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Agricultural Engineering in Support of the Kyoto Protocol

The Clean Development Mechanism for Conservation Agriculture

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Preface

The Kyoto Protocol specifies binding commitments by most industrialized countries to reduce greenhouse gas (GHG) emissions. The Clean Development Mechanism (CDM) is one of the three flexible mechanisms established under the Kyoto Protocol. The Clean Development Mechanism allows developed countries to invest indirectly in green house gas (GHG) emission reduction projects in developing countries, by buying the tradable Certified Emission Reductions (CERs). The latter can reduce their overall cost of compliance with the Kyoto Protocol commitments, while providing the CDM project hosting partners with additional funds and advanced technology. At the same time, CDM project activities contribute to sustainable development in the host developing countries. Potential for the application of CDM exists for Conservation Agriculture (CA) through reduction in fuel consumption and emission control. Conservation Agriculture involves practices such as minimum (or zero) mechanical soil disturbance, crop residue retention, permanent organic soil cover, diversified crop rotations, precise placement of agro-chemicals, in-field traffic control. The benefits of CA relate to reduced usage of fossil fuels with associate reduction in CO_2 emissions, improved soil carbon levels and carbon sequestration. CA not only contributes to the objectives of the Kyoto Protocol, but also has many other environmental benefits. Some form of CA is currently practised on 90 million ha of lands worldwide with the largest areas occurring in South and North Americas, Canada and Australia. In Asia, (e.g. India, Mongolia, China) research has been undertaken for some time, but little has been commercialised until now. CDM could be the catalyst for commercial expansion, by providing a financial incentive to farmers. This constitutes a new challenge to agriculture engineers and agronomists.

APCAEM conducts the study of the potential of CDM for Conservation Agriculture (CA). This paper provides convincing evidence of CA developments. It attempts to evaluate the comparative greenhouse impact of traditional and CA cropping systems in China, and speculates on their impact elsewhere. It concludes with a brief discussion of the measures necessary to reduce greenhouse gas production and other modes of environmental degradation by encouraging the adoption of CA. Wish you a lot of informative joy reading this report.

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Acknowledgments

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Summary

Nothing is more important to humanity than reliable food production, but the mechanization and intensification of traditional tillage-based systems has exacerbated major environmental problems, because:

1. Conventional tillage is a fossil-energy intensive process, which also accelerates oxidation of soil organic matter.
2. Conventional tillage buries residue, which is the surface soil's natural protection against erosion by wind and water.
3. Tillage and traffic cause subsurface degradation, reducing soil biological activity and promoting root zone waterlogging, which converts crop nutrients into nitrous oxide and methane -- both damaging greenhouse gases.

Conservation agriculture was originally developed to halt the soil erosion caused by traditional tillage-based agriculture (abbreviated here as TA). The first "CA1" conservation agriculture systems (correctly) identified soil tillage as a major problem, and replaced this with herbicide and other weed control measures. Fuel energy requirements are substantially reduced in this system, but fertiliser and herbicide energy requirements can increase. A number of studies have demonstrated a relatively small or even negative reduction in overall fossil energy requirement of zero tillage CA1systems as currently practiced in developed nations.

More recent research has demonstrated that field traffic (equipment wheels) are responsible for important aspects of soil degradation, and for major 'system' effects. Second phase "CA2" conservation agriculture practices such as permanent bed minimum tillage and controlled traffic farming use equipment with modular wheel track and working widths to keep all heavy wheels on compacted permanent traffic lanes, and eliminate wheel-induced soil degradation from the crop zone. Field equipment works more efficiently on hard permanent lanes, which facilitate precise and timely operation, and allow operations within growing crop. In these systems there is no requirement for tillage to repair compaction or level field surfaces.

The CA2 systems are relatively recent, but have been adopted rapidly in some areas, reducing fuel energy requirements and soil degradation, providing new options for weed control, facilitating double cropping and rotation, and eliminating the requirement to drill most fertilizer before or at planting. Importantly, these new systems also improve soil aeration and reduce waterlogging in the seed/fertiliser placement zone. Waterlogged, anaerobic conditions reduce fertilizer efficiency, and promote denitrification and production of nitrous oxide. This is a potent greenhouse gas with 310 times to global warming potential of carbon dioxide

This paper provides convincing evidence of these developments, together with information about the productivity and acceptability of CA2 systems in low-resource areas. It attempts to evaluate the comparative greenhouse impact of traditional, CA1 and CA2 cropping systems in China, and speculates on their impact elsewhere. It concludes with a brief discussion of the measures necessary to reduce greenhouse gas production and other modes of environmental degradation by encouraging the adoption of CA2.

The potential improvement in greenhouse gas emissions resulting from CA in northern China might be summarised as follows:

Evidence of the reductions in fossil fuel use when CA is applied to cereal production is clear. If field operations only are considered, then fossil fuel use would be reduced by 43% and 80% by the adoption of CA1 and CA2 systems respectively. Recent data on the energy requirements of herbicide manufacture are not available, but when the best estimates are of herbicide energy are included, CA might be expected to reduce fossil fuel energy requirements by 24% and 67% for CA1 and CA2 systems respectively, when compared with TA..

Evidence in relation to use of nitrogen fertiliser is much more complex. Nitrogen fertiliser can often be the largest single energy input to crop production, but denitrification is responsible for wasting 20 -- 60% of this input. This is severe in the waterlogged soil which occurs more commonly in the compacted root zone of CA1 systems oxide. Root zone waterlogging is common when rainfall events occur after planting, even in semi-arid environments, but its frequency and duration are substantially reduced in CA2 systems. Split fertilizer application, which will increass fertilizer efficiency and reduces pollution by closer alignment of fertilizer supply with crop demand, is much easier in CA2 systems.

Looking only at the traditionally single-cropped dryland and limited irrigation cropping areas of northern China, it appears possible the overall potential annual greenhouse impact of CA1 systems would be less than 2Mt carbon dioxide equivalent, while in permanent bed CA2 systems this value could approach 100 Mt carbon dioxide equivalent. These values are subject to one level of uncertainty related to uptake of CA2 technology. Adoption would occur only over the considerable period, but the large farmer benefits should ensure a high level was achieved. The larger level of uncertainty relates to nitrous oxide emissions from denitrification of fertilizer. This should be explored by people of greater expertise.

