Development Center, Muscle Shoals, AL. 30 pp. and Blouin and Davis, 1975, ibid. The energy requirement of ammonia is excluded in nutrient column.

[f] Author's calculation of Saskatchewan average of shaft and solution mining techniques.

[g] Both values from Blouin and Davis, 1975. ibid. Standard Frasch process and a representative figure based on the recovery of sulphur from sour and refinery gas. (The desulphuration of oil exclusively for sulphur recovery has a process energy requirement of roughly 35 MJ/kg).

TABLE 7.5

ADJUSTED ENERGY COSTS OF MAJOR N FERTILIZERS 1948-1981*

Year	Energy Cost (MJ/kg or N) Anhydrous Ammonia	Urea	Ammonium Nitrate
1948	98.4	119.0	113.8
1953	92.2	112.8	107.6
1958	86.0	106.6	101.4
1963	79.9	100.3	95.1
1968	73.4	94.0	88.8
1973	67.2	87.8	82.6
1977	62.2	82.8	77.6
1981	57.2	77.8	72.6

*1981 values from Table 7.4.

TABLE 7.6

ENERGY INTENSITY OF APPLIED NITROGEN

(Example Calculation For 1981)

Fertilizer Material	Fraction of N Supplied by Material*	Energy Cost of Nutrient** (MJ/kg)	Proportionate Energy Cost
Anhydrous Ammonia	218,805/617,121	57.2	20.28
Urea	173,069/617,121	77.8	21.82
Ammonium Nitrate	116,125/617,121	72.6	13.66
Ammonium Phosphate	80,392/617,121	57.2	7.45
N-solution	19,856/617,121	57.2	1.84
Ammonium Sulphate	8,874/617,121	60.0	0.86
		Energy Intensity of 1 kg of N	65.91

*Derived from WCFA 1981. Annual Fertilizer Sales Survey. Western Canada Fertilizer Association, Calgary, AB.

**Individual values from Table 7.4.

TABLE 7.7

ENERGY EQUIVALENTS OF NITROGEN
SUPPLIED TO THE PRAIRIE WHEAT CROP
1948-1981

Year	Applied N* (kg/ha)	Energy Intensity (MJ/kg)	Energy Equivalent (MJ/ha)
1948	0.3	97.2	29.2
1953	0.7	92.5	64.8
1958	0.7	88.0	61.6
1963	2.5	84.4	211.0
1968	9.9	82.6	817.7
1973	12.5	74.1	926.7
1977	20.5	70.5	1445.2
1981	30.7	65.9	2023.1

*Application rates from Table 7.2.

TABLE 7.8

ENERGY CONSUMED IN THE SYNTHESIS
OF DIAMMONIUM PHOSPHATE

Material or Process Step	Frasch Sulphur		Recovered Sulphur	
	MJ/kg	Percentage	MJ/kg	Percentage
Sulphur production	4.2	29.0	0.4	3.7
Sulphuric acid production	0.1	0.7	0.1	0.9
Phosphate rock preparation	0.4	2.9	0.4	3.7
Phosphoric acid preparation	0.3	2.2	0.3	2.8
Ammonia	8.9	60.9	8.9	82.5
Ammoniation and granulation	0.1	0.7	0.1	0.9
Product drying	0.5	3.6	0.5	4.6
Total	14.6	100	10.8	100

Sources: Blouin, G. M. 1974. Effects of Increased Energy Costs On Fertilizer Production Costs And Technology. TVA Bull. Y-84, National Fertilizer Development Center, Muscle Shoals, AL. 30 pp.; and Blouin, G. M. and Davis, C. H. 1975. Energy Requirements For The Production And Distribution Of Chemical Fertilizer In The United States. In Proceedings of the Energy in Agriculture Conference-Workshop, Southern Regional Education Board, Atlanta, GA. pp. 51-67.

TABLE 7.9

MAJOR PHOSPHATIC FERTILIZERS SUPPLIED TO THE PRAIRIE WHEAT CROP IN SELECTED YEARS

('000 tonnes)

Fertilizer Material	Phosphorus Fraction	1958		1968		1977		1981	
		Material	P content	Material	P content	Material	P content	Material	P content
Ammonium Phosphates*	0.21-0.24	31.77	5.67	233.17	48.56	243.76	51.76	404.39	89.68
Ammonium Nitrate Phosphate**	0.06-0.10	--	--	139.96	17.38	103.42	9.56	78.86	7.34
Urea Phosphate***	0.13	--	--	--	--	--	--	17.46	1.86
Ammonium Phosphate Solution	0.15	--	--	--	--	--	--	14.57	2.16
Total P			5.67		65.94		61.32		101.04
Shipping Ratio: Quantity Material / Quantity P			5.60		5.66		5.66		5.14

*Predominant analyses: 11-48-0, 11-51-0, 11-55-0, 16-20-0, and 18-46-0.
**Includes 23-23-0 and 27-14-0.
***Combined quantities of 29-29-0 and 34-17-0.

TABLE 7.10

ENERGY EQUIVALENTS OF PHOSPHORUS SUPPLIED TO THE PRAIRIE WHEAT CROP 1948-1981

Year	Applied P* (kg/ha)	Energy Intensity (MJ/kg)	Energy Equivalent (MJ/kg)
1948	0.5	9.3	4.7
1953	1.0	9.3	9.3
1958	0.7	9.3	6.5
1963	2.4	9.3	22.3
1968	5.6	9.3	52.1
1973	4.9	9.3	45.6
1977	6.2	9.3	57.7
1981	8.4	9.3	78.1

*Application rates from Table 7.2.

TABLE 7.11

ENERGY EQUIVALENTS OF POTASSIUM SUPPLIED TO THE PRAIRIE WHEAT CROP 1963-1981*

Year	Applied K** (kg/ha)	Energy Intensity (MJ/kg)	Energy Equivalent (MJ/ha)
1963	0.003	6.3	0.019
1968	0.104	6.3	0.655
1973	0.102	6.3	0.643
1977	0.112	6.0	0.674
1981	1.525	5.7	8.692

*Potassium was not applied in significant amounts prior to 1963.

**Application rates from Table 7.2.

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VIII. PESTICIDES

Nationwide it is estimated there are more than 2,800 species of insects, 250 species of weed, 500 varieties of disease and 50 different nematodes potentially threatening to Canadian agriculture. Yet there are only about 300 insect and 150 weed species which occur in numbers warranting control, and of this amount no more than a few dozen affect grain production annually. Historically cultural methods of pest management in Prairie agriculture have prevailed, however, with industrialization during the 1950s the use of chemicals became widespread. Consumption of pesticides was limited in the initial years of the study period, but by 1981 after rapid expansion some 81,000 t was being consumed annually in Western Canada. In this year alone there were 350 different active ingredients registered for use in a broad range of more than 17,000 products (CDA, 1983). Out of the three main categories of pesticide usage (insecticides, herbicides and fungicides) herbicides use since the 1960s has grown the fastest and now constitutes the major chemical input to Prairie wheat production. A brief review of both insecticides and fungicides are in order before we turn to analyzing the energy costs of herbicide use alone.

Insecticides

Fortunately for the Prairie grain producer, there are relatively few insects which pose a potential threat in Western Canada. Of the few that do, they generally fall into the occasional pest category and requiring chemical control only in localized areas where periodic infestations erupt and only when existing cultural and biological methods have failed. Applications of insecticide are limited therefore and below levels considered significant for the purposes of this study. Insects that infest growing wheat belong to seven taxonomic orders, including grasshoppers and locusts, wireworms and cutworms, maggots, cinch bugs, grain aphids and wheat midges, wheat stem sawfies, and hessian flies (Peterson, 1965; MDA, 1981). Insects which infest stored grain include beetles, moths and weevils (CDA, 1978). On an annual basis it is estimated that current losses from infestation are no more than ten percent and one percent, respectively, of field and stored grain (Turnock and Samborski, 1980).

Traditionally, control of insects was attained by cultivation (which served to disturb the insects nurturing environment by bringing unhatched eggs and larvae to the soil surface) and the frequent rotation of crops (which served to change the species of host plants). Poison baits, consisting mainly of a grain carrier laced with arsenic, Prais green, nicotene sulfate or rotenone, first came to be used around the turn of the century. As stomach poisons, they were placed randomly about fields in problem areas for subsequent insect ingestion. By the 1940s, the first of the modern insecticides -- led by toxic chlorinated hydrocarbons of which DDT (still the standard for effectiveness) is most widely known -- appeared in Western Canada. As broad spectrum biocides they where much more effective in controlling not only the orthoptera order but a wide range of other insects as well. Some 15 years after mechanization was well underway, these chemicals were in turn replaced by the environmentally less damaging, yet more selective carbamates and organophosphates.

Data from the agronomically comparable Northern Plains district of the U.S. indicate that the insecticidal treatment of wheat is the least important amongst all major crops, and additionally that applied quantities have been falling since records were first kept in 1966 (Schwartz and Klassen, 1981). Indirect evidence suggests that the use of resistant genotypes, fertilizer, finely seeding, good seed-bed preparation, crop rotation and the limited use of trap crops have been responsible for this development. Data for insecticide usage in Western Canada are not available. However, applications were considered to be similar to those of wheat production in the U.S., and at such levels were too small to warrant inclusion in energy-cost calculations.

Fungicides

Of the diseases commonly affecting Prairie wheat production the most important are caused by fungi and include leaf and stem rust, smut, mildew, foot and root rot, blight, blotch, ergot, tanspot and speckled-leaf disease; bacteria which include chaff and glume rot; and viruses which include mosaic and yellow dwarf. As a result of resistant cultivars, good sanitation, clean seed and machinery, fertilizer and the proper timing of field operations the incidence of these diseases has decreased with time. Eruptions, of course, do occur -- the last great stem rust, caused by the fungi strain 15b in 1954, wiped out nearly one-third of that year's wheat crop -- and new practices and new plant varieties will be continually in demand to offset recurring crop susceptibility brought on by these highly adaptive and evolving microorganisms, but the necessity of chemical control is now limited. However, regardless of their limited presence, diseases will always to be a problem in spite of the best efforts by producers to control them; in Western Canada wheat losses of ten percent are considered unavoidable (Turnock and Samborski, 1980).

Chemical control of diseases is often accomplished by no more than a simple fungicidal seed treatment. At present only an estimated one or two percent of about one million tonnes of wheat seed sown annually in Western Canada receives fungicide (MDA, 1982). And this has been the level for some time (Freshwater, 1983, pers. comm.). Translated onto a cropped hectare basis, such quantities are very small; dividing 10,000 t by a seeded area of 12 million ha results in less than one kg of wheat being treated per ha. One kg of wheat would receive no more than a few grams of chemical, and in energy terms the costs associated with such levels are negligible. As a result, fungicides, like insecticides, were excluded from energy calculations. Only herbicides, applied in quantities which have grown considerably since the late 1940s are of a magnitude that warrant energy accounting in Prairie production.

Herbicides

Occurring as a widespread and perennial problem in wheat agriculture weeds cause substantial production losses simply by doing what they do best -- competing with the growing crop for limited soil nutrients and moisture. When successful, weed populations lower yields, reduce crop quality, impart bad flavour to the grain and increase both harvest and cleaning requirements. The problem of undesirable plant species has, of course, existed ever since farming first began. In Western Canada weed infestations occurred shortly after the soil was first broken and quickly intensified under the widespread practising of short rotations and improper summer-fallowing (Hay, 1980).

At present there are some 100 weed species that affect Prairie wheat production in economic proportions, however, only about one-third are present in frequencies greater than five percent (Thomas, 1982). Survey data indicate that the normal Prairie grain field contains up to seven different species, out of which two or three constitute major problems. The most important species affecting annual wheat production are wild oats, green foxtail, quackgrass, Canada thistle, lambs-quarters, red root pigweed, wild buckwheat, wild mustard, night-flowering catchfly and stinkweed.

Prior to the introduction of chemicals in Western Canada the principal methods of weed control around the turn of the century were cultivation, summer-fallowing, the use of early maturing crops and the practising of rotations with both grass and forages (Jackson, 1923). Such techniques were for the most part labour intensive, and the introduction of chemical control in the mid-1940s offered an economical and highly effective alternative. The specific use of inorganic compounds for weed control was an offshoot of scientific plant hormone studies in the mid-1930s, which led to the concept of systemic growth regulation through the application and translocation of metabolizable substance some ten years later (NAS, 1968). Early herbicides included 2,4-D (first manufactured for use as an insecticide and later found to be more effective as a broad-leaf suppressant) and 2-methyl-4-chlorophenoxyacetic acid (MCPA). Two,4-D was first successfully demonstrated in Western Canada in 1947, where it was applied to roughly 200,000 ha of Prairie cropland; MCPA became used shortly thereafter. Functioning both as concomitants to and adjuncts of mechanization the acceptance of these two chemicals and their subsequent diffusion throughout the region was rapid. By the mid-1950s an estimated 25 percent of Prairie cropland (4.75 million ha) was receiving at least one field application annually, and within the decade the figure had risen to 75 percent (15 million ha). By the late 1970s a full 85 percent of Prairie cropland was receiving at least one application and another 50 percent at least two applications from one or more chemicals chosen out of a broad array of newly available compounds. Herbicides applied in Western Canada for each year in the time series have been listed in Table 8.1.

Consumptions of herbicides has grown dramatically during the study period, rising from 567 t to 19,000 t between 1948 and 1981. Over this period the early use of 2,4-D and MCPA, which together formed largest component of total consumption until the late 1960s, gave way to increased usage of wild-oat herbicides. Amounting to less than 1,000 t in 1968 wild-oat herbicide consumption rose by 10,000 t in just 15 years. In 1981 it accounted for 60 percent of total use. This pattern is interesting and underscores a development in weed-control practices which suggests that with increasing usage of these more energetically and financially expensive chemicals in the future, control practices will become more costly.

Agronomically the combination of cultural and chemical control practices in the past have maintained weeds below levels capable of causing significant production losses -- about 15 percent in wheat (Hay, 1980). Only wild oats, which seemingly unabated has infested close to 80 percent of Prairie wheat fields for more than 40 years (Manson, 1932; Alex, 1965; Thomas, 1982), and green foxtail continue to be major problems. Yet is these two grasses of the same Graminae family as wheat, plus a small number of the other lesser but still difficult to control species, that have come to be the focus of concentrated efforts. And it is precisely because of their taxonomic relationship and persistence that the more chemically selective -- and energy intensive -- wild oat and miscellaneous herbicides are becoming applied in ever greater quantities (Table 8.1). In the near future if no alternative methods of control are practiced, it is entirely possible that herbicides could lose their economic advantages over other cultural and especially mechanical means of control.

Herbicides, insecticides and fungicides are all energy intensive commodities. Synthesized from a variety of petrochemical feedstocks (e.g. benzene, naptha, propane, ethane, methanol, etc.) costs range anywhere from 85 MJ/kg for 2,4-D to as high as 454 MJ/kg for glyphosate (Roundup). Data on the energy requirements of the great range of pesticide materials that exist are not extensive. In calculating the cost of herbicide inputs in Western Canada Green's (1978) detailed accounting of some 14 commonly sold weed control products was used. Checking his results against other published values, the average of 23 different herbicides, insecticides and fungicides at 205 MJ/kg compared favourably with an average drawn from a broader array of chemicals (220 MJ/kg) calculated by Van Winkle et al. (1978), and was modestly lower than the aggregate figure (275 MJ/kg) used by federal reporting agencies (FEA/USDA, 1976).

In the attempt to develop a clearer picture of consumptive practices in Western Canada between 1948 and 1981, the costs of the various herbicides were arranged into three separate categories, each corresponding closely to those of the reporting agency in Table 8.1. Derived values were equal to 85 MJ/kg for 2,4-D, 135 MJ/kg for MCPA and 240 MJ/kg for an average of the miscellaneous and wild-oat chemicals. Intensities represent energy inputs on a 100 percent active ingredient basis and do not include the energy costs of application, formulation or packaging. Pull-type sprayers remain the most popular vehicle for herbicide application, with aerial spraying accounts for less than five percent of applied quantities (Anon., 1982). As such, attendant tractor fuel costs have been recorded elsewhere (see Chapt. V for details). Formulation and packaging requires too little energy to be included. These values and other contributing data have been collected in Table 8.2 to describe the energy costs of herbicide use in Prairie wheat farming over more than three decades of agricultural industrialization.

Herbicide consumption on a per hectare basis was calculated by dividing total use from Table 8.1 by the area sown to all principal crops in the region for each period. The approach, while it clearly entails no differentiation between crops, nonetheless allows for an accurate estimation of the amounts consumed in wheat production alone. Recommended rates of herbicide application depend principally upon the type and the severity of the weed problem encountered, not upon the type of crop grown. As a result, rates for wheat will be very close or identical to what is recommended for all other cereal grains. Of course, the type of crop will ultimately determine the type of herbicide possible to use but in the case of wheat production in the Prairies, there are very few formulations with which the crop is not compatible.

Similar to most other agronomic inputs on an areal basis, herbicide inputs per hectare have increased dramatically over the period of study. In 1948 several years after chemicals first became available consumption was a low 33 g/ha. Over the next decade, with the diffusion and intensification of mechanized practices, consumption rose quickly. Application rates tripled between 1948 and 1958, and doubled again between 1958 and 1963. Increases were less rapid during the 1960s, consumption was about 260 g/ha in mid-1960s; yet they picked up during the 1970s; rising from 366 g/ha in 1973 to 593 g/ha in 1977, and again to 800 g/ha by 1981. Over these last two periods increases were equal to 62 percent and 35 percent respectively. The energy intensities (Table 8.2, column 3) for each year in the time series were computed by adjusting summary costs (those shown) to reflect the proportional input of each three input categories. The results of this calculation indicate that unit chemical costs have increased significantly. Between 1948 and 1981 the energy intensity of one kg of applied herbicide grew by more than 135 percent, rising from 85 to almost 200 MJ/kg in just over 30 years.

