Evaluating options to reduce greenhouse gas emissions from an Australian temperate wheat cropping system.

S. Mark Howden[1] and Garry J. O'Leary[2]

1 Bureau of Resource Sciences, P.O. Box E11, Queen Victoria Terrace, ACT, 2600
2 Victorian Institute for Dryland Agriculture, PB 260, Horsham, Vic. 3400

Abstract. Increases in atmospheric concentrations of greenhouse gases are thought to be likely to result in changes to global climate. Australia, as a signatory to the Climate Change Convention, has agreed to stabilise emissions of these gases at 1990 levels. Therefore, there is a need to identify options that may reduce emissions from all industry sectors including those emissions arising from agricultural activities such as wheat cropping. The wheat cropping systems of the Wimmera region of Victoria studied here are likely to be significant net emitters of greenhouse gases with average annual emissions equivalent to 1350 to 2150 kg of carbon dioxide per hectare. Choosing stubble retention wheat cropping systems could reduce the average net emissions per hectare by up to 37% depending on the systems used. More importantly though, the stubble retention cropping systems which have lower emissions also tend to have greater yields, and thus may produce up to four times the grain yield per unit emissions than other systems such as conventionally tilled, continuous wheat. This indicates that there is significant potential to adapt wheat cropping systems to reduce greenhouse gas emissions in a cost effective way. This capability may be enhanced by tactical management decisions that change fertiliser inputs depending on soil moisture levels at sowing or on seasonal forecasts based on factors such as the Southern Oscillation Index. This approach is also likely to have financial and risk management benefits. Loss of soil carbon was the most substantial component of the emissions budget for all cropping systems, followed by nitrous oxide emissions (from 12 to 42% of total emissions) with methane forming a relatively small component (from 0.003 to 17%). Emissions from fossil fuel combustion (from 0.8 to 8%) and from burning crop stubble (from 0 to 20%) formed relatively small components of the emissions budget. Policy issues are discussed including the removal of barriers to adoption of the more sustainable, low-emission systems identified in this study.

1. INTRODUCTION

The atmospheric concentrations of radiatively-active (or 'greenhouse') gases such as carbon dioxide, methane and nitrous oxide have increased markedly over the past 100 years, largely through human activities such as burning fossil fuels, land clearing and increased agricultural production. The increasing atmospheric concentrations of these gases are now considered to have the potential to cause changes in global climate (IPCC 1994). Along with most other developed nations, Australia has made a commitment to stabilising greenhouse gas emissions through signing the Framework Convention on Climate Change. The recent First Conference of the Parties to the Convention raised the possibility of binding emission-reduction targets and timetables for developed nations including Australia. However, the Australian Government recognises that the measures in the National Greenhouse Response Strategy (1992) and the 21C package (Anon 1995) released earlier this year will not by themselves close the 'gap' needed just to stabilise emissions. Therefore, there is a need to identify further activities that may contribute to reducing Australia's net greenhouse gas emissions.

The National Greenhouse Gas Inventory (NGGI 1994) indicates that about 40% of the national net emissions occur through the activities of the Australian rural industries, both directly (e.g. methane from livestock, nitrous oxide emissions from fertilisers, soil carbon rundown in pastures), and indirectly (e.g. through activities such as land clearing), although it is recognised that large uncertainties surround land clearing which forms a significant component of these emissions. Whilst agriculture and related activities are significant contributors to emissions, there are opportunities for emission reductions. Previous studies (e.g. Howden *et al.* 1994) suggest that policies designed specifically to reduce greenhouse gas emissions from agriculture should concentrate first on encouraging the adoption of low emission technologies and management and the buildup of carbon sinks. These activities are often closely related to the adoption of sustainable land management practices. For example, Tongway and Ludwig (1994) show that rehabilitation of degraded grazing lands can result in substantial increases in soil carbon, and Ash *et al.* (1995) have suggested that rehabilitation could sequester about 440Mt of carbon in the northern Australian grazing lands alone. Howden *et al.* (1994) similarly suggest that there are options that could reduce net greenhouse gas emissions from tropical and temperate grazing systems that may increase the sustainability of these systems. In cropping systems, many studies (e.g. Li *et al.* 1995) suggest that conservation tillage can result in large-scale carbon sequestration whilst more conventional tillage practices may result in further run-down of soil carbon stores. Hamblin (1991) estimated that such management changes could result in an annual reduction of 10Mt of Australian carbon emissions.