There is good evidence that conservation agriculture will arrest the tillage-induced decline in the soil organic matter levels, and improvements have been observed in many cases. The extent of this improvement, and its impact on atmospheric carbon dioxide levels have been widely debated, and are not considered here.

Further investigation of each of these impacts would be useful, but there can be no doubt that wider adoption of conservation agriculture would be an important benefit in terms of greenhouse gas production, and have a broader positive environmental effects.

The Clean Development Mechanism could be used to provide continuing support for research on conservation agriculture, and more importantly a vigorous program of development and demonstration, aimed at the dryland grain production systems located largely in northern Asia.

Introduction

The association between cultivation (tillage) of the soil and conventional, traditional agriculture is so well understood that the term ‘cultivation’ is commonly used as a synonym for ‘agriculture’. ‘Conservation Agriculture’ (CA) is the generic title for a set of farming practices designed to enhance the sustainability of food and fibre production by conserving soil, water and energy resources. Different labels have been used for different aspects of CA, usually emphasizing a specific difference from ' Traditional' or ‘Conventional’ agriculture.

Conservation agriculture attempts to move the crop production process closer to that of natural vegetation; by maintaining soil cover with crops or plant residues; reducing mechanical soil disturbance by tillage; restricting in-field traffic to permanent wheel tracks; and by using crop rotations or cover crops. In most parts of the world conservation agriculture can be expected to use less fossil fuel, be more productive, and more sustainable, than traditional agriculture.

There is ample evidence of these improvements, and where possible this paper uses evidence from experimental work in low resource environments such as China and Pakistan, but more detailed information is often available from research in the developed nations. For many simple physical parameters, such as the percentage reduction in energy when zero-tillage planting replaces ploughing, this is likely to be valid in most environments.

Adoption of new and improved cropping systems will occur only if they are economically attractive and appropriate to the lifestyle of farmers. This paper concludes with information on this aspect, and a discussion of the steps necessary to promote widespread adoption of conservation agriculture.

This paper covers

1. Conservation agriculture (CA) – Rationale and Development.

2. Technology and climate impacts on CA operation and effectiveness.

3. Fossil fuel use in traditional and conservation agriculture.

4. Other greenhouse-gas implications of conservation agriculture .

5. Adoption of conservation agriculture.

6. Conservation Agriculture Effects on Greenhouse Gas Emissions from North-Western China -- crude estimates.

7. Conservation agriculture -- A major opportunity for the Clean Development Mechanism.

8. References, notes and appendix.

1. Conservation Agriculture –Rationale and Development

Crop establishment requires seed zone conditions facilitating seed uptake of moisture and air, root zone conditions facilitating rapid growth, together with soil surface conditions which will not obstruct shoot emergence, in addition to minimising competition and permitting effective planter operation. These conditions are not common after harvest of a previous crop, when weeds are often growing vigorously, crop residues are often concentrated, and soil surfaces are often rutted and compacted.

In traditional systems a primary tillage operation (ploughing) is used to bury crop residues, level the surface, de-compact the upper root zone and control weeds. Shallower secondary tillage operations attempt to produce a fine tilth in the seed zone, while continuing to level the surface and control weeds. The planter's task is then to cut a seed trench of the correct depth, meter seed into it, and ensure the return of covering soil. This is easily achieved given a soft, level soil surface, unencumbered by crop residues.

Although the traditional tillage-based (TA) systems have large energy requirements, they are still very productive in environments such as northern Europe, where soil erosion is uncommon, and yields are not normally moisture-limited. Tillage can also mix and incorporate fertilisers and animal manure, and provide a short-term yield benefit by promoting oxidation of organic matter. In drier, more erosion-prone environments, however, inversion of soil by tillage promotes unnecessary moisture loss, while burying the crop residues that should protect soil from erosion by wind or water and slow soil moisture loss after rain.

Residue retention is a priority of conservation agriculture, and practical conservation agriculture started with the replacement of inverting (plough) tillage systems with non-inverting tillage. These "stubble mulch" systems were effective because surface residue volumes declined over time allowing planting to proceed with relatively conventional equipment. They also allowed farmers to gain experience with herbicides, and move toward "zero tillage" farming systems, reducing and sometimes eliminating regular tillage.

If tillage is to be eliminated while heavy wheel traffic is uncontrolled, planting equipment must also be able to operate effectively in heavy residue on compacted, rutted and uneven surfaces. This means that each row unit must be able to cut through and/or displace residue from the planting row. It must provide an adequate soil condition in the seed zone, and ensure good seed/soil contact. Individual-row depth control is usually required, and the planter must have ample under-frame clearance so residue can pass through the machine.

Zero tillage planting equipment therefore tends to be larger, heavier and more expensive, and harvester modifications are also needed to provide more uniform distribution of residues. With inadequate equipment and systems "zero" tillage has often been achieved only when the system is compromised by burning residues prior to planting. More commonly, one tillage operation is used when required for surface leveling and residue management. In some areas subsoiling is required (regularly or occasionally) to undo some of the effects of wheel compaction. These reduced or zero tillage cropping systems might be seen as the first phase of conservation agriculture (CA1).

Permanent bed controlled traffic minimum tillage systems might be seen as a second phase of conservation agriculture (CA2), overcoming the direct costs, subsurface degradation and system impacts of wheel ruts from random wheel traffic[2]. This system, known as 'controlled traffic farming'

(CTF) in the drier parts of Australia, or 'permanent raised beds' (PRB) in irrigation or high-rainfall areas requires a modular system of equipment wheel track and operating widths, and accurate guidance. Track widths of commonly available equipment dictate bed width, so these vary with region and technology level. Values of 2 m - 3 m are used in Australia, but bed widths of 0.6m – 1.5 m are more common in Pakistan, Mexico and China, where harvesting equipment often spans 2, 3 or 4 beds.*

Permanent raised beds were originally developed for furrow-irrigated cropping, but there are now many instances of permanent beds being used in dryland conditions, where beds are sometimes "raised" only in relation to the permanently compacted traffic lanes which provide an equipment guidance system. The beds are higher (in relation to the traffic lane) where they are used for irrigation or drainage. Non-wheeled soil of permanent beds has been shown to provide better aeration, greater rainfall infiltration rates and plant available water capacity. Equipment operation from firm, permanent traffic lanes improves timeliness and efficiency, while more precise guidance has facilitated zero tillage planting with simpler equipment and reduced herbicide costs.