Underpinning this shift is, of course, the changing mix of constituent inputs. For example, 2,4-D and MCPA, the two most commonly used herbicides until the mid-1970s, represent two of the least costly chemical products to manufacture. On the other hand, the miscellaneous and wild-oat herbicides, represent many of the most expensive varieties. For example, dicamba, propachlor and diuron with energy costs respectively of 295, 290 and 270 MJ/kg respectively are now widely used, as is the earlier mentioned glyphosate with an intensity of more than 450 MJ/kg.

Together the shift towards consumption of more expensive varieties and the advent of higher application rates has lead to a total energy cost that rose from just under 50 TJ to more than 2,800 TJ between 1948 and 1981. Prorated on a per hectare basis it is equal to a 60-fold rise in equivalent energy consumption, from approximately 2.8 MJ/ha in 1948 to 159 MJ/kg in 1981. In terms of overall production energy costs it ranks fifth, and over the past decade at 225 percent it has been the fastest rising of all inputs.

Chemical weed-control practices are most often cost efficient owing to the large yield increases from a relatively inexpensive input. In Western Canada typical monetary returns in wheat production range from two to ten times the initial dollar investment in herbicide (Stobbe, 1974). At such levels of return it can be expected that the use of agrochemicals will continue to expand in the near future. However beyond the relatively restricted confines of such economic rational, there are definite environmental and ecological side-effects which may mitigate an excessive reliance solely upon this method of pest control in the future.

Chemical compounds within the herbicide family have not been implicated to the same degree as have the more environmentally persistent and damaging chlorinated hydrocarbons, or highly toxic organophosphates (Hance, 1979). Yet they are, nonetheless, dangerous substances and are the principal agents involved in the many poisonings which occur every year in the Prairie Provinces. As one report indicated, acute poisonings and a variety of cumulative ill effects have been reported in one out of every five operators handling pesticides, with 2,4-D being identified as the most problematic (NRC, 1978). Of course, simply following the recommended handling instructions would reduce operator injuries significantly but regardless of precautions there will always be some risk involved in using toxins.

Harm can be, of course, caused to the crop with improper applications affecting growth, yield and nutrient composition, plus the nutrient retention ability and quality of the grain post-harvest (Kadum, 1981), and to a great variety of non-target organisms as well. Damage in these instances can be the result of chemical transport through soil, water and air via the processes of leaching, seepage, run off, volatilization and drift. In fact one of the greatest dangers lies where the post-application action of these chemicals is unknown (Galloway, T. 1982 pers. comm.). There are reports of extended persistence: 2,4-D has been found to be stable in water for up to eight years (Edwards, 1973) and found deposited in lake-bottom sediments more than one year after application (Harlbert, 1975). (The laboratory specified life-time of the chemical is reported to be no more than three to four weeks.)

An associated problem of intensified agrochemical use through the 1970s has been the appearance of chemicals in Prairie surface waters on a widespread basis. In agricultural regions 2,4-D has been found present on a year-round basis (Gummer, 1979). In urban areas it has also been found, but only in significant quantities during the May to September cropping season. The problem here is one which results not only from cropping practices. Maximum levels were recorded at one Winnipeg sewage plant which received discharge directly from two upstream herbicide packaging plants.

Problems can also occur with the pests themselves in terms of conditioned chemical resistance. The condition is most common with insects, but the development of resistant species has been found in plant populations as well; albeit at much lower levels (Haas and Streibig, 1982). In fact, what has come as a surprise to many researchers is that the weed species which have developed resistance are so few. After 30 years of use no major population has developed dominant strains of individuals genetically capable of resisting the phenoxyacetic herbicides. But, this is not to say a problem may not arise in the future, for as herbicide applications increase so too does the selective pressure for adaptation. At present some individuals within the most common Western Canada weed populations do display the genetic component for resistance, but the incidence is rare (Le Baron and Gressel, 1982).

What of herbicide use in the future? Researchers point out that no weed species has ever been completely eradicated by herbicide use, and because of this they advise that the best use of herbicide lies in applying quantities which give good control, but which at the same time are adequate in maintaining a "predator-host" equilibrium. At this level the crop and the problem species are capable of competing naturally, and the potential of plant resistance is reduced (Gressel and Segel, 1982). Therefore in light of this recommendation we should expect to see a levelling off in future chemical use where the judicious use of herbicide serves as an adjunct to rather than a complete replacement of traditional methods; giving good results while simultaneously permitting the use of a given herbicide for a longer period (Johnson, 1980). At the same time we should expect research into all areas of associated problems to continue.

As noted earlier, chemicals are in most cases an efficient means of control: they make possible weed control where cultivation is difficult; they allow the pre-emergent suppression of weeds that would otherwise compete with the growing crop; they avoid crop damage from post-emergent cultivation; and they reduce tillage requirements. And generally they show an energetic advantage over the alternative mechanical practices (Hill, 1982). Yet it is certainly not true in all situations. Energy savings themselves and their magnitude will depend ultimately upon a host of site-specific and local variables (ranging from indigenous soil structure to the vagarities of daily weather), consisting of some over which the operator has control and some of which he hasn't. In comparing mechanical and chemical control systems energy costs can be determined first by calculating the energy of fuel consumed in the tillage operation, and second by the fuel consumed in the spraying operation plus the embodied energy cost of the chemical applied. The embodied energy cost of the tractor is a constant and the embodied cost of the tillage implement can be assumed to cancel out the cost of the spraying apparatus.

Considering the relatively minor quantities of fuel consumed in a spraying operation compared to that of a tillage pass chemical control should be expected to reduce associated energy requirements. And of course where the energy equivalent of the fuel reduction is greater than the energy cost of the chemical that will be the case. In the Red River Valley where a tractor and drag harrow might consume seven l of gasoline in one field pass, substitution with a spraying operation to give equal control -- one pass again (Anderson, 1980) -- can be expected to consume only one-seventh of that, or one l/ha with a much lower draft requirement. Adding on the cost of a common herbicide treatment 2,4-D and difenzoquat (Anon., 1982) will raise the energy requirement by roughly 160 MJ/ha, to total 195 MJ/ha. Compared to the cost of mechanical tillage, 250 MJ/ha, it is clear that chemical tillage is in this case less costly by a factor of one-fifth.

However, if the chemical cost is greater than the fuel reduction the advantage is lost. For example, if another commonly used but more expensive herbicide, glyphosate, is applied instead of the former combination, the new cost for the spraying operation would sum to almost 500 MJ/ha, a value 2.5 times greater than the original, and twice that of the mechanical control cost. Yet comparisons are not always so simple. Other contributing factors that would affect the energy costs in both examples are the requirement of more than one field pass with the tillage implement or the combining of the spraying, primary tillage and seeding operations. What should also be noted is that while the consumption figure of seven l/ha is for an average tractor pulling an average implement under average soil conditions, similar operations can vary in fuel requirements by as much as an order of magnitude (Firth and Promersberger, 1974). Incorporating these practical exigencies greatly complicates what may have otherwise been a straightforward calculation. As with many other agronomic inputs and energy costs, such variability is a fact of agricultural life. In evaluating alternatives just as in economics there is no definitive prescription for energy efficiency that will hold true across all environments: there are only options which must be studied independently.

One planning report in Western Canada indicated that under the prevailing economic conditions of 1982 the input cost of chemicals was up to twice that of liquid fuels on a unit production basis (Kyle and Wiebe, 1982). Under such conditions the monetary expense of increased herbicide use makes the complete replacement of mechanical tillage in wheat production highly unlikely. And at least one study has found this to be the case under experimental conditions (Lindwall and Zentner, 1983). Of course, what this indicates in the longer term -- where it is highly unlikely that the price of chemicals (and their major industrial feedstock, hydrocarbons), will not rise in a comparative fashion to fuels -- is that minimum tillage may not be as viable an energy conserving policy as is often posited.

TABLE 8.1

PRAIRIE HERBICIDE USE 1948-1981*

(All quantities in tonnes of active ingredients)

Year	2,4-D	MCPA	Chemicals Miscellaneous**	Wild Oat Herbicides***	Total
1948	567	--	--	--	567
1953	1,705	--	37	--	1,742
1958	1,590	266	40	--	1,895
1963	3,315	572	160	26	4,073
1968	4,245	1,208	304	726	6,858
1973	3,273	1,614	714	1,856	7,453
1977	3,500	1,594	1,102	6,650	12,846
1981	3,573	2,022	2,232	11,250	19,077

*Derived from MDA 1948-1981. Herbicides Used Agriculturally In Western Canada, annual, Manitoba Department of Agriculture, Winnipeg, MB

**Includes: TCA, Dalapon, 2, 4, 5-T, Dichloroprop, Dicamba, Bronoxynil, Nitrofen, Glyphosate, Propanil, Linuron and others. Composition of total varies year to year.

***Includes: Asulan, Atrazine, triallate, difenzoquat, barban, EPIC, eradicane, diclofop, flampropmethyl, trifluralin. Composition of total varies.

TABLE 8.2

APPLICATION RATES AND ENERGY EQUIVALENTS OF HERBICIDE USE IN WHEAT PRODUCTION

Year	All Crops Seeded Area* (10^3 ha)	Herbicide Application Rate (g/ha)**	Energy Intensity (MJ/kg)	Energy Equivalent (MJ/ha)
1948	17,463	32.5	85.0	2.76
1953	18,585	93.7	88.3	8.27
1958	17,967	105.5	94.6	9.98
1963	18,814	216.5	98.4	21.30
1968	20,926	327.7	124.7	40.86
1973	20,351	366.2	148.1	54.24
1977	21,665	592.9	184.1	109.17
1981	23,854	799.7	199.3	159.40

*From Statistics Canada, 1948-1958. Field Crop Reporting Series. Cat. 22-002, seasonal, Minister of Supply and Services, Ottawa.

**Calculated as Column I divided by totals from Table 8.1

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IX. TRANSPORT OF PRODUCTION INPUTS

In process analysis the assignment of energy costs is largely defined by the boundary conditions of study, and the approach taken here in the assignment of transport energy costs was to include only the energy costs of moving major production inputs to the farm--not the costs of shipping wheat to market. The decision was based first on the problems associated with determining the products final destination and, second, on proper accounting procedure. In the first instance, defining where the market boundary should be established, one is forced to make an arbitrary decision: is the delivery point the railway siding, the terminal elevator, the distant shore, the city, or the consumer? In the case of Western Canada wheat is trucked, railroaded and barged to countless locations in dozens of countries around the world, in distances ranging from several hundred to several thousands of kilometers. Choosing amongst them would only lead to great inaccuracies in associated energy costing and, ultimately, would show little about the practise of wheat agriculture itself, especially as it has developed over three decades of progressive mechanization.

But more importantly is to question in the second instance: is it appropriate that the wheat producers be charged with the rail company's or the freight liner's costs? For the purpose of this study, I think not. Only the downstream consumer should be assigned these transportation costs, be it the flour mill, the bakery or the family household. The wheat producer has no control over these inputs and they are obviously not a part of his production activity. As was noted in Chapter V, fuel consumed by the operator in performing farm duties included the associated energy costs of delivering grain to its initial market delivery point, the country elevator, and as a result the costs of transporting wheat to this point have been already recorded. Past this point, energy costs become constituent parts of another industry, and as such must be ignored in the construction of the wheat agriculture energy budget. The costs of transporting production inputs to the farm, however, must be accounted for, and as this has not yet been done it is to these that we now turn.

Out of all productive factors included in the wheat production universe only two: machinery and fertilizer, qualify for transport calculations. Reviewing other major inputs we find that animal feed is basically an "on-site" commodity; seed is typically home grown (less than one percent of Prairie wheatland is sown with certified seed, the common practice is to just hold back part of the previous year's harvest or simply purchase the required amount from a neighbour); fuel costs are too small to be accurately estimated (see Chapter V for details); and electricity has already been accounted for. The emphasis here is on the transport of inputs of major proportions, and for this reason herbicides too have been excluded.

Calculating energy costs involves a straightforward multiplication of the quantities of material consumed (or their per hectare equivalent) and the energy intensity of the mode of transport. Detailed estimates of the cost of transporting particular commodities are generally not available, and what must be used are averages, composed of a wide range of materials, or aggregates drawn from the total expenditures of the transport system in question. By their nature, such averages encompass costs proprated across a variety of shipping distances, load factors and terrain. The results for the two major transport modes of rail and highway trucking for each year in the time series have been assembled in Table 9.1.

For railway transport in Canada, calculations were made based on the energy equivalent of all fossil fuels consumed by locomotives and maintenance equipment both in regular freight and work-train service. No costs were assigned to the embodied energy of rolling stock nor to the specific costs of roadbed construction. To arrive at energy intensities of transport, total fuel consumption was divided by total tonnage for each year. The data in Table 9.1 indicate that the energy cost of rail transport has declined substantially since the beginning of the study period. Beginning with an average intensity for steam locomotives of approximately two MJ/kg in 1948, costs fell to 0.31 MJ/kg in just two decades. Responsible for the fall was not only the greater mechanical efficiency of the new diesel-electric traction system (locomotives equipped with the new system were introduced in the early 1950s), but larger engine size, longer consists, fewer starts and stops, improved rolling stock and reduced grades.

In the case of highway transport, estimates of energy costs were made on the basis of fuel consumed by motor-carriers employed in hauling large freight across the moderate to long distances typical of Western Canada. For each year in the time series total fuel consumption was again divided by total tonnage hauled to yield energy intensities on a MJ/kg basis. The energy costs for highway transport while they were originally much less than the comparable railway mode show a surprising rise of intensity between 1948 and 1981. And this occurred in spite of the transition to more efficient diesel tractor power. With an average intensity of 0.23 MJ/kg in 1948, the figure for 1981, 0.53 MJ/kg, is more than double the original value, and almost twice as high as railway costs in the same year. Partially responsible for the increase has been the trend towards a longer distance of haul.

In estimating the specific costs of transporting machinery it was assumed the shipping of equipment from the manufacturer to the dealer was in the majority of cases done by rail. Accounting for costs past this point in the distribution network, it was also assumed that almost every small town throughout the Prairies has a farm implement dealership located close to a railway siding, and that it was the farmer himself who would either drive or haul home the purchased equipment. The costs of this transport have been recorded already. (On some occasions it would be the dealer who delivers the machinery to the farm site, but this was considered to be practised too infrequently to warrant inclusion). Thus the energy cost of transporting equipment will be the direct multiplication of the mass of machinery worn out in servicing one ha of wheatland and the intensity of rail transport in the corresponding year. Machinery worn out in service is the product of the full complement per seeded ha and the yearly "wear-out factor" (1.10 15) = 0.073, from Chapter IV. The results of these calculations for each year in the time series are listed in Table 9.2.

In estimating the energy costs of fertilizer transport, the distribution network is much the same as it is for machinery: dealerships are generally in close proximity to a railway siding, and it is again the farmer who usually transports the materials past this point. After consultation with a number of fertilizer manufacturers and distributors it was found that fertilizer was just as likely to enter the distribution network by rail as it was by truck. Therefore, in assigning costs, all movements were split between the two modes of transport; assuming one-half of the shipping would be done by rail and the other by truck.

Determining the quantities of fertilizer materials transported in each year can be done two ways, either by summing all N-, P- and K- fertilizer materials to total and then dividing by the corresponding cropped area, or by multiplying the N-, P- and K- fertilizer application rates by the appropriate fractional nutrient content. The latter was chosen for the purposes of this study for it better describes what is an important development in transport costs: that is, the increasing nutrient content of applied materials and falling shipping ratio. Between 1948 and 1981 the total quantity of fertilizer materials consumed in Western Canada rose from 45,000 to 1,914,500 t. At the same time the quantity of nutrients rose from 14,200 to 816,700 t. Putting the two together, the average nutrient content of applied materials increased from 31 percent in 1948 to about 43 percent in 1981. Translated into shipping ratios (defined as the quantity of materials divided by the quantity of nutrients) corresponding values are equal to 3.2 and 2.3 respectively; which indicate that over the study period the energy costs of delivering nutrients to the farm gate have decreased. These calculations and the final energy costs of fertilizer transport have been assembled in Tables 9.3 and 9.4 respectively.

The total energy costs for the transport of production inputs are presented in Table 9.5. Together such costs have tripled, rising from 14.8 MJ/ha in 1948 to 47.9 MJ/kg in 1981. In the early years of study machinery accounted for by far the majority of costs, however, by the late 1960s with fertilizer use increasing, it accounted for falling proportions, and by the final period, 1981, it accounted for no more than 15 percent of total energy use. Overall, the actual contribution of transport energies to the wheat production energy budget is small and, somewhat surprisingly, its input has remained relatively constant: it constituted just under one percent in 1948, and again just under one percent in 1981. In the future, with physical inputs of machinery having apparently stabilized, changes in transport energy costs will most likely come about as a result of increased fertilizer usage.

TABLE 9.1

ENERGY INTENSITIES OF RAILWAY AND HIGHWAY TRANSPORT

Year	Railway* (MJ/kg)	Highway** (MJ/kg)
1948	2.01	0.23
1953	1.52	0.24
1958	0.57	0.26
1963	0.33	0.28
1968	0.31	0.42
1973	0.32	0.57
1977	0.36	0.61
1981	0.35	0.53

*Railway costs derived from Statistics Canada 1948-1982. Railway Transport. Cat 52-207, annual, Minister of Supply and Services, Ottawa.