Wheat cropping systems can be sources of carbon dioxide emissions through the run-down of soil carbon and other, more transient carbon stores such as litter, through stubble burning and through fossil fuel combustion during tilling and other operations. However, these systems can also act as sinks for carbon dioxide (CO_2) if soil carbon is increased through practices such as conservation tillage and reduction in stubble burning. These systems are also sources of methane (CH_4) through stubble burning and fossil fuel combustion, and are also sources of nitrous oxide (N_2O) through fertiliser application, the denitrification of soil nitrogen store, and from stubble burning and fossil fuel combustion.

This paper describes a framework for evaluating the effects of different management systems on greenhouse gas emissions and the long term carbon balance in the wheat cropping systems of the Wimmera region of western Victoria. A fallow-wheat crop simulation model (O'Leary, 1994) was used to estimate the likely changes in CO_2, CH_4 and N_2O emissions and soil C levels as a consequence of stubble retention, zero tillage and use of nitrogen fertilisation so as to develop recommendations as to likely least-cost ways to reduce greenhouse gas emissions.

2. MODIFYING A WHEAT CROPPING MODEL TO INCLUDE SOURCES, SINKS AND STORAGES OF GREENHOUSE GASES

2.1 Description of the fallow-wheat model

The model describes the growth and development of wheat in a fallow-wheat dryland cropping system with special reference to conservation tillage systems. The model is a revision of a previously published model (O'Leary *et al.* 1985), and now includes a treatment of soil water and nitrogen as affected by conservation tillage methods (O'Leary 1994). Its particular strength is that it defines the component processes in a compartmental manner. The model is designed to run either as single-year or multi-year scenarios with multiple management options.

The model has 27 state variables grouped into six sub-models, viz. soil water, soil carbon, soil nitrogen, crop biomass, crop nitrogen and phenology with two further modules on environment and management. It runs on a daily time-step.

Carbon enters the system through crop growth and nitrogen is added through atmospheric deposition and through fertiliser, when used. The carbon and nitrogen from the crop enter the soil through the decomposition of crop residues and root biomass. The soil carbon and nitrogen models use four main pools: fresh organic matter, microbial biomass, humic material and surface residues. Transfers between these pools and the crop occur with complex interactions. Temperature, soil oxygen and water content, tillage, soil type, C:N ratios and maintenance respiration demands of soil biomass all influence the rates of transfers between soil pools. There is also release of CO_2, NH_3 and denitrified N to the atmosphere. There is also a range of products produced during the burning of crop residues.

Net emissions of carbon dioxide were calculated as the difference between carbon dioxide emissions and the carbon dioxide absorbed from the atmosphere during growth.

The model does not distinguish between the release of N_2 and N_2O through denitrification. The relative proportions of N_2 and N_2O emitted can vary considerably. However, Duxbury (1984) found that in most cases, less than 20% of the emitted nitrogen was in the form of N_2O. The high clay content of the soils in the Wimmera region are likely to reduce this proportion further as the N_2O is adsorbed more strongly on to clay particles than is N_2 (Li *et al.* 1992). Thus an assumption was made for all management treatments that 10% of the losses of N through denitrification were emitted as N_2O. This empirical approach is inadequate in that different management treatments are likely to result in varying ratios of N_2O: N_2 due to differences in carbon substrate availability, nitrogen transfers, soil water content and temperature. However, sensitivity analyses showed that a wide range of ratios did not affect the thrust of the conclusions of this study. More effective simulation of N_2O emissions may be achieved through incorporation of routines from a model such as that of Li *et al.* (1992) which simulates population dynamics of both nitrifying and denitrifying organisms. However, there would remain a need to calibrate and then validate the completed model for a wide range of Australian wheat cropping situations.

2.2 Burning

Burning is a common management practice in the management of these wheat cropping systems. It is used to remove stubble to facilitate tilling operations and for the control of some diseases. Burning thus occurs only in the WWCT and NSCT treatments (described later). Of the carbon that was released from the crop residues, 0.35% was released as methane with the remainder released as carbon dioxide, carbon monoxide or non-methane volatile compounds (NGGI 1994). Of the nitrogen released, 0.76% was in the form of nitrous oxide with the remainder as NO_x or N_2.