The system aspect of permanent beds has been an important facilitator of 'opportunity cropping' where a greater range of crops is used to maximise soil moisture use via productive crops (rather than via weeds or soil evaporation from fallow). The underlying theme is that it is better to plant crops when soil moisture is adequate for emergence and short term growth, because the cost of seed and planting is usually not significantly greater than that of physical or herbicide control of the weeds that would otherwise use that moisture. If useful rainfall subsequently occurs, fertiliser can be applied. In moisture deficient zones opportunity cropping is a more economic variant of the cover cropping approach used in high rainfall zones -- particularly South America.

Permanent wheel lanes are an essential component of CA2 conservation agriculture systems. In addition to reducing fuel energy requirements of all operations, they allow access to crops during the early growth stages, and provide a more precise relationship between the crop (or its standing residue), for planting, fertilising or weed control devices. This enables valuable cropping system options such as interrow planting of the next crop, physical weed control and split fertiliser application. Each of these facilitates significant (but often indirect) pathways to reducing agricultural GHG emissions, in addition to other environmental and productivity benefits.

In developed countries, the cost of high-precision GPS guidance of farm equipment has reduced rapidly in recent years, and this option is increasingly common, but wheels or skids can also be used to follow furrows or the edges of beds. This simpler technology can easily be applied to the small-scale equipment used in developing countries, and provide an equivalent level of guidance.

Objections to permanent traffic lanes systems are often based on the idea that a percentage (often about 20%) of field area is "lost" from production in non-planted permanent traffic lanes (which often double as channels for irrigation or drainage). This ignores the fact that crop production is essentially related to sunlight, moisture and nutrients -- and these parameters are largely unaffected by permanent wheel lanes. In mechanised systems, permanent lane systems has usually demonstrated increased yield, and fears of yield loss have not been realised in practice.

* For a general information/explanation of permanent raised bed cropping systems, see Roth et al. *Evaluation and performance of permanent raised bed in systems in Asia, Australia and Mexico*. For controlled traffic farming systems, see Tullberg et al. *On Track for Sustainable Cropping in Australia.* Although these systems are not generally well known or understood, they are successfully practised over large areas in Mexico and Australia respectively.

2. Technology and Climate Impacts on CA Operation and Effectiveness

In traditional animal powered rain-fed cropping, tillage was relatively shallow and residue burial often incomplete. Various forms of zone and strip tillage systems reflected the need to minimise physical effort, ensuring that problems of soil erosion and degradation were not overwhelming. The demand for increased food production has subsequently led to intensification, and pushed cropping into more marginal areas. Development programs have encouraged mechanisation, usually providing small-scale, low-technology versions of European/North American tillage-based systems using mouldboard ploughs and rotary hoes. Soil degradation issues have often followed, and hence the concern with conservation agriculture.

The principles of conservation agriculture -- particularly the retention of crop residues for soil surface protection -- apply equally to high-technology and low-technology systems. Originally conceived to protect soil from erosion, conservation agriculture now also aims to conserve water and energy. Interest in conservation agriculture has been growing in areas such as northern China and India/Pakistan, initially under the label "conservation tillage" but progressing towards zero tillage CA1 and permanent bed CA2 systems. Published data on conservation agriculture in these areas has usually started with cooperative international projects. In most cases, the first step was importation of elements of conservation agriculture equipment from developed nations, and setting up research and demonstration units to evaluate and extend the technology.

Initial results of CA1 were often disappointing in low-resource areas, but some researchers and farmers saw the potential value of these systems, despite immediate problems of yield loss weed control and planter affordability Where combinations of individuals, communities and institutional support persisted, large-scale adoption sometimes occurred[3]. Farmers and researchers adapted and modified reduced/zero tillage equipment, experimented with herbicide weed control, and sometimes adopted permanent bed systems.

In the developed world, adoption of conservation agriculture has been very slow in areas such as northern Europe and the north eastern United States, where surface residue -- which slows soil warming in the spring -- presents a greater problem to farmers than soil erosion. Adoption of conservation agriculture was rapid only where large-scale soil erosion made the failure of traditional agriculture obvious to the whole community. Publicly-funded extension programs and financial incentives in those areas encouraged change, particularly from bare fallow to some form of residue retention.

In Australia this process took place largely in the 1970s -- 80s, by the end of which most dryland farmers were attempting to maintain some crop or residue cover during the periods of maximum erosion hazard. The first step in conservation farming was to replace full-inversion tillage (ploughing) with minimum -inversion tillage, so that residue levels were progressively reduced to allow planting with relatively conventional equipment. Subsequent development of CA1 systems saw herbicide progressively replacing most tillage operations, and planting equipment with increasing 'zero tillage' capability.

This process was driven partly by economics (cheaper herbicide and more expensive fuel), and partly by farmer's understanding that soil moisture was the limiting resource, which is wasted when moist soil is exposed by tillage. Critical aspects of this were the development of confidence in herbicide selection and application (spray application technology), and the development of seeding systems (a combination of residue management and seeders design)

By 2000, most large Australian farmers could use herbicides effectively, had a planter with some ' zero tillage' capability, and would claim this was their preferred system. They would also point out that tillage was sometimes needed to level field surfaces and deal with harvester wheel ruts, handle major weed problems or reduce residue volumes. These are issues which can be managed effectively in CA2 permanent bed/controlled traffic systems because wheel rut problems are eliminated by restricting field traffic to hard permanent lanes. Permanent lanes also reduce major weed problems by allowing more timely spraying, while greater precision reduces residue problems by allowing planting between rows of standing residue.

Controlled traffic farming research in the United States and Europe dates from the 1960s, and continued in Australia in the 1980s. Adoption on a practical scale started in Australia with a small number of enthusiasts (~10,000 ha) in the mid-1980s, but it was not until the mid-1990s that action learning research/extension programs encouraged large-scale adoption (~100,000 ha). Adoption of this second phase of conservation agriculture (CA2) has grown rapidly since then, and is now believed to be of the order of ~2Mha or >15% of Australian dryland farming[4]. CA2 systems in Australia are predominantly zero tillage, with soil disturbed only to the minimum extent necessary during the planting operations.