**Highway costs estimated from Statistics Canada catalogues 53-D-20, Motor Carriers, 1948-1953; 53-211, Motor Transport Traffic: Manitoba, 1958-1963; 53-212, Motor Transport Traffic: Saskatchewan, 1958-1963; 53-213, Motor Transport Traffic: Alberta, 1958-1963; and 53-222, Motor Carriers 1968-1981, Minister of Supply and Services, Ottawa.

TABLE 9.2

ENERGY FOR FARM MACHINERY TRANSPORT

Year	Machinery Mass* (kg/ha)	Machinery Depreciation** (kg/ha)	Transport Cost*** (MJ/ha)
1948	75	5.5	11.0
1953	101	7.4	11.1
1958	142	10.4	5.9
1963	170	12.5	4.1
1968	215	15.8	4.9
1973	275	20.2	6.4
1977	275	20.2	7.2
1981	275	20.2	7.0

*From Table 4.4.

**Machinery mass is multiplied by a repair and maintenance cost (1.10) and divided by a service life of 15 years.

***Calculated as the mass of machinery worn out in one year and the energy intensity of railway transport from Table 9.1.

TABLE 9.3

THE NUTRIENT CONTENT OF APPLIED PRAIRIE FERTILIZERS

Year	Fertilizer Material* ('000 tonnes)	Primary Nutrient Content** ('000 tonnes) N	P	K	Average (%)
1948	45.63	5.3	8.9	--	31
1953	91.24	11.0	16.5	--	30
1958	72.46	10.8	11.5	--	30
1963	260.21	42.7	39.4	0.01	32
1968	818.92	179.7	103.0	1.9	35
1973	881.19	228.6	89.0	1.9	36
1977	1207.50	369.5	111.5	2.0	40
1982	1914.55	617.1	168.8	30.8	43

*Calculated from: WCFA 1981 Annual Retail Fertilizer Sales Survey, Western Canada Fertilizer Association, Calgary, AB, and Statistics Canada 1948-1977. Fertilizer Trade, Cat. 46-207, annual, Minister of Supply and Services, Ottawa.

**From Table 7.1.

TABLE 9.4

FERTILIZER TRANSPORT ENERGIES

Year	Applied N, P, and K* (kg/ha)	Multiplier**	Transport Intensity*** (MJ/kg)	Energy Cost (MJ/ha)
1948	0.9	3.2	1.13	3.2
1953	1.7	3.3	0.88	4.8
1958	1.4	3.3	0.42	1.9
1963	4.9	3.1	0.30	4.6
1968	15.6	2.9	0.37	16.6
1973	17.5	2.7	0.44	20.9
1977	26.8	2.5	0.49	32.6
1981	40.6	2.3	0.44	40.9

*From Table 7.2.

**Inverse of fractional nutrient content from Table 9.3.

***Average of both rail and highway modes.

TABLE 9.5

TOTAL ENERGY FOR THE TRANSPORT
OF PRODUCTION INPUTS

Year	Machinery*	Energy Cost (MJ/ha) Fertilizer**	Total
1948	11.0	3.8	14.8
1953	11.1	4.8	15.9
1958	5.9	1.9	7.8
1963	4.1	4.6	8.7
1968	4.9	16.6	21.5
1973	6.4	20.9	27.3
1977	7.2	32.6	39.8
1981	7.0	40.9	47.9

*From Table 9.2.

**From Table 9.4.

X. WHEAT YIELDS AND THE ENERGY OF GRAIN

As could largely be anticipated, the earliest attempts at sustained wheat production in Western Canada met with initially poor and almost disastrous results. Working under harsh conditions with methods that differed greatly from the mechanized practices of today, inhabitants of the Red River settlement in 1812 toiled long hours with rudimentary implements to sow no more than a few sacks of imported seeds in the hard prairie soils. Plagued by insects and poor weather several complete crop failures were endured before a successful crop was first produced, and it was another decade before a truly satisfactory agriculture could be established. Yet upon establishment some of the best yields in the history of Prairie production were recorded. Data are by no means precise, but estimates for 1824 are that yields ranged from a low of 2900 kg/ha to a high of 4500 kg/ha (MacEwan, 1980). Taking 3700 kg/ha as an average, then these returns are the highest on record and, by comparison, were almost double the yields received with intensive management in 1981. The natural fertility of the newly-broken Prairie soils supported good yields for a number of decades before declining returns set in during the late 1800s. Mechanization brought with it increases after 1948, but it did so only after yields had been suffering for some time. A brief review of the statistical record during the late 1800s and early 1900s gives a deeper appreciation on the nature of these changes.

The first systematic statistics on wheat production in Western Canada record Manitoba yields in 1883 at approximately 1500 kg/ha (Statistics Canada, 1981). The year was not a particularly good one, and returns in the years which immediately followed averaged 1925 kg/ha (in 1887), 1700 kg/ha (in 1891), and 1875 kg/ha (in 1895). Not all yields were this high but during the first five years of regular statistics, between 1883 and 1887, returns averaged a healthy 1450 kg/ha. They fell moderately to about 1250 kg/ha over the next decade, only to rise slightly in the early years of the 1900s. The first data on returns across all three Prairie Provinces were collected in 1908, and over the next decade regional yields ranged from 940 to 1750 kg/ha. On the average, returns between 1908 and 1917 equalled roughly 1250 kg/ha, they fell during the years that followed (averaging 685 in 1918, 625 in 1919, 925 in 1920 and 850 in 1921) and rose marginally between 1921 and 1930.

However, thereafter yields plummetted in an extended period of extreme lows. For five years running yields did not rise above 800 kg/ha, and in the poorest year, 1937, they equalled no more than an incredibly low 425 kg/ha! Of course, during this period (the so-called "Dirty Thirties") several seasons of persistent drought served to severely depress production but, after nearly ten years of perennially poor results, the trend was becoming clear: yields had been falling for some time and, over the long term, had fallen noticeably since records were first kept.

Plotting yield data between 1908 and 1981 makes clear the curve of gradual decline during this period, and of subsequent increases afterwards (Figure 10.1). In fact, if the graph were extended to include the late 1800s, the picture would become more dramatic. Underpinning the period of decline were the continual mining of soil nutrient reserves and the practising of inappropriate agricultural techniques, which, in effect, did little more than to exacerbate an already serious condition by promoting widespread erosion (Endman, 1942; Newton et al., 1945; Hill, 1954; Marten and Paul, 1974; Campbell and Biederbeck, 1980). Using 1937 as a benchmark and the initial year of recorded yield information, 1824, as a starting point, comparison indicates that over the first century of Western Canada agriculture wheat yields fell (3700-425) = 3275 kg/ha, or on average about 30 kg/ha/year.

The great increase in wheat yields after 1937 (or more precisely after the mid-1940s when mechanization began its clearly recognizable diffusion) has been accompanied by the use of higher-yielding cultivars, improved soil management, fertilizer applications (which increased more than 40-fold between 1948 and 1981) and the use of chemical herbicides (which rose from a virtually non-existent use in 1948 to cover more than 85 percent of Prairie cropland in the mid-1970s). Between 1948 and 1981 yields increased by almost 100 percent, rising from roughly 1000 to 2000 kg/ha, or if we use 1937 again as a benchmark, almost 500 percent, which is itself equal to 1575 kg/ha or 35 kg/ha/year. Putting it another way, under industrialized practices yields have increased at a rate 15 percent faster than they were originally lost .

Increases which have occurred during the period of study, while they are impressive, have not always been smooth: this is clearly reflected in the hill and valley configuration of the graph in Figure 10.1. Located in one of the world's most variable climates, Prairie wheat production has always been influenced by weather: yields are extremely erratic, and the difference between good and bad years dramatic. The best example I could find of this were the Manitoba returns of 1900 and 1901: in 1901, at close to 1800 kg/ha, wheat yields were almost three hundred percent higher than what they had been one year previous! Other examples include: 1938 where yields were up 111 percent over 1937; 1942 where yields were 83 percent greater than 1941; 1954 where yields were 48 percent lower than 1953 (and 85 percent lower than the following year 1955); and 1961 where yields were 50 percent below those of 1960 (and 100 percent lower than those of 1962). The variability of wheat yields over the extended period 1909-1981 is shown in Figure 10.2. Comparing yield and climatologic data, it is found that in each and every instance good and bad weather correlates directly with high and low returns. And amongst all weather factors it is, of course, precipitation which fluctuates most and which has had the greatest impact on Prairie production (Staple and Lehane, 1954).

Climatic studies of Western Canada indicate that in at least one year in ten precipitation can be expected to fall below two-thirds of the long term average (Fraser, 1980). Moisture stress under the influence of strong Prairie winds and hot summer temperatures is high much of the time and, while drought is normally associated with poor rainfall during the growing season, its occurrence during the winter months (which in Western Canada is often) has a significant impact on the next year's yields. Translating the variability of precipitation into yields, it has been estimated that the probability of grain yields being at least ten percent above or below long term averages is one in three (Sakamoto et al., 1980). The probability of two such returns in consecutive years is one in five. Again looking at the variability pattern in Figure 10.2 it is clear that 50 percent differences from one year to the next are not uncommon, and that on several occasions the differences displayed have been almost as great as the yield itself! However, what is also evident from this Figure is that over the past 25 years or so, variances have more often than not been positive and have shown decreasing amplitudes. In fact, if we were to disregard the severe drought of 1961, these changes correlate well with the diffusion and intensification of mechanization since the mid-1950s.

Ultimately, the apparent strength of the relationship between moisture and yields has led to some debate over the exact causes of the increased returns and reduced variation of the past two-and-a-half decades of industrialized agriculture. The case is certainly not as clear-cut as that of corn agriculture in the U.S., which is conducted under less stressful climatic conditions in the more humid mid-west. As one U.S. Department of

Agriculture study concluded, technology in the form of better varieties of corn and improved cultivation and fertilization practices had reduced variation in yields in both good and bad weather during the years 1929-1962 (USDA, 1965). Yet, in Western Canada several authors have noted that the relatively benign weather patterns and reduced moisture stress of the 1960s and 1970s have had a substantial impact on rising levels of production (McKay and Allsopp, 1977; Mack, 1977; Treidl, 1977), and according to a survey of half a century of grain farming in Saskatchewan, after weather had been accounted for advances in technology showed little influence on wheat yield trends in terms of either productivity or variation (Robertson, 1974).

On the other side of the debate authors have implied that yield gains from fertilizer have been substantial, the contribution of chemical weed control significant, and the increases from improved management and moisture conservation large (Hedlin and Rigaux, 1976; Ferguson, 1977). Higher yielding wheat cultivars have also been implicated as supplying up to a 15 percent improvement (Leslie, 1980). Understandably, the precise quantification which would back the argument cannot be obtained -- how could it be scientifically measured? Unravelling the complex mechanisms of increased yields and decreased variation makes for intriguing research that would clearly have important ramifications: for example, by contributing to estimating optimum levels of inputs for greatest economic efficiency under variable climatic conditions, but unfortunately further inquiry is beyond the scope of this study. Perhaps it will suffice to say that whatever the level of applied technology, the availability of moisture will always have a deciding influence in dryland wheat production, creating periodic disturbances and making wheat yields unpredictable -- a discomforting reminder of man's struggle with nature.

Returning to the wheat yield increases of the 1948-1981 and looking to the future, it is likely that further increases are in order. Coming as a result of higher levels of production inputs and improved technology, estimates suggest that a conservative rise of 15 percent (consisting of five percent each from improved varieties (Leslie, 1980), more effective pest management (Turnock and Samborski, 1980) and better weed control (Hay, 1980)) is entirely possible by the mid-1990s. In dealing with such a complex and evolving process as agriculture though, it is inherently difficult to forecast future levels of production with great confidence, but assuming predictions are realistic wheat production could reach 2300 kg/ha.

Before proceeding to a summary of production inputs and the calculation of energy efficiencies, it is important that we have a relevant figure for the energy content of the wheat grain to begin with. To derive a reliable value it was necessary to first survey the published figures and then average them before arriving at a best estimate. These figures, assembled in Table 10.1, show the enthalpy of the harvested grain -- not the metabolizable energy content which is a somewhat dimensionless -- and range from a low of 17.20 MJ/kg to a high of 19.90 MJ/kg on a dry weight basis. Adjusting for the typical 13.5 percent moisture content of marketed wheat the corresponding values range, respectively, from 14.88 to 17.22 MJ/kg. The averages to be used in downstream efficiency calculation are 18.32 MJ/kg on a dry weight basis, and 15.85 MJ/kg at harvest. These values refer specifically to hard wheat, but with little more than one percent difference between it and the softer varieties and with the spread of published values for hard wheat alone at 15 percent, calculated averages can be applied to all varieties without error.

Applying the 15.85 MJ/kg energy value for wheat against returns for each year in the time series gives the energy yields per hectare shown in Table

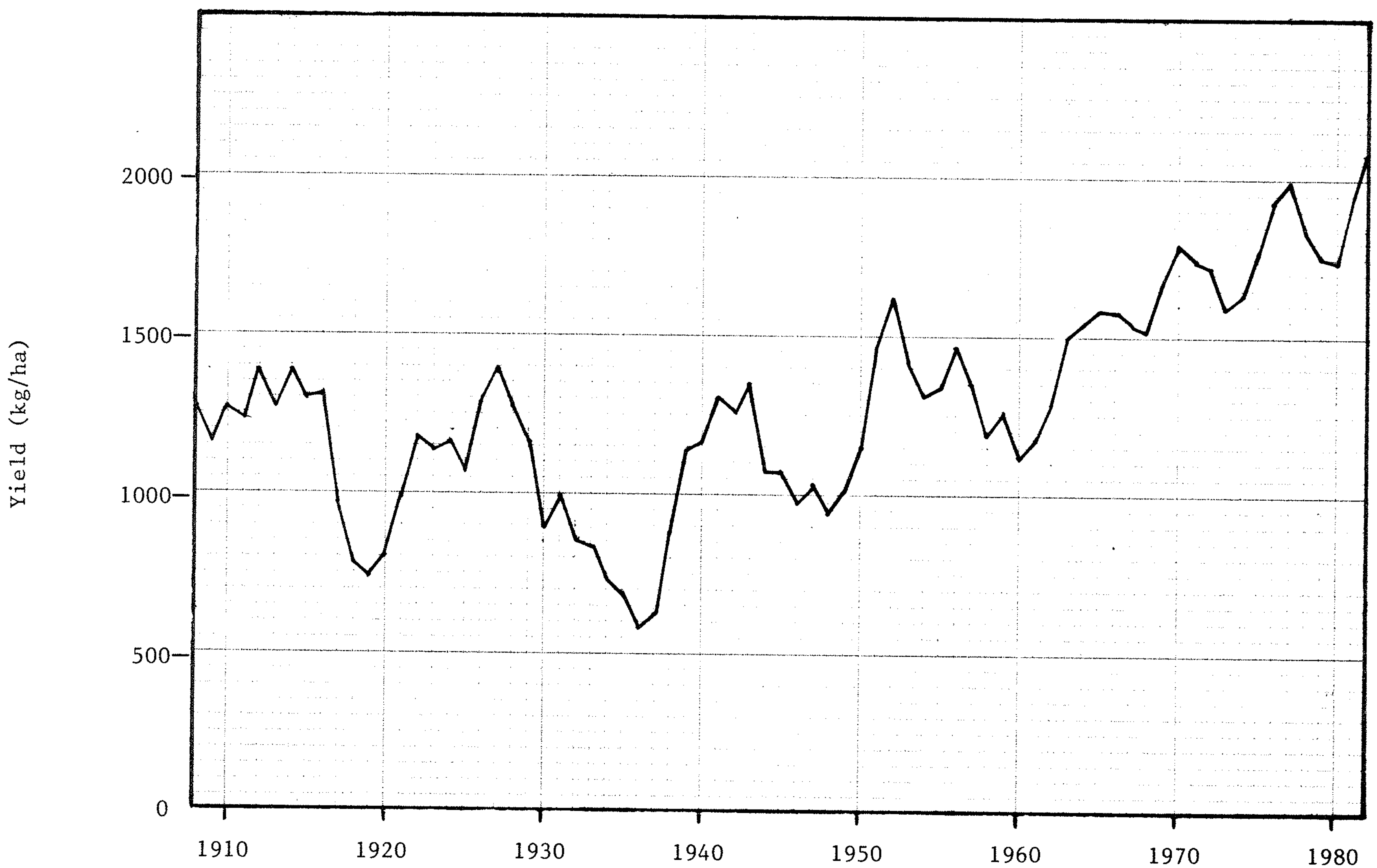
10.2. Over the study period grain energy returns have increased dramatically by more than doubling between 1948 and 1981. All the data in Table 10.2 has been calculated on a three-year moving average basis in the attempt to smooth out yearly variations. This was considered legitimate for while the yields fluctuate tremendously from year to year, the application of agronomic inputs will change little. In terms of future returns, if wheat yields reach 2300 kg/ha by the mid-1990s, then the energy yields will be 36.5 GJ/ha, or 5 GJ higher than what they were in 1981.

With this information at hand it is now possible to reflect on the growth of labour productivity in wheat agriculture.. Referring back to the data of Table 2.1, we recall that labour inputs fell over the study period from 10.0 hr/ha in 1948, to 7.2 hr/ha in 1958, and to 5.5 hr/ha in 1981. Combining these values with the crop yields that were increasing over the same period gives the mass and energy productivities of labour presented in Table 10.3. Prorated over time and rising from 95 kg/manhour (1,498 MJ/manhour) in 1948, to 353 kg/manhour (5,597 MJ/manhour) in 1981, the increase in productivity over the entire study period was 375 percent, or 11 percent annually. The increases were, of course, most rapid in the earliest years of transition, virtually doubling between 1948 and 1953 when the diffusion of machinery and modern inputs was at its height, but they continued to be strong even while the system intensified in the years that followed, increasing just over nine percent annually between 1958 and 1981.