Adoption of CA2 cropping systems has been facilitated in Australia by the development of precision GPS guidance for field equipment. Guidance systems have become steadily cheaper over the past five years, and current units are readily transferable from tractor to harvester to sprayer. A precision RTK GPS "autosteer" system capable of guiding equipment to within 2 cm of its proper position 95% of the time now adds less than 25% to the price of a medium tractor. There are several examples of growers saving more than this in the first year of ownership simply from increased field efficiency.

Appropriate-technology CA2 permanent bed minimum tillage has been in place on a small scale for several years in research and demonstration projects in India, Pakistan and China[5]. The principles are identical to those of high-technology systems, but in this case guidance is provided simply by furrows or wheel ruts. This allows more precise targeting of fertilizer, herbicide or mechanical weed control, and re-planting with simple equipment rapidly after harvest by drilling seed into the interrow spaces of the previous crop. Farmers can also use this precision to replace selective herbicide applications with physical control of inter-row weeds (hence the label permanent bed <u>minimum</u> tillage).

Physical weed control options are particularly valuable in the low-technology environment where farmers are still learning the practice, advantages and problems of herbicide use. Physical control is most commonly a very shallow, precise, interrow tillage operation. When soil disturbance is non-inverting, and restricted to the dry surface layer, moisture loss due to exposure of moist soil is avoided, residue burial and erosion hazard is minimal, and the operation requires little energy.

Interestingly, there is also an increasing of awareness of the potential value of physical weed control options in developed countries, where the development and spread of herbicide tolerant weeds represent a significant threat to reduced/zero tillage farming. It is interesting to note that serious problems with "resistant" list of weeds have occurred first in those areas of Australia (and other developed countries) which were the first to adopt herbicides as their principal weed control measure. There is a growing conviction that occasional use of physical weed control measures might be the best way to extend the effective life of some of the most useful and economic herbicides.

3. Fossil Fuel Requirements of Traditional and Conservation Agriculture

Conservation agriculture is still developing rapidly, and its productivity and sustainability continues to improve as farmers, the farm machinery industry and scientists focus on the issues and adaptations necessary in different environments. Conventional, tillage-based agriculture has many variants, and the same applies to conservation agriculture. For the purposes of this report, three systems are considered, representing conventional traditional agricultural practice (TA), the first phase of reduced/zero tillage (CA1) and the second phase of permanent bed minimum tillage tillage (CA2).

Fertiliser (particularly nitrogen) often represents the largest single energy input to crop production, exceeding that of machinery and herbicides by a factor of 2-3. The energy impact of increased nitrogen fertilizer requirements in zero tillage systems have been cited in a number of studies as the reason that CA1 conservation agriculture has little impact on overall energy requirements of food production and/or greenhouse gas emissions. Most reports confirm that more nitrogenous fertiliser is required, at least during the TA – CA1 changeover phase. A reduction in nitrogen requirement might be expected with increased nitrogen efficiency in CA2 systems (see 4 below).

The literature provides few valid comparisons between the fuel energy requirements of different units within one system, because research funding rarely allows direct measurement of implement energy input, and tractor fuel use measurements are suspect given the normal variation in fuel efficiency with engine loading. The approach taken here is to use the mean unit draft values set out in the American Society of Agricultural and Biological Engineers "Agricultural Machinery Management Data" as an unbiased estimate of implement energy input[6], together with reasonable assumptions regarding typical levels of tractive, transmission, engine and field efficiency.

The validity of this analysis clearly depends on these assumptions, so these are specified to provide transparency, and notes explain the rationale for some of these. Details of representative systems, assumptions, and calculations of their fossil fuel requirements is presented as an Excel spreadsheet in appendix 1. Field operations required by each system are summarised in Table 1, together with the outcome of calculations on fuel energy requirement. This fuel energy requirement includes an appropriate allowance for the "overhead" energy[7] used in equipment manufacture and maintenance.

The objective of this exercise has been to provide a reasonable assessment of comparative energy use. It would not be difficult to find examples of much greater (and much smaller) energy use than those set out here, but these values are based on published data, and correspond with the author's experience in China and Australia. The data used here are applicable to modern high-technology tractors and equipment. The small tractors used in low-technology agricultural systems are considerably less fuel efficient, so fuel use might be greater (and the advantage of CA systems correspondingly larger) than indicated here. Examples of the fuel/energy use values used by other authors are included in the appendix, for comparison.

Table 1. Machinery Operations and Energy Requirements for Three Tillage Systems

Operations:	Residue Management	Tillage Frequency, Operations/crop			Herbicide Spraying	Planting	Σ Fuel Energy MJ/ha
Representative Systems		Primary	Secondary	Seedbed			
TA. Conventional tillage, no herbicide.		1	2	2	0	1	1941
CA1 Reduced/zero, < 1 tillage./crop	1	0.6	0	0	4	1	1116
CA2 Permanent bed minimum till.		0.25	0	0	3	1	397
(Tillage frequencies < 1 represent operations that do not occur every year)							

Reduced/Zero tillage agriculture usually substitutes herbicide application for fallow tillage operations. The energy requirement of herbicide application is small (1-1.5L/ha) when compared with tillage operations, but the energy value of the herbicide's constituents, and that required by the manufacturing/distribution process must also be accounted for, and is highly significant in some cases. The statements of herbicide manufacturing energy set out in table 2 for herbicides commonly-in fallow situations are based on data from from Zentner *et. al.* (2004) [7] and Green (1987) [8]. The energy requirements of CA1 zero tillage seeding are greater, because the machine must do some element of seedbed preparation in much stronger soil.

In CA2 permanent bed minimum tillage field efficiency and tractive efficiency are greater because wheels operate on permanent compacted traffic lanes, and draft is significantly reduced by the absence of wheeling on permanent beds[9]. This also reduces timeliness constraints. More importantly (but not directly relevant in the present context) aeration, infiltration rate and plant available water capacity of non-wheeled soil is greater by a factor of almost 2.

Table 2. Energy Requirements of Herbicide Manufacture

Commercial Product	Herbicide/s	Manufacturing Energy MJ/kg	Application rate kg/ha (label)	Manfacturing Energy MJ/l/ha
2,4-D Amine	2,4-D	98	0.500	49
Atrazine	Atrazine	190	0.500	95
SpraySeed 250	Diquat	400	0.115	108.1
	Paraquat	460	0.135	
Roundup CT	Glyphosate	511	0.450	229.95

Total fossil energy requirements must include energy inputs to the materials, production and distribution of the herbicide (manufacturing energy). A major difficulty here is that of deciding which herbicides would be used. Glyphosate is an attractive broad-spectrum herbicide, in view of its comparative effectiveness and safety, but it is also the most energy-intensive to manufacture. A breakthrough in manufacturing technology in 2002 is claimed to have reduced energy requirements (presumably to a value less than that quoted in table 2), but no quantitative information is available. 2, 4 D is effective only against broadleaf weeds. Atrazine is a selective, but persistent, soil-applied herbicide with high pollution potential, so it is unlikely to be recommended to inexperienced farmers. Paraquat and related products are very effective knockdown herbicides, but are unpleasant and potentially dangerous to operators.

CA1 conservation agriculture has been shown to reduce the germination opportunities for weed seeds, and to reduce the weed seedbank. Some reduction in both fallow and in-crop herbicide requirements might be expected in the longer term, but this study assumes no net change in cropping phase herbicide inputs. Improved timeliness of spray, planting and harvesting operations in CA2 permanent bed systems has been found to reduce the opportunities for weed growth, and herbicide application requirements. In this study, one less spray application is assumed here for CA2 systems.

Herbicide selection and application rate will clearly have a very large effect on the total energy requirement of minimum and permanent bed zero tillage systems of conservation agriculture. When conservation agriculture is first introduced, effectiveness and safety considerations might well ensure that glyphosate is the major herbicide used for fallow weed control. Farmers and their advisers will subsequently learn to use a larger range of herbicides and new system management techniques, to provide effective weed control with reduced herbicide costs (and energy inputs).

It appears likely that the energy requirement of herbicide manufacture will decline with improved production techniques, and improved application efficiency will further reduce the net energy input per hectare. For the purposes of this analysis, a conservative mean value of 80 MJ/ha for herbicide weed control has been assumed. This is a somewhat arbitrary estimate, but it appears to be a reasonable medium-term prospect, given improvements in herbicide manufacturing efficiency and on-farm application techniques. It is the value assumed in the summary of total fossil energy requirements set out in Table3. Fuel energy requirements of field operations are taken from the appendix.

Table 3. Machinery, Herbicide and Total Energy Requirements for Three Tillage Systems

Operations:	Resid Mgmt	Tillage Frequency			Sprays	Planting	ΣHerbicide Energy MJ/ha	Σ Fuel Energy MJ/ha	Total Energy MJ/ha	Energy saving, % TA
Representative Systems		Primy.	Secondry	Seedbed						
TA Conventional till, no herbicide.		1	2	2	0	1	0	1941	1941	/
CA1 Reduced/zero, < 1 tillage./crop	1	0.6*	0	0	4	1	320	1116	1436	26
CA2 Permanent bed minimum till		0.25*	0	0	3	1	240	397	637	67
*Tillage frequencies < 1 represent operations occurring less than once each crop –e.g surface leveling, bedforming or subsoiling										

This data demonstrates that conservation agriculture can reduce the sum of field operation and herbicide energy by 26% and 67% for CA1 and CA2 systems respectively, when compared with TA traditional, tillage-based farming systems. Because the production of a given amount of food or fibre with permanent bed minimum tillage conservation agriculture entails the use of less equipment, and that equipment is used for less hours per hectare, a reduction of at least the same magnitude might be expected in the energy requirements of equipment manufacture.

The net energy value of most petroleum fuels is in the range 40 – 45 MJ/L, which allows us to calculate a liquid fuel use equivalent to the total energy values shown in table 3, (which assumes that these values can also be applied to herbicide manufacture). The equivalent liquid fuel values can in turn be converted to a greenhouse impact statement because carbon dioxide and other greenhouse gas emissions resulting from the combustion of petroleum fuels is approximately 2.75 kg CO_2 per litre of fuel. [10].

The mean fossil impact of these systems can thus be estimated as:

TA Conventional tillage   total fossil fuel use – 48.5 L/ha   GHG emissions --133 kg CO_2 E per crop

CA1 Reduced/Zero tillage   total fossil fuel use – 35.9 L/ha   GHG emissions – 98.7 kg CO_2 E per crop

CA2 Permanent bed min till us   total fossil fuel use -- 15.9 L/ha   GHG emissions – 43.8 kg CO_2 E per crop

Clearly, different assumptions could be used to produce substantially different answers. Assumptions and methodology behind this data is set out in the Excel spreadsheet submitted with this paper, to facilitate the examination of other system options.

4. Other Greenhouse Gas Impacts of Conservation Agriculture

In addition to changing the fossil fuel requirements of cropping, changes in the crop production system might also be expected to impact soil emissions of nitrous oxide, methane and carbon dioxide. These are important, because nitrous oxide has the greatest global warming potential of any of the naturally occurring greenhouse gases (310 x greater than CO_2). Methane is a product of anaerobic decomposition of soil organic matter. Carbon dioxide is produced directly by the oxidation of soil organic matter, and there is good evidence that its production is accelerated by tillage.

There is equally good evidence that reduced and zero tillage cropping systems will reduce or reverse the long-established decline in the organic matter content of cropping soils, which must involve an increase in net CO_2 absorption (when compared with conventional tillage). This evidence is unanimous in the case of sub-tropical soils in which organic matter levels have been monitored from the date when they were first converted from forestry or pasture to cropping.

I claim no particular expertise on this topic, but independent monitoring of soil organic matter in one of my own experiments recently demonstrated a statistically significant improvement of 0.3% soil organic matter between TA tilled and CA2 conservation agriculture plots after six years permanent bed zero tillage[11]. The same work showed that earthworm numbers, and soil biological activity in general increased by a factor of between two and four when CA2 permanent bed zero tillage cropping replaced traditional practice.