Comparing the values we now have for modern wheat production in Western Canada with other less industrialized systems, it is possible to show again the great differences that exist between agricultures in various stages of evolution (see Chapter I for details). Using as an example Chinese agriculture in the mid-twentieth century (after Buck, 1937) where, with few inputs an estimated 500 hours of labour was required to produce an average wheat crop of 1100 kg/ha, the necessary computations reveal productivities of 2.2 kg and 35 MJ per manhour respectively. Employing mid-nineteenth century Prairie production as an example of an animal-based system, where horse and oxen supplied the majority of power, some 80 manhours of input and 1600 kg/ha of harvested grain yields productivities of about 20 kg/manhour and 317 MJ/manhour. Comparing both of these systems with the productivities just calculated for the mechanized system in 1981, we find that in terms of mass returns outputs rise from 2.2 kg/manhour in the system relying solely on human labour, to 20 kg/manhour in the system relying on animals and human labour, to 353 kg/manhour in the highly industrialized example. In terms of energy, outputs increase from 35 MJ/manhour, to 317 MJ/manhour, to 5597 MJ/manhour in each system respectively. Such values, of course, must be seen as just proper orders of magnitude, not as precise quantifications; but even so, revealed differences are impressive. At such levels it is easily understood how the industrialized farmer can feed so many; but this is only half the story, what remains to be calculated are the energy costs of industrial productivities, and it is to the summing of all productive inputs in Chapter XI that we now turn.

FIGURE 10.1

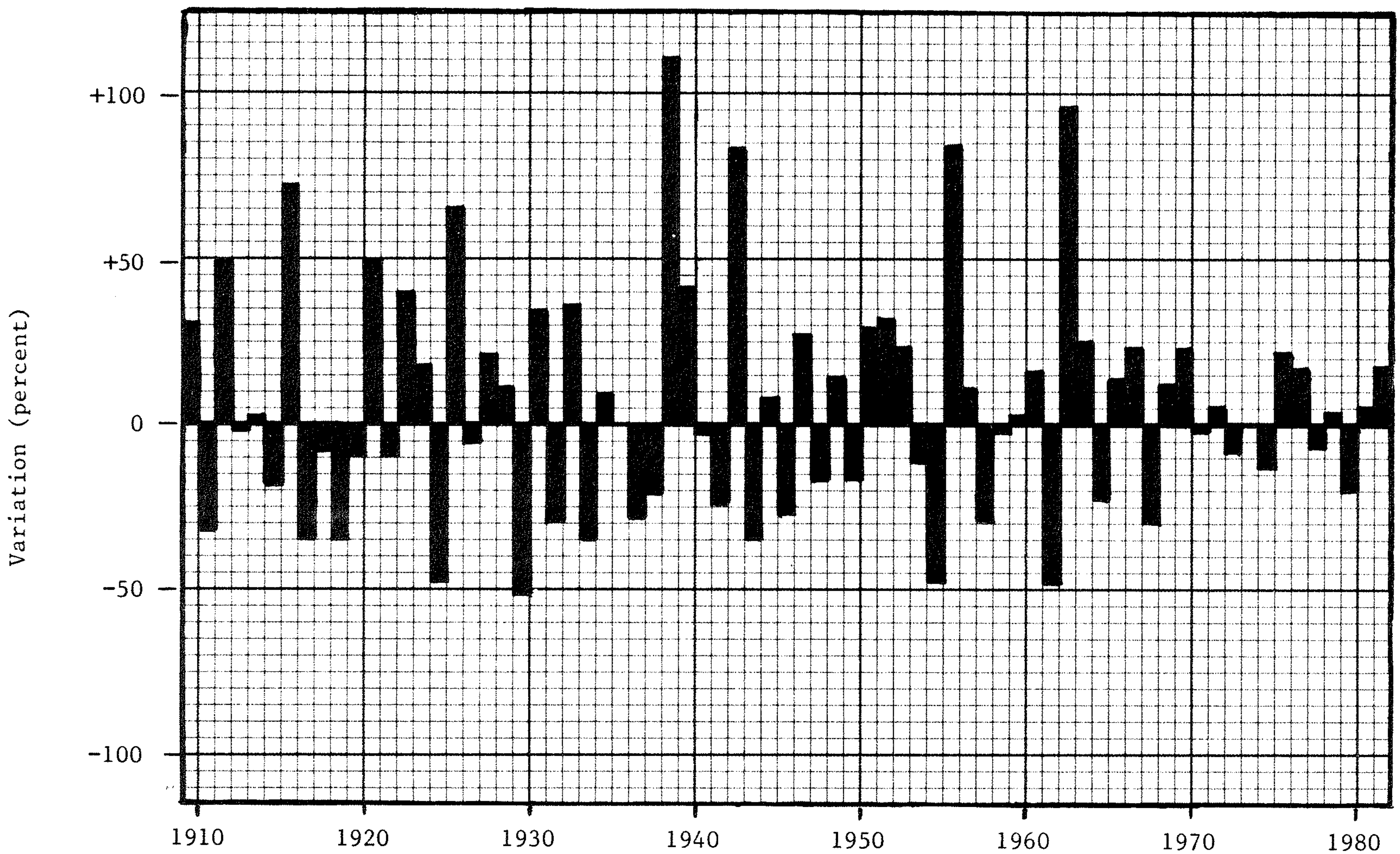
PRAIRIE WHEAT YIELDS 1908-1981*



*Data calculated as three year moving average from Statistics Canada, 1964. Handbook of Agricultural Statistics, Cat. 21-507, occasional; and Statistics Canada 1965-1981. Field Crop Reporting Series, Cat. 22-002, Minister of Supply and Services, Ottawa.

FIGURE 10.2

VARIATIONS IN THE PRAIRIE WHEAT YIELD 1909-1981*



*Calculated as absolute change from preceding year. Data from Statistics Canada 1964, Handbook of Agricultural Statistics, Cat. 26-507, occasional; and Field Crop Reporting Series, Cat. 22-002, seasonal, 1965-1981, Minister of Supply and Services, Ottawa.

TABLE 10.1

THE ENERGY CONTENT OF WHEAT GRAIN

(All values in MJ/kg)

Dry Weight Basis	13.5% Moisture Basis
19.90	17.22
18.67	16.15
17.51	15.15
17.20	14.88
Average Values	
18.32	15.85

Sources: Miller, D. F. 1958. Composition of Cereal Grains and Forages. NAS-NRC, Washington, DC, pp. 502.

Inglett, G. E. 1974. Wheat: Production and Utilization. AVI Publ. Co., Wesport, CT, pp. 385.

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TABLE 10.2

WHEAT YIELDS AND ENERGY RETURNS

Year	Average Wheat Yield (kg/ha)*	Energy Content of Grain (MJ/kg)	Energy Return (MJ/ha)
1948	945	15.85	14,978
1953	1406	15.85	22,285
1958	1189	15.85	18,845
1963	1496	15.85	23,712
1968	1523	15.85	24,140
1973	1595	15.85	25,281
1977	1991	15.85	31,557
1981	1942	15.85	30,781

*Calculated as three year moving average from Statistics Canada, 1948-1981. Field Crop Reporting Series, Cat. 22-002, seasonal, Minister of Supply and Services, Ottawa.

TABLE 10.3

INCREASES OF LABOUR PRODUCTIVITY IN
PRAIRIE WHEAT FARMING
1948-1981

Year	Labour Input Manhours/ha*	Wheat Yield kg/ha**	Productivity kg/manhour	Productivity MJ/manhour
1948	10.0	945	95	1,498
1953	8.1	1406	174	2,751
1958	7.2	1189	165	2,617
1963	5.4	1496	277	4,390
1968	5.6	1523	272	4,311
1973	6.0	1595	266	4,214
1977	5.7	1991	349	5,536
1981	5.5	1942	353	5,597

*From Table 2.1.

**From Table 10.2.

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XI. THE ENERGY COSTS OF PRODUCING WHEAT: SUMMARY

Calculation of Energy Requirements

As stated in the opening chapter, the primary objectives of this investigation were threefold: (1) to perform a rigorous longitudinal analysis of wheat production and to obtain accurate time-series accounting of all major direct and indirect energy inputs, (2) to supplement and broaden our understanding of the industrial efficiencies of modern agricultural systems, and (3) to assemble empirical information on Canada's number one agricultural activity. From the data generated in previous chapters we are now in a position to estimate the energy costs of producing wheat, calculate the impact of process improvement and technological change, compute the conversion efficiencies of production and identify the potential for future conservation.

Keeping within suggested IFIAS (1974) guidelines, the energy intensity or unit energy requirement of wheat, is defined as the sum of fossil fuel-derived energies expended in the process of producing the crop yield divided by the physical crop output. The product, the unit of energy per unit of mass, is measured in MJ per kg. In the attempt to maintain comparability between studies, the symbol for energy intensity used here, is the same as in Smil and his colleague's (1983) comparable study of corn production in the U.S.: "I". Solar energy inputs were excluded from calculations as were all inputs lying beyond the previously defined system boundary. A summary of all production inputs and corresponding energy requirements are shown in Table 11.1.

Before proceeding with final calculations we have yet to determine the explicit energy requirements of both seeds and draft animal feed. To do this, however, we must first know the energy cost of wheat grain or, more precisely, the energy intensity of the system itself. In terms of the seed or grain (the two here are used interchangeably, strictly speaking the correct term for grain is caryopsis, the dry indehiscent fruit of cereals that contains one seed). Pimentel et al. (1973) and Pimentel and Terhune (1977) calculated their energy cost as the energy contained within the caryopsis. However it should be pointed out that such an approach is clearly illogical. Process analysis is defined as the empirical investigation of energies sequestered in the provision of goods, processes and services, and is the sum of the fuel energies supplied to drive all the process stages within the system boundary. Using fertilizer as an example, it is not the energy content of nitrogen which is important, it is the energy equivalent of the non-renewable resources that went into its synthesis. Applying this same logic to seeds, it is not the particular chemical energy of the grain which is the object of investigation, it is the energy that went into growing it. Of course, energy contents are sometimes important, for example in studies of heterotrophic metabolism and chemical conversion efficiencies, but methodologically if we were to use the energy content of seed as an input in process analysis the derivation of I would be impossible: one would be, in effect, comparing the energy content of seed with the energy content of seed! Surprisingly, Pimentel while aware of the criticism (Pimentel, 1984) continues to use this approach in his agricultural studies (for example see Dazhong and Pimentel, 1984).

The same rational holds true for draft animal feed as well: the energy cost feed (calculated in wheat-grain equivalents) depends on the value of I, the energy intensity of the system. Therefore, both animal feeds and seeds, can be calculated according to the same formulas:

$$I = E/Q \qquad (1)$$

and

$$E = I \cdot Q \qquad (2)$$

where Q is the physical quantity of feed or seed (in kg) and E is the amount of fossil fuel-derived energy needed to produce Q in each case. The value for I, however, remains as yet unknown. Therefore, to solve for I and find the E cost of both feeds and seeds at the same time, we must first subtract the quantities of each seed and feed from crop yields (in essence treating the two inputs as feedback costs) and divide the remainder into the energy requirements of all other inputs (E_{aoi}) listed for each year in the in Table 11.1.

Algebraically the energy intensity for the wheat crop is:

$$I = E_{total}/Q_y \qquad (3)$$

where E_{total} is the sum of all fossil fuel-derived energy inputs to wheat agriculture and Q_y is the crop yield. From the preceding discussion it is clear then that:

$$E_{total} = E_{seeds} + E_{feeds} + E_{aoi} \qquad (4)$$

Combining Equations (4) and (2) with Equation (3) we obtain:

$$I = (E_{aoi} + I \cdot Q_{seeds} + I \cdot Q_{feeds})/Q_y \qquad (5)$$

Solving Equation (5) gives:

$$I = E_{aoi}/(Q_{yield} - Q_{seeds} - Q_{feeds}) \qquad (6)$$

With this formula we are now prepared to solve I for the system; except that we do not yet have values for Q_{seeds}. The quantities of seed consumed in Prairie wheat agriculture for each year in the time series are shown in Table 11.2. Specific seeding rates were obtained from the division of total seed requirements by areas sown to wheat. Over time mechanization has had little impact on seeding requirements: hybridization, in spite of years of experimental breeding and wheat crossing, was still in the 1980s not a practical reality. Seeding rates were 106 kg/ha in 1948, 99 kg/ha in 1958 and 92 kg/ha in 1981. On average seed requirements account for about five percent of annual production by weight. The majority of wheat seed is home-grown with the producer simply holding back part of his previous years harvest, or purchasing the required amount from a nearby neighbour. Certified seed, which is perhaps slightly more demanding of inputs than home-grown varieties is typically sown to less than one percent of Prairie wheatland (MDA, 1982; SDA, 1981).

Thus in Western Canada the energy cost of seed requires no adjustment for additional production requirements. If the energy intensity of seed production were higher than this would alter the calculation procedure. For example, in U.S. grain corn agriculture the extra care that goes into producing hybrid seed raises subsequent energy costs by a factor of three (Smil et al., 1983). The energy intensity of seed in Equation (1), therefore, would be 3·I, not I alone as for wheat. In Table 11.3 it is simply the physical quantities of wheat seed which have been recorded along with draft-animal feed and all other energies needed for the solving of Equation (6), the energy intensity of the wheat production system.

Having calculated I for each year in the time series it is now possible to derive the explicit energy costs for both seeds and feeds from Equation (2). The results of these calculations are shown in Table 11.4. In the early years of the study period each input commanded a significant proportion of the system's energy budget. In 1948, the energy equivalents of feed (390 MJ/ha) and seed (369 MJ/ha) placed them, respectively, third and fourth in overall rankings. However, with the replacement of draft animals by machines in the early 1950s, the cost of keeping animals delined rapidly, falling to 130 MJ/ha in 1953, 125 MJ/ha in 1959 and 69 MJ/ha in 1963. After 1963 animals were no longer contributing to Prairie agriculture, and the cost of their upkeep is correspondingly zero in each of the last four intervals. Seeds, on the other hand, have shown variable costs largely as a result of the system's changing energy intensity. Energy costs fell from 369

MJ/ha in 1948 to 240 MJ/ha in 1953 (a year of good weather and high yields), rose to 427 MJ/ha in 1958 and remained between 350 and 450 MJ/ha for the rest of the study period. They have therefore maintained a fairly high ranking in the energy budget. In 1981 seeds were fifth in overall requirements.

The item by item listing of all inputs in Table 11.1 indicates that the sum of non-renewable fossil-fuel energies sequestered in Prairie wheat production rose between 1948 and 1977 by (8964 - 2533) = 6431 MJ/ha. Over the 20 year period this 250 percent increase prorates to approximately 222 MJ or 9 percent per annum. The two productive factors most responsible for change have been, not surprisingly, machinery and its attendant power source liquid fuels. Together they have dominated all inputs, consistently accounting for close to three-quarters of process requirements for over three decades. Energy equivalents of fuel use in 1977 were more than 2.5 times 1948 levels, while the indirect costs of machinery tripled over the same period. The costs of these two items show the increase of greatest magnitude, but the largest percentage increases lie with the consumption of electricity and chemical fertilizer. Between 1948 and 1977 each rose by two orders of magnitude. Over the past decade the energy equivalent of nitrogen increased the fastest among all inputs and by 1981 it surpassed machinery to become the second highest requirement of the production system. Between 1977 and 1981 alone nitrogen's energy cost rose by 40 percent. The input did not, however, contribute to the falling of total production costs over the same period. The reduction of energy costs from 8964 MJ/ha in 1977 to 8366 MJ/ha in 1981 was almost entirely accounted for by reduced fuel use.

Energy costs are, however, only one part of the analysis. Compensating for the apparent one-sided increase of production costs have been rising production outputs: wheat yields approximately doubled from 1000 to 2000 kg/ha over the 1948-1981 period. Equating input costs with output costs allows the derivation of the well-known energy efficiency ratio that is often considered to be the most telling characteristic of any energy conversion process.

Energy Ratios

The determination of the energy efficiency ratio is basically an extension of the calculations used earlier to determine production intensities. The ratio of grain energy output to fossil-fuel derived energy input is obtained from the equation:

$$E = (Q_{yield} \cdot C)/(Q_{yield} \cdot I)$$
$$= C/I$$

where C is the energy content of wheat (15.85 MJ/kg). Performing the calculation for each year in the time series gives the eight separate efficiency ratios shown in Figure 11.1.

Graphed ratios are, of course, the outcome of changing production intensities and yields. Initially high at 4.6 and 5.7 in 1948 and 1953 respectively, ratios fell to 3.7 in 1958, rose to 4.4 in 1963 and varied between 3.5 and 3.0 over the rest of the period. Vagarities of weather underpin some of the high and low values recorded (1953 for example was a year of bumper crops, 1963 was above normal, and 1973 was below normal); however, even this cannot disguise what appears to be an obvious trend: declining efficiencies since 1948. This outcome should not really come as a surprise though. The Prairie wheat production system of the late 1940s and early 1950s was still dependent on both human and animal muscle power for most of its labour requirements. Very little of the wheat crop received fertilizer, there were virtually no pesticides being applied and rural electrification had only just begun. Mechanization was only just beginning to diffuse throughout the region at this time, it was not until 1958 that it could be said the new mode of production was clearly entrenched. Compared to the final years of the time series (when inputs of fuel were double, machinery triple, herbicides ten times, and fertilizers and electricity 100 times what they were originally, and where the inputs of human and animal labour had been reduced to inconsequential quantities) it is largely predictable that efficiencies would be lower. To conclude from this evidence, however, that industrialization of agriculture has brought lower efficiencies is only partly true, and in effect shows little.