The more significant change in greenhouse gas emissions is likely to occur as a result of improvements in nitrogen fertilizer efficiency, and reductions in nitrous oxide emissions brought about by two mechanisms:

a) Improved soil structure and greater porosity and permeability of seed zones and root zones in CA2 permanent bed minimum tillage conservation agriculture will reduce the extent of waterlogging of the zone where seed and fertilizer reside, and thus reduce ***denitrification*** and nitrous oxide production.
b) The ability to access growing crops without damaging them, and precisely drill fertilizer in the interrows of narrow-spaced crops will greatly improve the alignment of fertilizer supply with crop demand. ***Split fertilizer application*** will reduce the current inefficient and greenhouse-unfriendly requirement to apply most fertilizer at or pre-planting, or post-planting surface broadcasting.

There is an extensive literature on nitrogen fertilizer dynamics and efficiency, the interpretation of which is better left to experts in this field. Some of the important ideas of this topic have been reported by Dalal et al.[12] and summarized by Eckard and Armstrong[13]. What is clear is that nitrogen efficiency and denitrification are closely related to soil moisture status, and the residence time of some nitrogen fertilizers in the soil.

a) ***Denitrification*** occurs rapidly when air-filled porosity of the soil is in particular ranges, and commonly those exceeding field capacity (ie at or approaching waterlogging) and results in much greater production of nitrous oxide gas than the normal aerobic process. It is much more common in modern agriculture than in natural systems, due to the combination of nitrogen fertilizers with cultural practices promoting waterlogging. The greenhouse gas dimensions of this can be illustrated considering that when nitrogenous fertilisers are applied at a rate that will optimise yield, application rates are usually greater than 100 kg N/ha. Conversion of fertiliser N to plant available nitrate can occur via a number of complex bacterial pathways, which always involves some denitrification loss of N[14].

Denitrification commonly involves a loss of 20 -- 60% of applied nitrogen and this loss is significantly greater in compacted soils[15]. It is particularly severe in waterlogged soils, where a substantial proportion of N loss is emitted from soil as nitrous oxide N_2O, a potent greenhouse gas. Data on this topic is very limited, but it could be reasonable to assume that 50% of N lost is converted to nitrous oxide. With an application rate of 100 kg N/hectare and 40% denitrification, this could account for 0.4 x 100 = 40 kg N/ha. 50% of this -- 20 kg -- might be converted to nitrous oxide

Greater soil porosity reduces the frequency and duration of waterlogging, so CA1 permanent bed conservation agriculture might reduce denitrification by 50%, or by 10 kg N/ha. The atomic weight of nitrogen is 14, and oxygen 16, so when 10 kg of fertiliser nitrogen (N) is converted to N_2O, the N_2O emitted = (14+14+16)/(14+14) = 15.7 kg. The global warming potential of N_2O is 310 times that of the major greenhouse gas, carbon dioxide (CO_2), so 10 kg of N lost is equivalent to 4870 kg CO_2E.

If these assumptions are correct, permanent bed conservation agriculture will reduce greenhouse gas emissions due to denitrification by almost 5000 kg/ha CO2E/crop. A brief survey of the literature on this topic suggested a unanimous view that nitrogen use efficiency was smaller, and denitrification greater in more compact, zero tilled soil. Unfortunately there is little quantative information, but even if the calculation here overestimates denitrification by a factor of 10, the greenhouse gas impact of the change in nitrous oxide emissions is still large compared with that of fossil fuel.

Impact calculations presented below and in table 4 are based on arbitrary but reasonable assumptions that soil which is still compacted at planting time will produce 2000 kg/ha CO2E/crop greater emission. This is the likely outcome with both CA1 zero tillage and traditional tillage-based (TA) systems. In permanent bed CA2 systems no fertiliser is applied to compacted soil, so this can be regarded as the base line for comparison.

Denitrification represents a greenhouse gas problem, while loss as a nitrate solution in runoff or deep percolation represents a pollution threat to watercourse or underground water supplies. This loss of fertilizer also represents substantial economic cost to the farmer. CA2 systems should reduce this loss both by two mechanisms: reducing compaction and waterlogging of the seed zone, and facilitating spatial and temporal fertilizing to correspond more closely with crop needs (ie split applications, rather than all at planting).

Methane, a product of anaerobic decomposition of soil organic matter, can also be a very significant greenhouse gas (21 x greater than CO_2). The increased organic matter levels in conservation agriculture could promote methane production, but this should be more of than balanced by the lower frequency and duration of anaerobic conditions (waterlogging).

b). ***Split fertilizer application*** will provide better alignment between fertilizer inputs and crop requirements, and thus reduce the time in which excess nitrogen is available for denitrification or loss by deep percolation. It is rare at present, because fertilizer application post-planting is either expensive (foliar application) for extremely inefficient (surface broadcasting). In CA2 systems precision interrow fertilizer drilling will overcome these problems.

5. Adoption of Conservation Agriculture

The ideas of conservation agriculture are deceptively simple, so farmers' reluctance to change has often surprised scientists and administrators. Farmers everywhere are cautious about change, and conservation agriculture requires radical change in thinking, and in most aspects of farming practice. New systems bring new challenges, often related to highly practical, but unforeseen aspects of equipment operation. When immediate solutions are not available yield loss is likely, and this is very common in the first year of conservation agriculture.

This is particularly frustrating for the "good" farmers who have mastered the traditional system, and expect similar results from conservation agriculture. The outcome can sometimes be widespread disillusion with the new system and its advocates.

Some aspects of conservation agriculture were widely adopted in the drier areas of developed nations such as Australia, and western North America from the 1950s onwards. CA1 stubble mulching occurred from the 1940s to the 80s, driven initially by the demonstrable need to reduce soil erosion, and subsequently by a combination of increasing fuel costs and reducing herbicide costs in the 80s/90s. From the 1990s, CA2 permanent bed controlled traffic systems in Australia have been driven by recognition of the system impacts of wheel damage to soil. The approach was summarised in the farmer comment "zero tillage benefits occur only under controlled traffic ".

It is important to recognize the substantial grass-roots learning process that is an essential component of all conservation agriculture. Some aspects of this -- such as the selection and use of herbicides -- are obvious, and can be supported by training. Other aspects are more subtle, and depend on individual observation and learning. These include a number of important practical issues of (for example) residue management, and recognition of system advantages, such as the potential for opportunity cropping and changes in the weed spectrum.