As was indicated at the outset the purpose of this study was not to discover whether industrialized production systems are more or less efficient than semi- or non-industrialized ones -- we already know from more focussed studies on the topic they are more efficient -- rather it was to discover what had happened within the industrialized system itself. To accomplish this we must compare years after 1958, when the transition to mechanized farming was virtually complete. In so doing we find out that efficiencies have actually changed little with time. The 1981 value of 3.5 was within five percent of that for 1958, 20 percent below 1963, identical to that of 1968, and 15 percent above the poorest value recorded in 1973. Considering the complex nature of an inquiry of this kind, these ratios in fact show a surprising regularity. Moreover, if an adjustment is made for the exogenous and unaccountable influence of weather, it becomes apparent that the energy efficiency of modern fossil-fueled farming has remained virtually constant over more than two decades of intensifying practice. Mechanization has not brought with it irreversible declines as is the impression given by Pimentel et al. (1973) and Pimentel and Terhune (1977).

In energy analysis only similar systems are truly comparable. Changing input variables and different process conditions will greatly affect the outcome of results. Yet efficiency ratios are themselves prone to misinterpretation. The comparison of grain energy to the sum of fossil-fuel derived energies implies that the two energies are in some way exchangeable (Spedding et al., 1981; Smil et al., 1983). But clearly, food energy and fuel energy cannot be traded off: the express purpose of agriculture is to develop a nutritionally balanced and palatable foodstuff composed of proteins, lipids, carbohydrates, micronutrients and fibre. Only where the grain is to be used as a fuel or feedstock in specific energy transformations (direct combustion, gasification and fermentation) would it be logical to divide the chemical energy of the product by the sum of nonrenewable energies that went into its production.

Moreover, it is somewhat obvious that agriculture is not primarily concerned with maximizing the gross conversion efficiency of sunlight into plant mass (natural systems do this much better), rather its object is the redirecting of plant mass into recoverable portions. Industrial agriculture has evolved as a highly successful system based on the application of large doses of energy aimed at reducing environmental stress and mitigating those factors which are limiting to plant growth. In the conditioned agroecosystem natural photsynthesis is allowed to channel maximum quantities of photosynthate to select target tissues. Therefore, perhaps the best way to express the efficiency of wheat agriculture is by calculating ratios comparing mass grain outputs to unit energy inputs. This was done and the results of these mass-energy ratios expressed on a kg/GJ basis for each year in the time series are shown in Table 11.5.

The best conclusion to be drawn from this analysis is that the energy efficiency of Western Canada wheat production has remained about the same during nearly two and a half decades of industrial modernization. Historically rising fossil fuel subsidies have been offset by higher grain yields. These findings support and reinforce the conclusions reached by Smil et al. (1983) under similar circumstances for corn production in the U.S.

Together, the findings of both analyses suggest that industrialized grain agriculture has not suffered from efficiency declines, rather it has performed quite respectably over time and under the impetus of higher input prices it will most likely do even better in the future. In fact, if the noticeable improvements made after 1973 are part of a trend (between 1973 and 1981 efficiencies rose from 3.0 to 3.5, or from 192 to 221 kg per GJ of energy input) then such a process is already underway.

FIGURE 11.1

ENERGY EFFICIENCY RATIOS

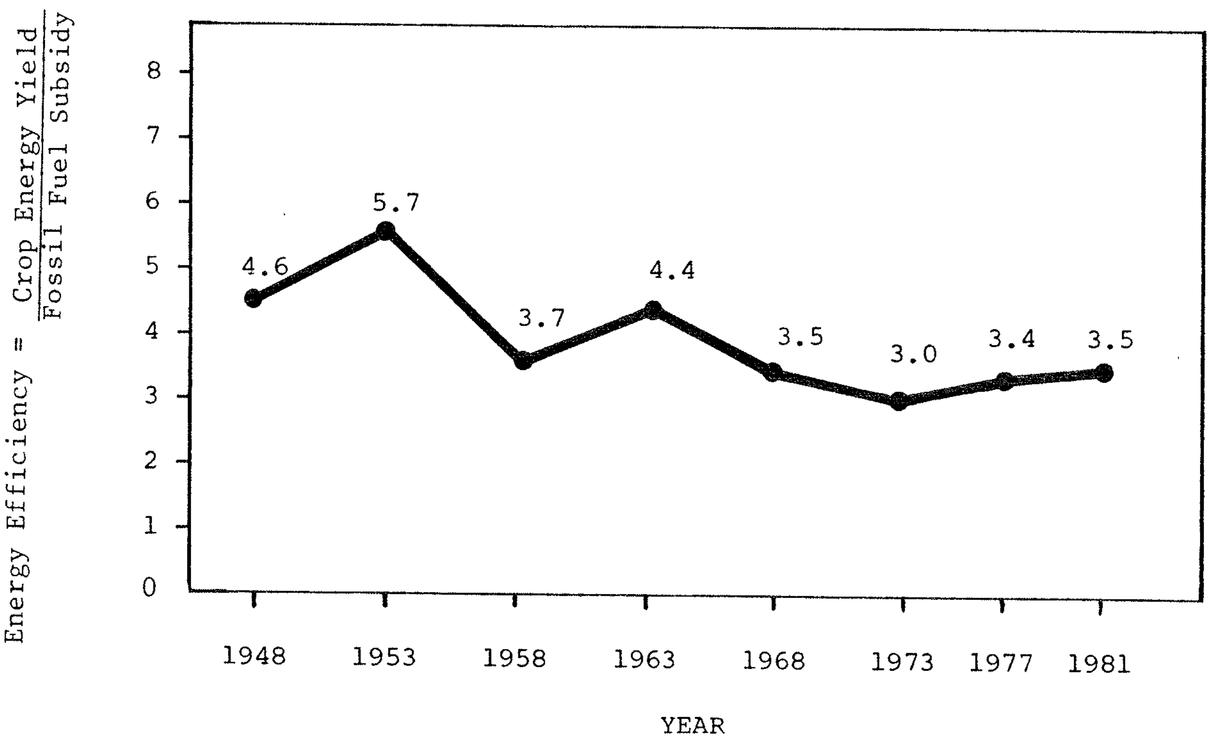

TABLE 11.1.

SUMMARY OF PHYSICAL INPUTS AND EQUIVALENT ENERGIES

(All quantities (Q) are in kg/ha[a], all energies (E) are in MJ/ha)

PRODUCTIVE FACTOR / YEAR	1948		1953		1958		1963		1968		1973		1977		1981	
	Q	E	Q	E	Q	E	Q	E	Q	E	Q	E	Q	E	Q	E
FUEL	b	1895	b	2622	b	3268	b	3388	b	3935	b	4598	b	5046	b	3896
MACHINERY	5.5	583	7.4	763	10.4	1110	12.5	1147	15.8	1387	20.2	1755	20.2	1654	20.2	1513
NITROGEN	0.3	29	0.7	65	0.7	62	2.5	211	9.9	818	12.5	927	20.5	1445	30.7	2023
PHOSPHORUS	0.5	5	1	9	0.7	6	2.4	22	5.6	52	4.9	46	6.2	58	8.4	78
POTASSIUM	0	0	0	0	0	0	0	0	0.1	1	0.1	1	0.1	1	1.5	9
HERBICIDES	0	3	0.1	8	0.1	10	0.2	21	0.3	41	0.4	54	0.6	109	0.8	159
ELECTRICITY	0.7	3	5.9	29	15.9	105	28.1	197	41.4	301	63.6	470	79.3	611	85.3	640
SEEDS	106	-	87	-	99	-	103	-	76	-	83	-	95	-	92	-
ANIMAL FEED	112	-	47	-	29	-	19	-	0	-	0	-	0	-	0	-
TRANSPORT	-	15	-	16	-	8	-	9	-	22	-	27	-	40	-	48
SUM OF ENERGIES		2533		3512		4569		4995		6557		7878		8964		8366

[a]Electricity recorded as kWh/ha.
[b]Quantities of diesel fuel, gasoline, other fuel, lubricating oil and greases in variable proportions.

TABLE 11.2

SEED REQUIREMENTS AND SEEDING RATES
OF PRAIRIE WHEAT

Year	Seed Requirements* (10^3 tonnes)	Area Sown** (10^3 ha)	Seeding Rate (kg/ha)
1948	1,006.68	9,452	106
1953	898.49	10,268	87
1958	838.24	8,450	99
1963	1,099.01	10,618	103
1968	913.08	11,967	76
1973	702.94	8,418	83
1977	935.37	9,794	95
1981	1,115.04	12,120	92

*From Statistics Canada 1948-1981. Grain Trade of Canada. Cat 22-201, annual, Minister of Supply and Services, Ottawa.

**From Table 1.1.

TABLE 11.3

ENERGY INTENSITIES OF PRAIRIE WHEAT PRODUCTION
1948-1981

Year	Sum of Energies* (MJ/ha)	Yield** (kg/ha)	Feed*** (kg/ha)	Seeds[t] (kg/ha)	Intensity (MJ/kg)
1948	2533	945	112	106	3.48
1953	3512	1406	47	87	2.76
1958	4569	1189	29	99	4.31
1963	4995	1496	19	103	3.64
1968	6557	1523	--	76	4.53
1973	7878	1595	--	83	5.21
1977	8964	1991	--	95	4.73
1981	8366	1942	--	92	4.52

*From Table 11.1.

**From Table 10.2.

***From Table 3.2.

[t]From Table 11.2.

TABLE 11.4

ENERGY COST OF DRAFT ANIMAL FEED AND SEEDS

Year	(MJ/ha)	(MJ/ha)
1948	390	369
1953	130	240
1958	125	427
1963	69	375
1968	--	344
1973	--	432
1977	--	449
1981	--	416

TABLE 11.5

RATIOS OF WHEAT OUTPUT TO ENERGY INPUTS
1948-1981

Year	Mass-Energy Ratio (kg/GJ)
1948	287
1953	362
1958	232
1963	275
1968	221
1973	192
1977	212
1981	221

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XII. CONVERSION EFFICIENCIES AND THE ENERGY COST OF BREAD

Solar Conversion Efficiencies

Categorically different from the energy efficiency of growing wheat, is the process of converting the sun's radiant energy into edible plant phytomass. Calculated on the basis of solar insolation and chemical grain energy, conversion highlights the magnitude of thermodynamic loss and portrays the very small energy efficiencies of field agriculture. Moreover, by including the losses incurred in raising grain-fed livestock and the metabolic conversions of individuals it gives some idea of the thermodynamic costs of maintaining a somewhat luxurious North American diet.

In the prairie region of Western Canada annual global solar radiation under comparatively cloudless skies ranges from roughly 46 TJ/ha in Edmonton, Alberta to 51 TJ/ha in Swift Current, Saskatchewan (Hay, 1978). Such values are, of course, lower than comparable insolation in equatorial regions (averaging 58-73 TJ/ha/yr), and would not normally support intensive agricultural, but seasonal variation is great. Typical ranges of 7.5 TJ/ha in July to 1.0 TJ/ha in December in the Prairies show more than a sevenfold difference (equatorial means for comparison are steady at about 4.8-6.1 TJ/ha/month). From early May until late August the 6.6 TJ/ha monthly average totals roughly 50 percent of the annual mean, and establishes a short but adequate growing season. Using the annual mean of Winnipeg, Manitoba, 49.29 TJ/ha, as the starting point in downstream calculations, 45 percent or 22.26 TJ/ha falls on the wheat field during its 100 day production cycle.

To begin calculations we must first separate sunlight into its active components. On average only about 45 percent of full sunlight consists of photosynthetically active radiation (PAR) between the wavelengths of 400 and 700 nanometers (Yocum, 1964). Out of the amount that is directly involved in the reduction of carbon dioxide into the products of photosynthesis, and which hits the plant, roughly 11 percent is not intercepted by the plant canopy and another 11 percent is reflected away: the result, only 78 percent of PAR is capable of being utilized by the plant (Holliday, 1976).

Total net primary production of the cultivated wheat crop is proportionally divided between the grain and other plant parts. On a dry weight basis an average crop will yield 2,000 kg of grain, 4,000 kg of shoots and leaves (Coupland, 1973) and 2,000 kg of roots (Bray, 1963). On the basis of 18.3 MJ/kg for grain (Chapter X), 19.2 MJ/kg for residues (Buchanan, 1982) and 13.7 MJ/kg for roots (Coupland and Van Dyne, 1979) total crop energy is equal to 140.8 GJ/ha. Dividing this figure by the amount of radiation reaching the field during the season gives a conversion efficiency of $(140.8 \times 10^9 J \div 22.26 \times 10^{12} J) = 0.633$ percent. Solving for the conversion efficiency of grain alone gives 0.165 percent. Annual sunlight efficiency values will, of course, be less: for whole plant and grain only they are 0.286 percent and 0.074 percent respectively. Calculating for only the PAR utilized by the plant during the season, efficiencies will, of course, rise; to $[(140.8 \times 10^9 J)/(22.26 \times 10^{12} J \times 0.45 \times 0.78)] = 1.80$ percent for the whole plant, and 0.469 percent for grain only.

How does this compare with the potential efficiency of photosynthesis? From the above figure of PAR at 45 percent of full spectrum, and an interception rate of 78 percent, then only $(0.45 \times 0.78) = 0.35$ of the total sunlight falling on a field can be used in photosynthesis. Photosynthesis begins with the absorption of light in minute packages or quanta by the photosynthetically active pigment chlorophyll, located in the green leaves of the plant. Each quantum is capable of exciting one chlorophyll molecule, which through an electron transferral process involving water and CO_2 supplies the electrons required to convert CO_2 into carbohydrate and other cell substances. The electron transport pathway is such that two sequential photochemical acts and eight quanta of light are required to reduce one molecule of CO_2. Reducing one mole of CO_2 to the level of carbohydrate where the energy input is assumed to come from useful light with a wavelength of 550 nm (the mid-range of the PAR spectrum) requires an estimated 1,765.2 kJ (Good and Bell, 1980). Dividing the energy content of the product into the process requirement yields a maximum conversion efficiency of (477.5 kJ ÷ 1,765.2 kJ) = 0.27, or 27 percent.

From a combination of the value for usable sunlight (35 percent) and the thermodynamic efficiency of photosynthesis (27 percent) it is clear that maximum conversion efficiency can be no higher than 9.5 percent. (To emphasize the importance of this upper limit on efficiency, it must be stressed that regardless of anthropogenic engineering of plants, nothing whatsoever can be done to affect its level until evolution develops an entirely new mechanism of photosynthesis.) However, to arrive at a value specifically for wheat we must account for the fact wheat utilizes C_3 carbon assimilation in its photosynthetic process. Therefore, the 9.5 figure must be reduced one-third to account for photorespiration losses, and one-third again to compensate for the production costs of respiration, resulting in a new value of only 4.21. In other words, the proportion of incident solar radiation conservable as chemical energy in the wheat plant is limited to about four percent.

At this level Prairie wheat production is approximately (4.26 ÷ 0.286) = 14.9 times below the theoretically possible. (For the efficiency of grain production alone we are 58 times below it.) However, all of these calculations are based on the availability of sunlight as being the only limiting factor in the growing environment, and under natural conditions limitations of CO_2, moisture and nutrients will affect plant growth in dramatic ways. In the field, low efficiencies of assimilation are common.

They range from highs of about 0.95 percent for sugarcane in Hawaii to lows of 0.18 percent for soybeans in Canada (Good and Bell, 1980). Under one of the highest yielding wheat agricultures in the world, conversion efficiencies in the Netherlands, are no more than 0.35 percent. This is about 20 percent above the Western Canadian average. However, it should be noted that agronomic differences between the regions (e.g. in the Netherlands, wheat has up to a 300 day production cycle as opposed to the 100 days which is more typical of Western Canada) distorts values and makes international comparison largely irrelevant. Under the prevailing climatic conditions it is extremely unlikely that Prairie conversion efficiencies would ever match those of the Netherlands yet at the same time they compare favourably.

In practical terms comparison to the natural grassland ecosystem makes for a much more relevant inquiry. Using data from the Matador experimental site in southern Saskatchewan, Prairie vegetation yields annually close to 29,000 kg/ha (Coupland and Van Dyne, 1979). Multiplying the biomass by its average energy content, 15.57 MJ/kg, gives an equivalent 450 GJ/ha. Calculating for the conversion efficiency of sunlight produces ($450 \times 10^9 J \div 49.29 \times 10^{12} J$) = 0.91, a ratio three times larger than that for wheat, and three times closer to the theoretical maximum of 4.0 percent. Out of total biomass production by native grasses, however, only about 25 percent is above ground. Thus, of a total production of 29,000 kg, 7,250 kg is recoverable. This compares to the 6,000 kg of above ground parts produced in the wheat agro-ecosystem. Multiplying for energy yields in this case gives (7,250 kg X 15.57 MJ/kg) = 112.9 GJ for grassland production and (6,000 kg X 18.9 MJ/kg) = 113.4 GJ for wheat production. Thus, on an above ground basis, assimilation rates conversion efficiencies are virtually identical for the two systems. However, the distinguishing characteristic of the anthropogenic system is, of course, its grain yield.

Animate Conversion Efficiencies

Wheat grain once it is harvested enters the human food chain primarily through two routes: (1) indirectly through the feeding of livestock, and (2) directly in the consumption of bread and other flour products. Determination of the energetics of each of these consumption routes is a logical extension of solar efficiencies.