Wide variations occur within and between regions and industries. In Australia, for instance, some sort of conservation agriculture is practised in most extensive grain production, with herbicide progressively replacing stubble-mulch tillage. Most grain farmers now prefer to avoid tillage, except when dealing with harvester ruts, or difficult situations with weeds or residue. A growing number (>15%) are using CTF (controlled traffic zero tillage) permanent bed systems. This 15% includes a large proportion of the large, technologically-aware leading farmers, in addition to the early adopters, so the agricultural extension and consulting community has started to understand that CA 2 systems will be a prerequisite of productive and sustainable cropping.

CA2 systems have been adopted more rapidly in Australia than the USA or northern Europe. This has occurred without significant support from government extension organisations -- perhaps because the farmer benefits are clearer in a more severe, moisture-limited environment. In the absence of production subsidies, the improved economics of CA also increase the incentive for change.

In low resource areas such as northern China, India/Pakistan and northeast Russia, interest in conservation agriculture generally started only after mechanisation, often with cooperative international projects. In many cases the first step was importation of elements of CA1 conservation agriculture equipment from developed nations, and setting up research and demonstration units to evaluate and extend the technology. Initial results of this first phase were disappointing unless people persisted in learning and adapting the new system.

CA2 permanent bed minimum tillage agriculture has been in place on a small scale for some time with research and demonstration projects in India, Pakistan and China. These systems have increased productivity, while reducing soil loss and degradation, capital equipment requirements and energy input. They provide an easier approach to zero-tillage conservation agriculture, by facilitating a precise, shallow minimum tillage weed control option. This is important in reducing the barrier to adoption presented by a total dependence on herbicides.

There is clearly great potential for the adoption of CE 2 systems throughout the developing nations, and particularly in the more arid low-resource areas of North Asia. CE 2 systems will enhance productivity while meeting the growing community demand for environmental protection. North China, Mongolia and Eastern Russia all present opportunities for this technology.

6. Conservation Agriculture Effects on Greenhouse Gas Emissions from North-Western China

North China has used as an example here, because of the authors experience in that area, and the availability of data on areas of dryland single cropping (33 Mha) and single cropping with limited irrigation (7Mha). These values were provided by Prof Li Hongwen of the Conservation Farming Centre at China Agricultural University. Beijing(E Campus).

Table 4. Greenhouse impact of conservation agriculture in Northern China

			TA	CA1	CA2
Fossil fuel	kg/ha CO2E	Per Crop	133	98.7	43.8
Emission reduction	"	"		34.3	89.2
Nitrous oxide	"	"	2000	2000	0
Emission reduction	"	"		0	2000
Total Impact/ha	"	"	0	34.3	2089.2
Single dryland crop Mha		33			
Annual Emission		Mt CO2E	0.0	1.1	68.9
Potenial double crop* Mha		7			
Annual Emission		Mt CO2E	0.0	0.5	21.9
Total Annual Impact		Mt CO2E	0	1.6	90.9
*with limited irrigation		Cropping	Single	X 1.5	Double

Estimates of total gross impact are necessarily crude multiplications of available area and impact per hectare. It is assumed that most of the single crop area will be restricted to that by rainfall limitations, but conservation agriculture does improve water use efficiency and the potential for double cropping, particularly when growers take advantage of the timeliness benefits of CA2 systems. For present purposes, it has been assumed that the area currently in single cropping with limited irrigation has the potential of 1.5 crops per year under CA1, and two crops per year under CA2.

As noted earlier, the fossil fuel outcome is based on reliable field data and published information on herbicides, and is certainly achievable, but this represents roughly 10% of the mean effect presented here. There is little point in greater sophistication when the major input parameter -- nitrous oxide emissions -- are so uncertain. On the basis of data currently available, it would be possible to argue that the nitrous oxide emission outcomes for conservation agriculture should be three times greater, or three times smaller than those quoted here. Greater expertise in mine is required for this purpose.

7. Conservation Agriculture – a Major Opportunity for the Clean Development Mechanism

Adoption of conservation agriculture has been slow even in developed nations with good agricultural extension services and well-educated farmers. Significant effort will be needed to foster the adoption of conservation agriculture in low-resource areas. This has the potential to provide large, long-term positive environmental effects, but it will require long-term investment in research, development, demonstration and extension to farmers, their suppliers and information networks[3].

CA2 conservation agriculture will provide significant and provable reductions in GHG emissions via reduced mechanical energy inputs. Research demonstrating the mechanisms of large GHG emission reductions as a result of improved nitrogen fertilizer efficiency is already available, but has not yet been brought together to demonstrate the integrated effect of CA2 systems. Some of the initial research requirement might usefully be carried on in the developed nations, particularly in relation to conservation agriculture impact on waterlogging and split fertilizer application, and the consequent effects on nitrogen use efficiency, nitrous oxide and methane emissions. Involvement of developing nation scientists in this work would be critical.

Most research activity should be carried out within the target areas, aligned with a simultaneous machinery development and technology extension program appropriate to the local scale and technology level, perhaps assisted by cooperative international research, development and demonstration projects.

One major objective of this research program would be to provide locally-relevant information to support adoption. A second major objective should be to nurture a cohort of broadly-trained field agronomists and mechanisation specialists to be the core of an ongoing demonstration and extension program. This could be built around the loan of small-scale equipment allowing local farmers to operate demonstration/extension sites, monitor inputs and outputs, and build their confidence in this technology.

This would appear highly appropriate for funding under the Clean Development Mechanism.