Wheat grain fed to animals is converted to live weight at relatively low but widely differing rates. Data collected by the U.S. Department of Agriculture (USDA, 1981) indicate that consumptions per unit of production (measured as the mass of wheat required to produce one kg of live body weight) vary from 20-25 kg for sheep and lambs to 5-6 kg for chickens. Converting these requirements into mass efficiencies gives ratios ranging from four percent for sheep and lambs to 20 percent for chickens. Using beef cattle (which supplies most of the meat to North American consumers) as the standard, feeding with 2000 kg of wheat harvested from the average Prairie hectare in 1981 will produce with an average 6.9 percent conversion efficiency approximately 138 kg of live weight.

Live weight is, however, much different from the final meat product, and an adjustment must be made for the waste contained in bone, fat, tendons, ligaments and inedible trimmings. The dressed weight equivalent for beef in the late 1970s was 59 percent (USDA, 1979), while the yield of boneless meat trimmed to retail cut is itself equal to 73 percent of dressed weight. Assuming the average food energy in raw retail cuts is 11.0 MJ/kg (Watt and Merrill, 1963) the associated yield will be (138 kg X .59 X .73) = 59.4 kg, or (59.4 kg x 11.0 MJ/kg) = 658 MJ: a sum equal to just 2.1 percent of the energy conserved in the grain.

Nutritional uniqueness is not a characteristic attribute of mankind, and metabolism between individuals varies greatly. However, as a gross average an estimated 27 kJ of food energy is required in the formation of one gram of body weight (Schutz, 1979). Thus, the consumption of 658 MJ will deposit (assuming complete digestion) 24.4 kg of lean wet body tissue. With an energy equivalent of approximately 8 MJ/kg (Brobeck, 1968), the content of this deposition will equal 195 MJ. Comparing this value with the original radiant energy received in Western Canada, we find that in a full system sequence of growing wheat, feeding cattle, and eating meat, solar efficiencies are no more than (195×10^{6} J/ha ÷ 49.29×10^{12} J/ha) = 0.0004 percent.

An obvious conclusion from these calculations is that the luxury of consuming 100 kg of meat annually in the North American diet (Statistics Canada, 1981) commands a high thermodynamic price, one which could be, of course, reduced by eliminating the heterotrophic link and consuming grain directly. Meat has always been an integral part of the North American diet, but only over the past few decades has its consumption risen to such high levels. Globally, wheat supplies more protein than any other individual product of plant or animal origin, and is only slightly behind rice in supplying the greatest amount of energy to the human diet (Silano et al., 1981); however, in Canada wheat plays a secondary role on both accounts. Canadian consumption of animal flesh per capita is virtually double that of wheat, supplying greater percentages of protein and equal amounts of energy. In direct consumption wheat comprises 80-85 percent of all cereal intake and is the grain of greatest importance.

In computing the conversion efficiency of direct consumption the starting point again for calculations is the 49.29 TJ/ha input of full spectrum year-round sunlight for the Prairie region. Assuming the final product for our investigation is standard white bread, baked commercially with flour of an 80 percent extraction rate, the yield bread from a 2000 kg/ha crop will be approximately 2100 kg, at a standard flour to bread conversion rate of 1:1.3. The nutritive content of bread depends mainly on the flour from which it is made and the amount of water present (Aykroyd and Doughtly, 1970). Enriched white bread in North America with small amounts of skim-milk powder, sugar and fat added and with a 36 percent moisture content has some 11.3 MJ of metabolizable energy per kg (Watt and Merrill, 1963). In the human diet consuming 2100 kg of bread, equalling 23.75 GJ, and converting it to body mass at the same rate as before results in the deposition of 880 kg of body tissue with an energy equivalent of 7,040 MJ. Dividing this value into the energy of falling sunlight gives a conversion efficiency of 0.014 percent. A ratio 35 times better than that already obtained for consuming meat! The various solar conversion efficiencies associated with each mode of consumption have been assembled in Table 12.1.

Clearly, with savings of at least an order of magnitude, the dropping of the animal link would make energetic sense, but the comparison of animal to vegetal products in such a direct manner is simply not valid. Wheat grain has a lower amino acid score than beef and consequently offers only an incomplete source of protein, supplementation with proteins from other sources is a necessity for proper nutrition. Adding complimentary plant foods with comparable system efficiencies would maintain the wheat only conversion ratio and at the same time providing a well-balanced diet. However a complete replacement of meat by plant foods is unrealistic.

Wheat consumption per capita has remained virtually static in Canada since the mid-1950s at about 55 kg. At the same time consumption of beef and other meats has risen steadily from less than 75 kg per person in 1953 to almost 100 kg per person in 1981. The increased energetic cost of obtaining this additional quantity of meat is dramatic. For example, if consumption levels were to fall back to characteristic 1950 levels, savings in feed would be the equivalent of 25 kg of dressed meat. The energy value of dressed meat in Canada is roughly 11.0 MJ/kg which, when prorated, is equal to 275 MJ per person per year. Taking an average energy conversion efficiency of wheat to dressed animal weight at 2.8 percent, it would require 9,820 MJ of grain energy or (9,820 MJ ÷ 15.85 MJ/kg) = 620 kg of wheat to produce a corresponding amount.

However, in food energy terms the compensating requirement must be met. Substituting for 275 MJ of meat would increase bread consumption by (275 MJ ÷ 11.3 MJ/kg) = 24 kg, or flour consumption by 18.7 kg, or wheat grain consumption by 23.4 kg (after milling losses have been accounted for). Subtracting this quantity from the above savings yields a difference of (620 kg - 23.4 kg) = 595 kg of wheat. Multiplying 595 kg by the corresponding energy intensity of wheat in 1981, 4.5 MJ/kg (see Chapter XI for details), results in a product of 2,678 MJ. Such saving would be, of course, substantial: it is equal to 77 l of gasoline, 15 gal of diesel oil or about half a barrel of oil. The most telling characteristic, however, is at the national level. With a population of 24.343 million in 1981, total conservation would equal 1,875 million l of gasoline, 365 million gal of diesel oil or 10.65 million bbls of crude oil. In strict energy terms each of these inputs equal roughly one-half the total energy from all non-renewable fossil fuel resources it took to produce the 1981 crop. Put another way, reducing meat consumption to 1950 levels would free up more than one-half current annual production! And in all likelihood would in no way affect our nutritional status. Clearly, it has been through the great excesses of commercial production (where we consume no more than one-tenth of what is produced) that the predominantly meat-based diet has arisen.

<u>Production, Processing, Distribution and the Energy Costs of Bread</u>

Before going on to identify the many roads open to future conservation measures at the producer level, it is of course imperative that we place the production process itself in proper perspective. Growing wheat on the farm is only the first step in a long series of events leading to the retail sale and consumption of finished products. Identifying the associated energy intensities of each step in a typical production, processing and distribution sequence allows for a detailed estimation of cumulative costs: up to and including the energy requirements of bread. However, here the concern is with quantities of fossil-fuel derived energies, not as was in the preceding section, conversion efficiencies.

Having already established the energy intensity of production during the early 1980s, the value 4.5 MJ/kg serves as the starting point for calculations past the farm gate. The cost of transporting wheat grain from the farm to its initial collection point is an integral part of the operator's production energy requirements, and as such is subsumed in the 4.5 MJ/kg intensity. Assuming, however, that the grain must be moved from the elevator to the flour mill, a rail transport cost of 150 km at 0.36 MJ/t-km (Chapter 9) was assigned. The cost for one kg of wheat is therefore 0.05 MJ, which has been recorded in Table 12.2 along with all other requirements in the production, processing and distribution system. Once in the mill, the primary energy costs of grinding wheat are in fuel and electricity use. From manufacturing census data (Statistics Canada, 1971a) it was estimated that the PER of flour milling is equal to 1.47 MJ/kg. This value was found to be in close agreement with a more detailed value of 1.2 MJ/kg reported by Beech and Crafts-Lightly (1980) for flour prepared in British mills. The cost of packaging the flour in paper sacks and transporting it 50 km to bakeries where calculated, respectively, at 0.38 MJ based on 40 kg size sacks weighing 325 g and a kraft paper cost of 46.8 MJ/kg from Berry and Makino (1974), and 0.14 MJ based on trucking costs of 2.75 MJ/t-km computed from fuel consumption data (Statistics Canada, 1972). From fuel and electricity use data (Statistics Canada, 1971b) the energy requirement of bread baking was estimated at 10.45 MJ/kg. This value can be compared to the almost identical 10.2 MJ/kg computed from input-output tables constructed by Deachman and Hamilton (1978). Intensities includes not only the specific energy costs of baking bread but also overhead costs such as power for lighting, fuel for delivery vans and so on, and, as a result, obviates the need for calculating the energy costs of transporting bread to retail outlets. The packaging of bread in polyethylene bags, to which was assigned a cost of 0.80 MJ/kg, was estimated from Berry and Makino (1974).

Once in the retail outlet, bread must be purchased and taken home by consumers. Ignoring the embodied energy cost of the automobile, if a person were to take a car and drive 2 km to pick up a loaf of bread from the grocery store the equivalent energy cost of gasoline consumed at an average consumption rate of 17 l/100 km (Statistics Canada, 1984) would equal 11.5 MJ. However, rarely would one make such a trip for bread alone. Assuming a more realistic scenario, if the price of a loaf of bread of this size ($2.00) were to be assigned to a grocery bill of say $50.00, a proportionate energy cost would be 0.5 MJ. At this point the full sequence of energy costs from production to home delivery sums to a total of 18.29 MJ/kg. This cost is somewhat surprising, for actual production costs amount to no more than one-quarter of total requirements (an easy way to remember this is to note that the energy costs of all requirements past the farm gate are virtually identical to the human metabolizable energy content of the grain, 13.8 MJ/kg).

By far the largest energy input in the sequence belongs to the baking of bread; at 10.45 MJ/kg it is more than double the energy costs of wheat production, and comprise more than one-half of total requirements. Put into perspective then, the energy costs of growing wheat are relatively small.

And if the goal of energy analysis is to pinpoint large consuming sectors, then efforts aimed at system conservation may benefit more by focusing on other areas. As an example, Beech (1980) reports that baking in Britain consumes an average 7.0 MJ of non-renewable energies per kg of bread produced. The savings in this case are clear: if intensities could be lowered to a comparable level in Canada, reductions would amount to three-quarters the energy costs of production alone! Clearly any efforts aimed at reducing energy costs are worthwhile, yet we must concentrate first where returns are greatest.

One more step in the sequence remains to be quantified: that is, the energy cost of toasting our daily bread. Assuming an average size toaster of 1150 watts takes 90 seconds to brown bread two pieces at a time, associated energy consumption will equal 51.75 kJ/slice, or 2.0 MJ/kg at 40 slices per loaf. Adding this amount to the already determined sequence requirement of 18.29 MJ/kg, yields a new value of 20.29 MJ/kg (this cost was not included in Table 12.2 as it was considered to represent an activity only sometimes practised). At this level the full non-renewable energy requirement of morning toast is approximately 1.5 times its chemical energy content.

There is one additional cost which is undoubtedly incurred by society at large but which has not been incorporated in production costs so far. Having made the decision not to include the energy cost of labour in Chapter 2, I have until now ignored the important contribution of public research. However, because of its considerable magnitude mention of its associated energy costs -- which can be calculated from input-output tables -- are warranted. In 1971 the estimated cost of wheat research to the Canadian taxpayer was 11.1 million dollars (Zentner, 1983). During the same year, the government consumed 374.415 PJ (Hamilton & Deachman, 1978) in the process of expending 18.368 billion dollars on goods and services (Statistics

Canada, 1973). Dividing energy consumed by dollar expended gives an energy intensity for public research of (374.415×10^{15}J $\div$ 18.368×10^{9} dollars) = 20.38 MJ/dollar. Multiplying total research expenditures by 20.38 MJ/$ gives 226.21 TJ. Dividing this total by the area sown to wheat in 1971, 7.642×10^{6} ha, produces a cost of 29.60 MJ/ha: dividing it by the 13.880×10^{6} t of wheat produced in that year gives a corresponding intensity of 0.016 MJ/kg.

At 0.016 MJ/kg, the calculated energy intensity of research is so small that it does not warrant inclusion in sequence requirements. However, on an areal basis the situation is different -- costs are significant. At 29.60 MJ/ha, they are greater than the energy cost of transporting all major production inputs, and five times greater than the calculated energy inputs of farm labour itself!

Mechanization has brought with it many things amongst which the transfer of energy costs off the farm and onto support industries is important. I have attempted to include as many transfers as possible in this analysis; yet many are hidden and are, like the energy cost of any farm input, ultimately beyond the control and interest of the farmer himself. Wheat production is an economic enterprise guided by income and monetary expenditures; these are the major concerns of the operator and determine the choice of production strategies. In the last chapter then, we turn to a consideration of these costs and the likely direction of future change.

TABLE 12.1

WHEAT SYSTEM CONVERSION EFFICIENCIES

System Stage	Product	Assimilation of Sunlight* (%)
Growing wheat	grain	.074
Human consuming bread	body mass	.014
Livestock consuming feed	retail cuts	.0015
Human consuming beef	body mass	.0004

*Original input of radiant energy is equal to 49.29 TJ/ha annually at full spectrum.

TABLE 12.2

WHEAT PRODUCTION, PROCESSING AND DISTRIBUTION ENERGY COSTS

Sequence Stage	Energy Requirement (MJ/kg)
Production	4.50
Transport to mill	0.05
Flour milling	1.47
Flour packaging	0.38
Transport to bakery	0.14
Baking bread	10.45
Bread packaging	0.80
Car pick-up	0.50
Total	18.29

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XIII. ENERGY, MONEY AND THE IMPETUS FOR CHANGE

As was pointed out earlier (in Chapter XI) the performance of wheat agriculture in Western Canada during modern times has been quite respectable. Inputs of productive factors have risen dramatically, as could be expected, but at the same time increasing yields have served to offset growing energy costs to produce relatively constant efficiency ratios. However, anticipated increases in the real cost of inputs such as fuel, fertilizer, electricity and herbicides, will most likely lead to changes in the cropping practices of the 1990s.

An itemized comparison of the energy inputs shows some of the major shifts that have occurred in wheat farming between the late 1950s and early 1980s (Table 13.1), and in relative terms they have been significant. The shares of fuel and machinery have become much less prominent, while those of nitrogen, phosphorus and herbicide have become much more. In absolute terms, the energy used to fabricate and fuel the larger more powerful machinery fell by 30 percent, the energy costs of nitrogen grew by a factor of 17, the cost of phosphorus by a factor of nine, and that of herbicides by nine and a half. Putting it another way, the direct energy inputs accounted for a greater percentage of total requirements in the 1980s, than they did two and a half decades earlier.

Underpinning these changes were, of course, the level of physical inputs themselves. Since the late 1940s the adoption of industrial inputs has followed a predictable pattern of increase: initial market penetration, slow then rapid acceptance (as the new technology's economic advantages become apparent over a wide segment of the market), and slow again as the market becomes saturated. Yet in all cases while the magnitude of inputs has risen (except for animal feeds which by 1963 was no longer a productive factor) improving process technology has contributed to holding the cost of these inputs down. Between 1958 and 1981 the energy intensities of both nitrogen and farm machinery fell by almost 25 percent. Applied against actual amounts consumed, this reduction manifests a budget saving of 15 percent or 1125 MJ/ha.

Future changes will not be as dramatic as those of the past -- we will not likely see the birth of a radically new agriculture in the 1990s -- but they will be nonetheless significant, and most likely affect the input of non-renewable resources. Any attempt at foretelling the future is, of course, wrought with uncertainty, and predicting wheat agriculture in precise quantitative terms where so many intangible variables affect even its daily operations would create false expectations. The more preferable route, therefore, is to review the developments of the past few years and offer a trend forecast. In the case of Western Canada, however, even the results of this process must be interpreted with caution, for here, under the influence of an incredibly variable climate, environmental conditions are largely beyond the control of the producer. Irrigation is not widespread and out of economic necessity inputs must be kept below levels optimum for maximum production.

As noted in Chapter IV machinery had been around some time before it became widely employed; as late as 1936 its economic advantage over animal power was still not clear (Grest, 1936). This situation soon changed, however, as both the machinery and the fuel required to run it rapidly diffused over the 1948-1958 period. By 1958 nearly all farms had one or two tractors and a full complement of disks, harrows, seeders, fertilizer spreaders, packers, and combines. Since that time the power and size of machinery and implements has grown, but by the early 1970s the increases were entering a period of slow down. Over the last three intervals of the time series, machinery mass and power were either leveling off or slowly declining, and after 1977 fuel consumption alone fell 20 percent. Field sizes in the meantime were still growing appreciably -- a development which would suggest that a saturation point had been reached and that machinery was being applied more efficiently in 1981. Electricity, which experienced its most rapid diffusion during the rural electrification process, was reaching virtually all farms by the late 1960s, and since that time increases per service have been falling off.

The adoption history of fertilizers and pesticides is quite unlike that of the power-related inputs. Increasing use accompanied industrialization, but at a slower rate and, unlike the levelling off of machinery, fuel and electricity consumption during the late 1970s, physical quantities of fertilizer and pesticides continued to rise, and at a much faster rate than at any other time during the history of modern practices. Nitrogen rose quickly from ranking third behind fuel and machinery in 1977 to become the second most intensive-energy input by 1981, and should be expected to rise to even greater levels in the future. Using the U.S. corn crop as an example of what could be expected to happen, the diminishing returns to fertilizer inputs and the formation of an unmistakable logistic curve which have accompanied its intensified use over time (see Smil et al., 1983) have not set in for wheat production in Canada. At an average application rate of 30 kg/ha amounts are still far short of the recommended minimum, 50 kg/ha, and far below the point where returns could be expected to diminish. Recalling the growth curve in Figure 7.1, the formation of a logistic curve has not occurred -- there was a slow-down in the rate of application increase between 1977 and 1981, but it is likely that rates will pick up again as they did once before in the early 1970s.

Summer fallowing, a practice which substantially reduces fertilizer requirements where employed (and increases them where not) is now being used less extensively than in the past. Causes of this have been largely economic, and the farm operator in the attempt to maintain positive cash flow, will likely keep even more of his land under production in the future, increasing both the demand for chemical fertilizers and the associated energy costs. "Mining" of the soil is also a physical factor which must be taken into account in future scenarios. Continued removal of soil nutrients will alone necessitate higher application rates without any significant change in summer fallowing practises.

The energy intensity of applied nitrogenous fertilizer will likely fall over the next decade as a result of continued process improvements. However, little benefit should be expected to come from a less intensive fertilizer mix: greater use of urea, the most energy-expensive variety, will offset any savings that could be expected to come from increased utilization of anhydrous ammonia, the least energy-expensive variety. Application of phosphorus and potassium will increase slightly, and part of the increased cost will be offset by more efficient industrial technology.

Herbicide use underwent historic expansion between the mid-1970s and the early 1980s, and as there is yet no sign of abatement of the weed problem the trend will likely continue for some time to come. Contributing to increased costs for this input will be a continued shift towards more expensive chemicals (needed to control persistent species) and a movement towards reduced mechanical tillage. The result: herbicide use and energy costs could easily double over the next decade.

Clearly, fertilizer and pesticide use are determined by the physical realities of crop production and in the future their applications will depend on evolving field conditions. The same is true, of course, of all productive factors; yet producers operate under definite financial constraints and we must first review the changing economic landscape in the attempt to identify those changes that will affect production most dramatically and be the targets of future conservation efforts.

Financial Costs

Historical statistics on the selling price of Canadian wheat have been available for at least 75 years and are listed for the postwar decades in Table 13.2. Canada'a contribution to the world trade of wheat is important, but owing to the presence of other large exporters (the United States, France, Australia and Argentina) and an export to production ratio which is high, prices received by farmers are subject to fluctuations of the international marketplace, and only to a much lesser degree by local production costs (and by extension the climatic influences of good and bad years). Adjusting by the appropriate deflator, prices have been recorded in constant as well as current dollars using 1945 as the base year. From the data it is clear that there is no consistent pattern of price change or increase, rather what is reflected in more than three decades of Prairie farming are wide fluctuations. In 1948 the price of wheat in current dollars was roughly ten dollars per tonne higher than what it was in 1953 (a year of extremely good weather and abundant yields). Prices rose slightly in 1964 only to fall back to 1953 levels by 1968. Under the influence of a world wheat glut prices did not rise again until 1973, at which time they tripled in a matter of one or two years. In constant dollars the 1973 price of 77.12 dollars per tonne was the highest price ever paid for wheat. However, by 1977 the price was the second lowest in the study period, and in 1981 prices were below what they had been more than three decades earlier. The total farm value of wheat in constant dollars even with increasing yields did not surpass postwar levels by a large margin until the early 1970s, and only then on a temporary basis.

Throughout most of the study period farmers were paying relatively stable prices for inputs. The price of fuel did not change dramatically and the cost of nitrogen fertilizer in the early 1970s was less in constant dollars than what it had been 20 years earlier. Figure 13.1 shows relative price changes (expressed as a percent of prices prevailing in the base period 1948) of the major farm inputs between the late 1940s and the early 1980s. In terms of major inputs, only machinery underwent increases in the 1948-1973 period; it was not until 1973 that the costs of petroleum products, fertilizer and pesticides rose decisively. Between 1973 and 1981 the price increase of petroleum products equalled 290 percent, of fertilizers 360 percent and of pesticides 260 percent. Other input costs rose substantially as well (such as farm rent, building repairs, hired farm labour and electricity) but none was as significant as the fossil-fuel derived inputs.

The case for conservation is, of course, apparent when we compare these costs with the changes that have occurred in the price of wheat. Sound business rationale predicates that to remain solvent a productive enterprise must equate input requirements with revenue; yet the most startling development of the past decade has been the growing divergence in exactly those two factors. Increasing yields have partially offset lower wheat prices but they are not enough: clearly, some changes in cultural practice will be needed to raise production efficiencies.

A breakdown of actual production costs for Prairie wheat farms in the years 1958 and 1981 are available. Compiled jointly by Statistics Canada and the Canadian Department of Agriculture (Fitzpatrick, 1967) the earlier survey lists commercial wheat farm variable operating expenses at $33.25 /ha. Of this, expenditures on machinery and fuel accounted for by far the largest proportion at approximately $15.50 /ha, or just under 50 percent of total amounts. In the same year fertilizer costs summed to $0.60 /ha, and pesticides to 0.75 $/ha, accounting for, respectively, 1.7 percent and 2.2 percent of total costs. On a comparable economic basis, the Manitoba Department of Agriculture (MDA, 1981) estimated 1981 variable operating costs at 203.00 $/ha, equal to roughly double those of 1958 in constant dollars. Machinery and fuel costs in this more recent appraisal summed to 37.00 $/ha, or 18 percent of expenses, while fertilizers accounted for a substantially greater 65.25 $/ha, or 32 percent. Pesticides were higher with an estimated input cost of 40.90 $/ha, representing 20 percent of the total. Yields over this period increased by roughly 60 percent, (100 percent would have been required to meet the higher expenses). In terms of total production costs (including both fixed and variable expenses) changes were such that in 1958 producers had little trouble in meeting expenditures with revenues. However, in 1981 a breakeven point of 2500 kg/ha necessitated returns 25 percent above average.

Having said this, it should also be stressed that producers have been aware of changing production economies. If we recall the energy gains of the post-1973 period (see Chapter XI), the move towards greater efficiency is already underway: between 1973 and 1981 production efficiencies (measured as crop energy yield divided by the non-renewable energy subsidy) rose by more than 15 percent. After decades of little change the improvements of the last few years mark only the beginning of a long and complex series of energy use adjustments and transformations.

Energy analysis is, of course, no substitute for financial accounting. But under unavoidably increasing energy costs and the uncertainty of future energy supplies, economic choices will undoubtedly reflect physical realities in the targeting of conservation efforts. There are countless avenues and options open, all of which can be easily met before the turn of the century without the loss of yield or need for agricultural re-structuring. In fact, many consist of applying just good common sense. Western wheat production has performed well in the past and there is little doubt it can't do better in the future. A brief review of options for conservation -- some already being practiced and some not -- indicates where future changes will probably lie.

Fuel and Machinery

Fuel for field machinery and farm trucks, after a fall of more than 20 percent in use since 1977, was still the most important energy input in 1981, and its consumption can be further reduced in several ways. Replacement of gasoline-fueled tractors, combines and trucks by diesel-fueled ones reduces energy consumption by an average of 25 percent for identical tasks. In 1981 about two-thirds of Prairie tractors were diesel powered (Statistics Canada, 1983) and they consumed roughly 50 percent of all motive fuels. Converting these units alone to diesel power would reduce energy consumption about 10 percent. Farm implement dealers are aiding in this process by promoting a new line of four-wheel drive tractors in the lower 100 to 120 horsepower range which will facilitate conversion in what was previously a gasoline dominated area (Newman, 1984). Trucks, especially in the one-half ton category, offer additional conversion potential as do combines and self-propelled swathers.

Design changes for higher efficiency in combustion, cooling, power transmission, air conditioning, hydraulic and power take-off systems, and lighter components could result in substantial long-term savings (Council for Agricultural Science and Technology, 1975). Of more immediate importance, however, is the extension of both gasoline and diesel fuel use by improved maintenance, improving mechanical efficiency and equipment longevity, and a streamlining of operational practices. Savings are possible by the matching of tractor power to load requirements, operating tractors in the gear up throttle down mode, installing radial tires and maintaining proper ballast, and better control over field operations, such as depth of seeding and tillage (USDA/FEA, 1977; Mathews, 1975; Zoerb and Kushwaha, 1984). The cooperative employment of machinery (Scott, 1952) as well as the purchasing of custom work would trim on-farm equipment manifests. One author has also indicated that the use of smaller implements offers a potential fuel saving over standard equipment through the reduction of turning loss and overlap (Palmer, 1984).

There are many fuel-conserving measures, many of them small and not necessarily additive; yet cumulative effects can be impressive. An excellent example of a seemingly minor but important conservation measure is the reduction of wasteful idling time. Assuming that a tractor engine idles just ten minutes daily (a time which can be used up easily by just climbing down from the machine to open farm gates and close garage doors), the annual total is 61 hours; for a 75-horsepower diesel tractor this means about 110 l of fuel a year (USDA/FEA, 1977), enough to farm just over one hectare of wheat.

In farm business activities unnecessary trips can be deleted or combined with others, and, of course, an efficient automobile is a far better user of gasoline than the pick-up truck for trips into town. Fuel savings can come from a combination of field operations, such as once-over techniques of tilling, seed and fertilizer application, or the complete elimination of some passes. In terms of cultural practices themselves, it appears that the conventional three year wheat-wheat-fallow rotation offers both an economic (Zentner and Campbell, 1984a) and energetic (Zentner and Campbell, 1984b) advantage over the shorter two year or continuous cropping alternatives.

Zero-tillage and its less extreme forms of conservation tillage have met with only limited success in Western Canada. In the late 1970s, being practiced on no more than an estimated one-tenth of one percent of Prairie cropland (J. Forbes, Zero-Tillage Assoc., 1984, pers. comm.), and in spite of its often cited benefits of reduced fuel and machinery costs, improved erosion control, greater moisture retention and increased yields (Donaghy, 1973; Stobbe, 1977; Sing et al., 1979) the necessity of increased herbicide applications has made adoption economically unattractive (Zentner and Lindwall, 1983).

The wider implications of zero-tillage -- increased pest populations, greater susceptibility to disease, chemical carry-over, resistance and a shift in weed species (Hinkle, 1983) -- appear to have dampened early expectations. As one author stated in a cogent and outstanding review on the topic, the espoused virtues of the system may have been premised more on fashion than fact (Gersmehl, 1977). The adoption history of zero-tillage, limited by a poleward gradient of soil temperatures, a westward gradient of moisture problems, an equatorward gradient of weed efficiency, and such factors as pride in workmanship, perception of acceptable risk, and problem of inadequate farm size and labour underutilization, suggests that its practice will only be viable in a small part of the North American continent; amounting to no more than an estimated ten percent of midwestern U.S. farm land. Given present technology, market conditions and regulations, Gersmehl comments prophetically that the "no-till revolution is a thing of the past, not a wave of the future". In fact, if we are to accept the findings of a Statistics Canada survey (Statistics Canada, 1983) farmers in Western Canada appear to be moving away from zero-tillage -- not towards it -- by increasing their number of field operations.

A somewhat distinct but currently topical means for decreasing dependence on petroleum products altogether is the extension or replacement of gasoline and diesel fuels with alcohol from grain. In selected processes involving fermentation, gasification and hydrolysis it is possible to turn wheat grain, chaff, straw and even screenings into ethanol, methanol, biogas, and synthetic natural gas. Yet a number of key issues in the biomass debate must be addressed, foremost of which is whether or not the plant should be used as an energy feedstock (something that, of course, energy analysis alone cannot answer). The question is argued at some length by Brown (1980) for a variety of food crops, especially the more productive C_4 species of sugarcane and corn, but as a photosynthetically inferior C_3 species wheat is not among them.

The case against using Prairie wheat for an energy feedstock, however, is clear. Straw residues, chaff and screenings are only of limited use in fermentation processes owing to their high fibre content; no commercial technology for the hydrolysis of cellulose presently exists. And if one did, the initial product market would likely be the chemical not the refinery industry (Bungay, 1982). Thermochemical production of gaseous fuels via gasification is not competitive on a small scale without expensive densification, and on a larger scale a steady supply of phytomass for feedstock cannot be ensured. In the Prairie region as a whole there is a deficit of wheat residues for adequate erosion control, only in a few locales is there any surplus of straw in excess of essential soil requirements (Canadian Resourcecon, 1982), and even they are not perennial. The best use of crop residues is to put them back into the ground in the attempt to rebuild soil tilth and offset future fertilizer requirements. With occasional bumper crops, part of the excess straw could supplement space heating requirements by direct combustion, where labour and time are plentiful.

With regards to the wheat grain itself, it makes little energetic sense to pump a host of fossil-fuel derived energies into its production, exhaust the soil of nutrients, ship it to a processing plant, synthesize ethanol and subsequently distribute the product for commercial consumption -- when the same ends could be met through widespread conservation of those fuels originally in short supply. One of the key contentions of the gasohol debate, in fact, is whether or not the fuel actually produces net energy. The limiting factor in alcohol production is grain starch content. In Chapter XI it was calculated that the intensity of non-renewable energies consumed in the farming process is about 4.5 MJ/kg. At a theoretical conversion ratio of 0.565 kg alcohol per kg of starch (Miller, 1969), wheat will yield approximately 0.281 kg or 0.36 l of product per kg; thus, each l of alcohol acquires about 12.5 MJ of farming energies.

The largest share of ethanol's energy cost is in the distillation process rather than the growing of the grain. Current distillery practices consume about 21 MJ per l of alcohol produced (Chambers et al., 1979; Parker, 1981). Summing the embodied energy cost of the grain and processing requirements gives a total consumption of 33.5 MJ/l, a value roughly 1.2 times the energy content of the alcohol itself. This is, of course, only a rough average calculated across a whole range of growing intensities and processing requirements; farm scale production -- a process which U.S. experience has shown can be expensive, time consuming and frustrating (Schulte and Splinter, 1983) -- typically leads to higher distillation costs (CDA, 1980). From this lower efficiency, consumption on average rises to about 38.0 MJ per l of product. The possibility of pure wheat-derived ethanol as a commercial fuel is thus (on both accounts) definitely an energy-losing proposition. In fact, losses of low-entropy fuels would be avoided by simply not producing ethanol at all! Farm conservation measures would reduce the energy costs of wheat production and by extension alcohol production, but with such high processing requirements it is unlikely their magnitude would be sufficiently large to offset losses.

Fertilizers

Increasing consumption of nitrogen over the past decade has boosted fertilizer into becoming the second highest energy input in recent times. The potential for savings with this input, while it may not be as great as for fuel and machinery, remains nonetheless substantial. Under current conditions of soil nutrient "mining", fertilizer applications of nitrogenous compounds will undoubtedly rise in the future. Regional averages for nitrogen are still less than half recommended levels, and as a result energy cost reductions will lie with improvements in field efficiency, and, of course, with continued advancements in process technology.

The principal target of past processing efforts has been a lower cost for ammonia. However, while the drop in energy requirements of its synthesis over the past few decades has been impressive, there does not appear to be any commercially feasible technological breakthrough that will dramatically reduce it below today's best plant energy intensity of 29 MJ/kg (Mudahar and Hignett, 1982). This prediction is physically reinforced by the fact that the PER of new plants has come very close to what is believed a practical minimum for production efficiency (IFIAS, 1975). As the principal feedstock for virtually all nitrogenous fertilizers, downstream products will as well reflect this reality in their cost.

In existing plants appreciable savings can come from implementing many general measures for energy conservation, such as the updating of operation procedures, increased equipment maintenance, installation of more efficient hardware components where possible, the use of heat and electricity cogeneration and power recovery turbines (FEA, 1974), and operating at battery limit performance levels. Nearly a decade after these recommendations were first published there is still much room for improvement in the chemicals and allied products industry (DOE, 1983). Alternative sources of fuel and feedstock (naptha, fuel oil or coal) would not lower the energy cost of ammonia synthesis per se, but at the national level savings are anticipated as older less efficient processing plants retire. Under the current structure of the Northern American fertilizer industry the average PER of plants now in operation is about double that of the units just coming onstream. Yet, in spite of this, the evolution towards efficiency will be slow: the world's first ammonia synthesis plant in Germany shut down only in 1982, after more than 75 years of service (Chementator, 1982). The average age of plants in North America is less than half that.

By the mid-1990s cumulative savings could result in a 15 percent lowering of average energy requirements. Reflected in the unit cost of N, intensities could be as low as 48.5 MJ/kg. Little change is foreseen in the mix of applied Prairie fertilizers: energy savings resulting from a shift towards greater use of anhydrous ammonia will likely be mitigated by increased urea applications. The cost of Western Canada nitrogen may thus be somewhere in the range of 55 MJ/kg in 1996. Energy savings are possible in the production of phosphatic fertilizers, through increased use of crushed phosphate rock, and general conservation measures, but such measures translate into no more than minor savings in the overall budget. In terms of potassic fertilizers, no fundamental changes are envisioned in potash mining, and again realized savings would have little effect on system requirements.

Future application rates of each of the macro-nutrients will be higher than what they are today. A conservative estimate of Western Canada inputs, would be N at 40 kg/ha, P at 10 kg/ha, and K at 2.5 kg/ha in 1996. The most important conservation options open to producers involve optimizing the rate, timing and methods of application. Few operators have their fields tested regularly by soil analysis for specific nutrient requirements (Ewanek, J., Tomasiewicz, D. J., Goettel, A. W., pers. comm., 1984) and of those which do, 50 percent or more ignore the recommendations (Corry, 1981). Savings here could easily reach 20 percent. Applying nitrogenous fertilizers as close to the period of plant uptake as possible could improve field efficiencies by as much as 30 percent (Ridley, 1976). Broadcast fertilization should in most instances be replaced by soil incorporation (Racz, 1980), and in the case of phosphatic fertilizers, dressing with large doses every few years could offset yearly requirements with no loss of efficiency and appreciable energy savings (Karlowsky, 1981).