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Appendix 1; Fuel and Herbicide requirements of Cropping Operations

Traditional Tillage

		Residue management		Tillage-primary		Tillage-secondary			Spraying	Planting
Fine soils		Chopping	Subsoiling	Moudboard	Chisel	Chisel	Disc	Harrow		
	Depth cm			15	12	10	8	5		5
Frequency	Ops/crop			1		1	1	2		1
Unit Draft	kN/m			10.0	6.0	5.0	4.0	2.5		2.0
Drawbar Energy	MJ/ha			100.0	60.0	50.0	40.0	25.0		20.0
Tractive Efficiency	%			75.0	75.0	70.0	70.0	70.0		70.0
Axle Energy	MJ/ha			133.3	80.0	71.4	57.1	35.7		28.6
Transmission Efficy.	%			85.0	85.0	86.0	87.0	88.0		90.0
Engine Output	MJ/ha			156.9	94.1	83.1	65.7	40.6		31.7
Engine efficiency	%			30.0	30.0	31.0	32.0	33.0		35.0
Energy Input	MJ/ha			522.9	313.7	267.9	205.3	123.0		90.7
Energy "Overhead"	%			15	15	15	15	15		20
Field Efficiency	%			80.0	80.0	80.0	80.0	80.0		70.0
Total energy	MJ/ha			751.6	451.0	385.1	295.1	176.8		155.5
Fuel requirement	L/ha			18.8	11.3	9.6	7.4	4.4		3.9
							Grand Totals		**Energy**	**1940.9**
									Fuel	**48.5**

Reduced/Zero Tillage

		Residue management chopping A		Tillage-primary		Tillage-secondary			Spraying A	Planting
			Subsoiling	Moudboard	Chisel	Chisel	Disc	Harrow		
Fuel Use	l/ha	4							1.5	
Tillage Depth	mm		30	15	12	10	8	5		5
Frequency	Ops/crop	1	0.2		0.4				3	1
Unit Draft	kN/m		16.0	10.0	6.0	5.0	4.0	2.5		4.0
Drawbar Energy	MJ/ha		160.0	100.0	60.0	50.0	40.0	25.0		40.0
Tractive Efficiency	%		75.0	75.0	75.0	75.0	75.0	75.0		75.0
Axle Energy	MJ/ha		213.3	133.3	80.0	66.7	53.3	33.3		53.3
Transmission Efficy.	%		84.0	85.0	85.0	86.0	87.0	88.0		90.0
Engine Output	MJ/ha		254.0	156.9	94.1	77.5	61.3	37.9		59.3
Engine efficiency	%		29.0	30.0	30.0	31.0	32.0	33.0		35.0
Energy Input	MJ/ha		875.8	522.9	313.7	250.1	191.6	114.8		169.3
Energy "Overhead"	%		15	15	15	15	15	15	30	20
Field Efficiency	%		80.0	80.0	80.0	80.0	80.0	80.0		70.0
Total energy	MJ/ha	160	1258.9	751.6	451.0	359.5	275.4	165.0	78.0	290.2
Fuel requirement	L/ha	4.0	31.5	18.8	11.3	9.0	6.9	4.1	2.0	7.3
							Grand Totals		**Energy**	**1116.4**
									Fuel	**27.9**

Permanent Bed Minimum/Zero Tillage

		Residue management		Tillage-primary		Tillage-secondary			Spraying A	Planting
		chopping	Bedforming	Moudboard	Chisel	Chisel	Disc	Harrow		
Fuel Use	l/ha								1	
Tillage Depth	mm		30	15	12	10	8	5		5
Frequency	Ops/crop	0	0.25	0	0	0	0	0	3	1
Unit Draft	kN/m		7.0	10.0	6.0	5.0	4.0	2.5		2.0
Drawbar Energy	MJ/ha		70.0	100.0	60.0	50.0	40.0	25.0		20.0
Tractive Efficiency B	%		80.0	80.0	80.0	80.0	80.0	80.0		80.0

Axle Energy	MJ/ha	87.5	125.0	75.0	62.5	50.0	31.3		25.0
Transmission Efficy.	%	84.0	85.0	85.0	86.0	87.0	88.0		90.0
Engine Output	MJ/ha	104.2	147.1	88.2	72.7	57.5	35.5		27.8
Engine efficiency	%	29.0	30.0	30.0	31.0	32.0	33.0		35.0
Energy Input	MJ/ha	359.2	490.2	294.1	234.4	179.6	107.6		79.4
Energy "Overhead"	%	15	15	15	15	15	15	30	20
Field Efficiency B	%	85.0	85.0	85.0	85.0	85.0	85.0		80.0
Total energy	MJ/ha	486.0	663.2	397.9	317.2	243.0	145.6	52.0	119.0
Fuel requirement	L/ha	14.3	19.6	11.7	9.4	7.2	4.3	1.0	3.5
						Grand Totals		**Energy**	**396.5**
								Fuel	**10.1**

Process: Unit draft is a direct measure of mechanical energy input to the soil by drafts implements, easily converted to energy/ha.
Tractive efficiency, transmission efficiency, and engine efficiency are used to calculate total engine energy requirement.
Field efficiency and energy overhead account for additional losses, and energy for equipment manufacture, respectively.
Fuel requirement per operation calculated as total energy/40 (approximate fuel net energy -- MJ/L)
Grand total energy (MJ/ha) and fuel(L/ha) take account of the frequency of that operation (number of times per crop)

Notes A Chopping and spraying are both quoted as simple mean fuel requirement/ha from survey data

B Tractive efficiency and field efficiency improved by at least 5% in permanent bed systems.

Miscellaneous Data

1 L Diesel fuel = 2.75 kg CO^2 Equivalent (Australian greenhouse office)

Fuel consumption, direct and overhead energy values for various tillage implements Lobb D (1989)

Implement	**Fuel consumption**[1] (1/ha)	**Operating Energy** [2](MJ/ha)	**Overhead Energy**[3](MJ/ha)	**Total Energy** (MJ/ha)
Mouldboard plough	12.35	557.1	66.8	624.0
Chisel plough	9.21	415.5	49.9	465.4
Disk harrow	6.51	293.7	35.2	328.9
Cultivator	4.04	182.2	21.9	204.1
Inter-row cultivator	3.59	161.9	19.4	181.3
Rotary hoe (non-powered)	2.90	130.8	18.3	149.1
Adapted Lobb 1989, cited 17.				

[1]Equivalent fuel energy expressed as fuel consumption per ha
[2]Energy value expressed as the fuel energy required to perform each operation.

Mean fuel consumption of tillage operations, Queensland Department of Primary Industries (2004)

Subsoiler 20cm	24.1 L/ha
Chisel plow	9.8
Bed former	8.6
Offset disc	9.6
Planter (zero till or conventional)	6.1
Sprayer	1.4