Reduced use of inorganic fertilizer through increased crop rotation, intercropping with nitrogen-fixing forages or perennial grasses, and the planting and plowing under of green manure crops all offer theoretical potential. However, such practices are often beyond the reach of the operator who is forced by financial constraints to reduce rotations or continuous crop. The application of organic wastes offers some potential, although it could only be modest owing to the relative absence of livestock farms in the region, and the fact that the less concentrated and quickly-decomposing manure cannot be considered a direct replacement for high quality fertilizer.

Herbicides

Herbicide use, like that of nitrogen fertilizer, underwent dramatic intensification over the past decade. Between 1973 and 1981 applications doubled while attendant energy costs tripled. The input is low on the list of wheat system energy requirements, but if an extrapolation from current trends is realistic, energy use equivalents could be expected to be at least double their present levels by 1996: the result of both increased quantities and higher unit costs. Over the 33 year time span of this study the evolving mix of applied varieties has led to the doubling of input intensities, and it is quite likely that more selective and energy expensive types will be required to combat persistent weed species in the future.

Detailed information concerning the processing of pesticides is scarce, however, it is probable that the industry itself will employ general conservation measures and replicate the modest efficiency gains shown by the entire chemicals and allied products sector. The prime target of operator savings will again be, as in the case of fertilizer inputs, field efficiency. Misapplication of chemicals costs wheat producers a great deal of money annually and come from actions that are largely avoidable. Wastage is typically the result of use without established need, incorrect choice of chemicals and exaggerated levels of usage. One recent survey in the Great Plains area of the U.S. showed that more than three-quarters of farmers using pesticides applied incorrect amounts, with errors ranging from 60 percent under to 85 percent over recommended rates (Dickey et al., 1981). Both conditions result in not only energy waste but have the potential of causing significant ecological and health damage. As was suggested earlier, education should be the prime area for operator awareness.

A more endemic problem is, of course, the method of application itself. Herbicide sprayers are extremely inefficient. In Western Canada it is estimated that no more than ten percent of post-emergent chemicals actually hit their target (Green, 1983). Controlled droplet application could partially offset the problem and improve the effectiveness (Finney, 1979), but ultimately the only permanent solution lies with making a shift to pre-emergent varieties: something which is neither always technically feasible nor ecologically sound, owing to potential soil leaching and chemical carryover.

Electricity

Although electricity is often thought of as minor energy consumer in grain production (where irrigation is not widely practiced) its input to farming requirements can be significant, as this study has shown. At 85 kWh/ha its energy cost ranked fourth in the 1981 budget. Confined to use in many secondary farm practices, reduction can come about from many simple changes of habit, such as the turning off of shop lights when not in use, and from minor adjustments in mechanical operations. Electricity used by small motors that power grain augers, fans and compressors, can be saved by installing higher efficiency units, matching unit output with maximum requirement, and utilizing variable speed regulators (Monette and Tripone, 1983).

As was noted in Chapter VI, electricity generated from Prairie windmills supplied a substantial amount of energy to farms before rural electrification began in the late 1940s. The low power density and high demand for generating space of these units makes them ill-suited to urban settings, but the prevailing winds and broad, sparsely populated Prairie landscape makes them well-suited to agricultural use. A renewed application of this simple technology is an attractive possibility for many small-scale applications.

Some potential exists for reducing electrical energy demands in terms of low-temperature and in-storage crop drying with improved solar technology. Solar collectors can offset electricity consumed in grain drying by up to 25 percent under average Western Canadian conditions (Fraser and Muir, 1980); however, the use of commercially produced systems is largely restricted by cost ineffectiveness (Muir, 1980). The alternative: low-cost home-made varieties (with an average pay-back period of five years), have been meeting with some success, and their use can be expected to spread in the future (Heid and Trotter, 1982). Taken individually the potential for energy saving from these changes are small, however, together they can lead to modest reductions: by 1996 a fall of 15 percent in electricity requirements is entirely possible.

Future Energy Costs

In the energy savings just described, the year 1996 (15 years down the road from the last entry of the study period) was used a a convenient forecast horizon. Attaining these savings in each and every instance was considered to be entirely feasible as an extension of current trends, (especially in the area of continued process improvement) and demand no more than minor conservation efforts. The estimated changes in wheat energy inputs by 1996, listed in Table 13.3, should be seen therefore as consertive estimates. While I have given some indication of the changes that likely to come about over the next few years, predictions are not rigid: the system is far too complex and too susceptible to a host of unaccountable variables, ranging from unpredictable weather and unpredictable crude oil prices to unpredictable political intervention to be precisely quantified.

Underpinning the 1996 forecasts are a drop in fuel, machinery and electricity inputs, a rise in fertilizer, farm chemical and transport consumption, and a fall in the energy intensity of all inputs except herbicide. Together these changes will result in a decline of the sum of energies from 8366 MJ/ha in 1981 to 7561 MJ/ha. Assuming no major breakthroughs in breeding techniques occur -- hybridization after years of intensive research has not yielded a commercially profitable wheat (Allan, 1980) and genetic engineering is presently far too futuristic to be seriously considered as a viable alternative (Johnson, 1982) -- gradual increases should result in wheat yields of 2300 kg/ha. Accounting for the feedback requirement of seeds (85 kg/ha) and dividing the remainder by the energy of all other inputs, gives a 1996 mass-energy ratio of 290 kg of grain per GJ of invested energy, nearly a 25 percent improvement over the 1981 value.

A more optimistic forecast of future energy inputs could easily lift the mass-energy ratio above the 325 kg/GJ level and, under conditions of excellent weather, even match those of the 1948-1958 transition period. Above all, it must be stressed that no scientific or technological breakthroughs are needed to achieve this; no untried processes and approaches have to be tested and adopted. In fact it could be argued that with stronger conservation measures truly impressive performances could be had. With attention to operational detail, sound management and slightly greater inputs of labour (much of it during the off-season), one large farm in central Saskatchewan is presently returning an average of more than 700 kg of wheat per GJ of invested energy (Table 13.4). This is more than three times the calculated 1981 value, and over two-and-one-half times the 1996 estimate!

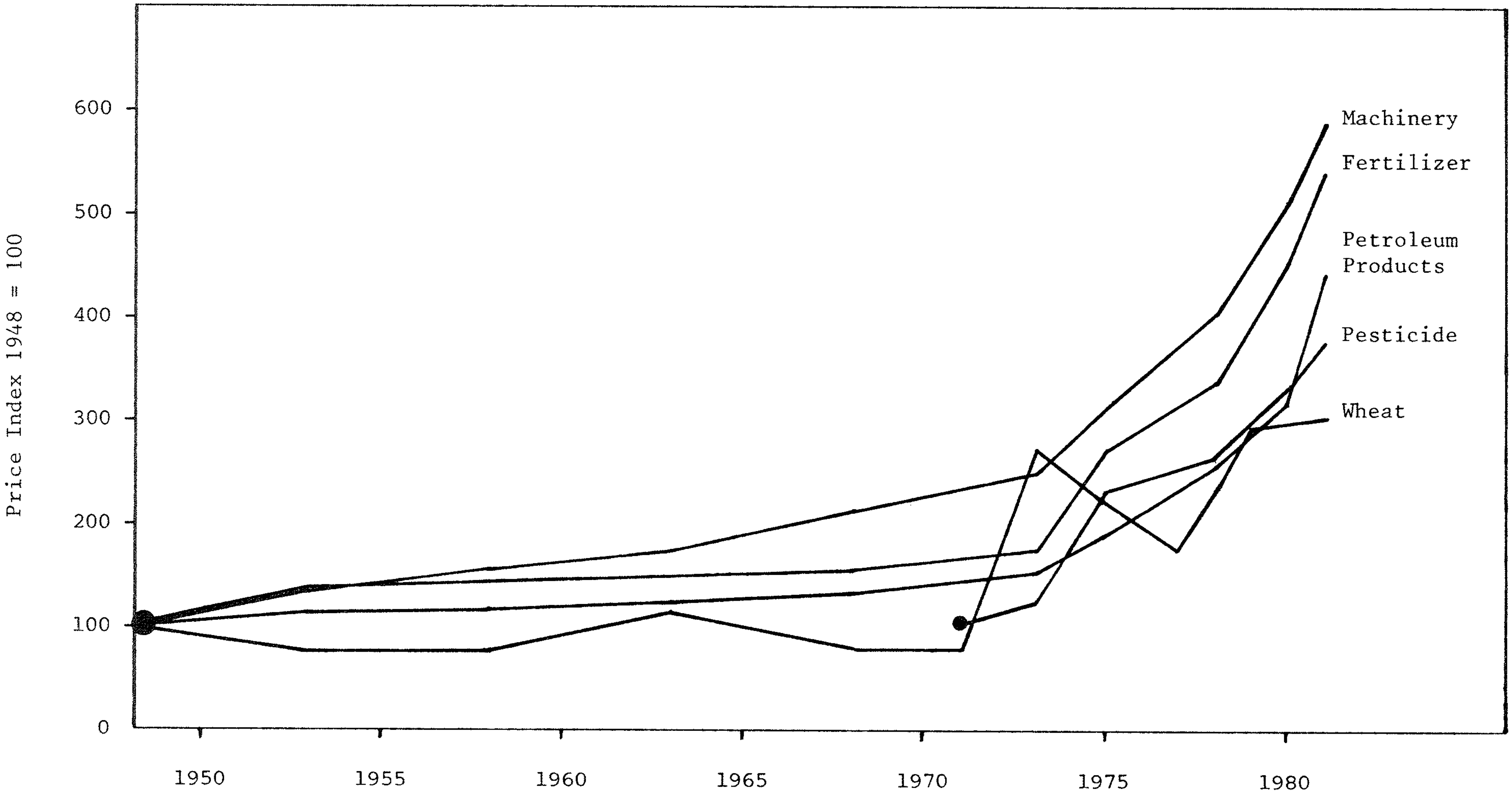
Looking ahead leaves only an insignificant probability that the efficiency of wheat agriculture will not get better. Over the next few years the non-renewable energy consumed in Prairie wheat production will almost certainly assist the photosynthetic process in a more efficient way than at any other time since modern fossil-fuel subsidized farming became entrenched in the mid-1950s. However it is imperative that we avoid misleading impressions and place wheat agriculture's energy use in a wider perspective.

In 1971 the energy consumed in producing that year's crop of 13.881 million t, at an energy intensity of 4.75 MJ/kg, amounted to an approximate 65.935 PJ. During the same year with an output valued at 4.929 billion dollars and an energy use coefficient of 35.59 MJ/dollar (Deachman and Hamilton, 1978) Canadian agriculture consumed in both direct and indirect inputs some 175.423 PJ of non-renewable fossil fuel resources. Comparing the two figures, wheat production accounted for about 38 percent of total agricultural energy consumption. Extending this analysis one step further, it is found that agriculture itself accounts for only about three percent of the nationwide energy total; and as a result wheat comprises just over one percent of the country's aggregate energy use. This is less than one-third the equivalent of all electrical energy expended for home operation of stoves, refrigerators, dishwashers, toasters, kettles, can openers and other household gadgets, and less than one-sixth the energy cost of the almost 20 billion litres of gasoline burned annually in passenger automobiles.

Yet as an even better example, the wheat producer can grow and harvest the nation's largest field crop, and one of its top export earners, at less than one-half the energy density (MJ/m^2) of mowing and watering a well-manicured suburban lawn (Falk, 1976). Over the past decade the energy efficiency of producing wheat has improved after years of relative constancy, and there are many ways by which it can be improved further in the future: but it would be rather unfair to overlook the many truly energy-wasting facets of the North American lifestyle while focusing on agricultural in general or wheat production in particular as exigent drains on our finite energy reserves.

FIGURE 13.1

PRICE CHANGES IN WHEAT FARMING 1948-1981*



*Data collected from Statistics Canada, Farm Price Index, Cat 62-004, 1948-1981. Minister of Supply and Services, Ottawa.

TABLE 13.1

CHANGES IN THE ENERGY INPUTS TO PRAIRIE

WHEAT PRODUCTION BETWEEN

1958 AND 1981

ITEM	Relative Shares* 1958	1981	Absolute Changes 1981/1958
Fuel	71.5	46.6	0.65
Machinery	24.3	18.1	0.75
Nitrogen	1.4	24.2	17.28
Phosphorus	0.1	0.9	9.00
Potassium	--	0.1	--
Herbicide	0.2	1.9	9.50
Electricity	2.3	7.6	3.30
Transport	0.2	0.6	3.00

*Calculated on the basis of input totals of 4,569 MJ/ha in 1958 and 8366 MJ/ha in 1981.

TABLE 13.2

AVERAGE FARM PRICE AND TOTAL FARM VALUE
OF PRAIRIE WHEAT PRODUCTION IN CURRENT
AND CONSTANT DOLLARS

Year	Average Farm Price (dollar/t)		Total Farm Value (millions of dollars)	
	Current*	Constant**	Current*	Constant**
1948	59.81	59.81	579	579
1953	48.66	38.48	800	633
1958	48.65	35.45	492	359
1963	64.02	43.79	1,225	838
1968	48.85	28.66	836	491
1973	164.61	77.12	2,572	1205
1977	104.00	34.16	1,957	643
1981	184.39	41.12	4,396	980

*Statistics Canada, The Grain Trade, Cat. 22-201, annual, 1948-1981, Minister of Supply and Services, Ottawa.

**Measured in 1948 dollars according to the purchasing power of the Canadian dollar from Statistics Canada, The Consumer Price Index, Cat. 62-001, monthly, 1945-1981, Minister of Supply and Services, Ottawa.

TABLE 13.3

ESTIMATED CHANGES IN WHEAT AGRICULTURE EFFICIENCY 1981-1996

Productive Factor	Percentage Change Quantity	Energy Intensity	Total	Energy Input 1996 (MJ/ha)
Fuel	-23	+ 3	- 25	2922
Machinery	- 8	- 8	- 15	1286
Nitrogen	+35	- 8	+ 20	2428
Phosphorus	+ 8	- 3	+ 15	90
Potassium	+67	- 4	+ 55	14
Herbicide	+67	+20	+100	318
Electricity	-15	--	- 15	544
Transport	+10	--	+ 10	53
Sum of Energies				7655

TABLE 13.4

ENERGY COSTS OF A 1000 HECTARE FARM IN CENTRAL SASKATCHEWAN*

Input Item	Units	Quantity per hectare	Unit Energy Intensity (MJ)	Input Cost (MJ/ha)
Fuel	l	44.5	36.5	1,626
Machinery	kg	7.6	87.0	665
Nitrogen	kg	--	--	--
Phosphorus	kg	--	--	--
Potassium	kg	--	--	--
Pesticides	kg	2.0	180.5	359
Electricity	kWh	18.0	7.5	137
Seeds	kg	92.0	--	124
Transport	--	--	--	8
Sum of Energies				2,919
Yield	kg	2159	15.85	34,112
Energy efficiency				11.7
Mass-energy ratio				740 kg/GJ

*Inputs per hectare according to 1981 survey data. Energy intensities are identical to those used throughout this study.

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APPENDIX

WEIGHTS, MEASURES AND CONVERSION FACTORS

Energy

Basic Unit = 1 joule

1 joule = 0.000 000 277 78 kilowatt-hours
= 0.000 000 372 505 horsepower-hours
= 0.000 947 8 Btu
= 0.000 238 85 kilogram-calories

1 kilogram-calorie = 4 186.7 joules
= 3.968 3 Btu
= 0.001 163 kilowatt-hours
= 0.001 559 horsepower-hours

1 British thermal unit (Btu) = 1 055.04 joules
= 0.000 293 07 kilowatt-hours
= 0.000 393 01 horsepower-hours
= 0.252 0 kilogram-calories

1 watt-second = 1 000 joules

1 kilowatt-hour = 3 600 000 joules
= 3 600 kilowatt-seconds
= 1.341 0 horsepower-hours
= 3 412 Btu
= 859.85 kilogram-calories

Power

Basic unit = 1 watt = 1 joule per second
= 0.001 341 horsepower

1 horsepower = 745.7 watts
= 10.688 kilogram-calories per minutes

1 kilowatt = 1 000 watts
= 1.341 horsepower

Linear

Basic unit = 1 metre = 3.281 feet
= 39.37 inches
= 1.094 yards
= 0.0006214 miles

Area

1 hectare = 10 000 square metres
= 2.471 acres
= 107 600 square feet

Volume

1 litre = 0.028 38 bushels (U.S. dry)
= 1 000 cubic centimetres
= 61.02 cubic inches
= 0.220 gallons (British imperial)
= 0.878 quarts

Weight

1 gram = 0.03527 ounces
= 0.002205 pounds

1 kilogram = 1 000 grams
= 2.2046 pounds
= 0.001 tons (metric)
= 0.000 984 2 tons (long)
= 0.001 102 tons (short)

Miscellaneous

1 kilometre per hour = 0.6214 miles per hour
1 tonne per hectare = 0.445 973 short tons per acre
1 kilogram per hectare = 0.892 191 pounds per acre
1 gram per hectare = 0.014 274 ounces per acre
1 section = 1 square mile
= 2.588 988 square kilometres
= 640 acres
= 259 hectares
1 bushel wheat = 60 pounds
= 27.216 kilograms
1 tonne per hectare = 14.869 8 bushels wheat per acre

International System (SI) Prefixes

Factor	Prefix	Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10^{1}	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a