2.3 Fossil fuel emissions

The wide variation in crop management results in substantial differences in the energy requirements for cultivation. This is due to variations in the number of operations, tractor and implement combinations, and the fuel demands imposed by the nature of the material being cultivated (Huzzey 1986). For example, conventional cultivation, particularly of retained stubble, requires much more fuel than the herbicide spraying operations in the zero tillage treatments. Energy requirements for the individual management treatments were drawn from Huzzey (1986). Carbon dioxide, methane and nitrous oxide emissions from the combustion of this fuel were calculated using the relationships in NGGI (1994)

2.4 Global warming potentials

Gases vary in their radiative activity and in their atmospheric residence time. To allow for these differences, relative Global Warming Potentials (GWPs) have been calculated for the common greenhouse gases (IPCC 1994). These represent the relative warming effect of a unit mass of the gas when compared with the same mass of carbon dioxide over a specified period. The relative GWPs used in this study were the 100-year integration period values given by IPCC (1994) for carbon dioxide (1), methane (24.5) and nitrous oxide (320). However, it should be noted that these cropping systems produce carbon monoxide, non-methane volatile hydrocarbons and NO_x, all of which are recognised as greenhouse gases but for which GWPs have not yet been assigned. Inclusion of these gases in the emissions budget of these cropping systems will slightly alter the results.

2.5 Validation

The model has been validated for soil moisture, total mineral nitrogen, biomass accumulation, grain yield and other agronomic variables (O'Leary 1994). However, some aspects of the soil carbon/nitrogen model have not been validated for the Wimmera cropping systems. Validation of this application of the complete model would be difficult because of 1) the large number of variables, the difficulty of measuring many of these, 2) the long time-frame needed for sampling due to large seasonal variations in climate and some lags in system response to climate and management (see Table 2), and 3) the large number of treatments needed to cover the range of options to be investigated. Given the considerable time and cost that would be involved in establishing such an experimental program, it is unlikely to be supported. However, the effectiveness of the model in simulating biomass accumulation and total mineral nitrogen which form the basis of the carbon and nitrogen flows, suggests that some confidence can be attributed to the results. In view of this, an exploratory study was conducted. This is outlined below.

3. EXPLORATORY STUDY

An exploratory study was undertaken with the modified model using eight simulation experiments. These were conducted using 100 years of synthetic weather data generated from long-term statistics from Dooen, Victoria (Lat. 36° 40'S. Long. 142° 18'E. Elev. 155m) using the weather generator SIMMETEO (Geng *et al.* 1988) which was derived from WGEN (Richardson and Wright 1984). The soil type is a chromic vertisol (grey cracking clay, Ug5.2; Northcote 1979) that is representative of the major soil type of the Wimmera region of Victoria. All simulations were continuous from year to year for a 100 year period to highlight trends in time that might be important in the management of greenhouse gas emissions. Sowing time was simulated by the method of Hammer and Goyne (1982) which provides a window of sowing opportunity based upon time of year and pre-sowing rainfall (O'Leary 1994).

Net emissions of CO_2 and emissions of CH_4 and N_2O from all sources were recorded in each simulation treatment and adjusted using GWPs to give CO_2 equivalent emissions.

Eight treatments were chosen for the simulations to investigate the effects of continuous cropping vs fallow cropping, stubble retention vs stubble burning, conventional cultivation vs zero till management and fertiliser addition (Table 1). These are addressed in more detail below.

Table 1 Cropping systems used in the simulations. All systems were simulated with or without the application of fertiliser at the rate of 40kg N at sowing time.

WWCT	Continuous wheat cropping system with crops planted each year. No stubble retained and conventional cultivation practiced.
NSCT	Fallow cropping system with an 18 month fallow following previous crops. No stubble retained and conventional cultivation used.
SRCT	Continuous cropping with stubble retained between crops. Conventional cultivation is used for weed control.
SRZT	Fallow cropping system with stubble retained between crops and zero tillage used (i.e. weed control through herbicide application)

In semi-arid environments where water supply is the major factor limiting grain yield, such as in the Wimmera region of Victoria, the agronomic option of fallowing provides a way to increase both water and nitrogen supplies. The fallow represents that period between the harvest of a preceding crop and the time of sowing of the next crop. Its length of about 18 months is typical for crops with high water demands like wheat and canola in the Wimmera. Fallowing has been widely practiced in the past, but continuous cropping without such a long fallow is becoming more popular as the choice of available crops increase (e.g. grain legumes and oilseed crops). Fallow-wheat systems would have occupied less than 20% of the land area of the Wimmera in recent years. Simulations were run of fallow-wheat systems (NSCT and SRZT treatments) where wheat is sown every second year and continuous wheat cropping systems (WWCT and SRCT) where wheat is sown every year. Each of these treatments was repeated with and without 40 kg N/ha fertiliser applied near sowing time (Day 160) in each wheat crop.

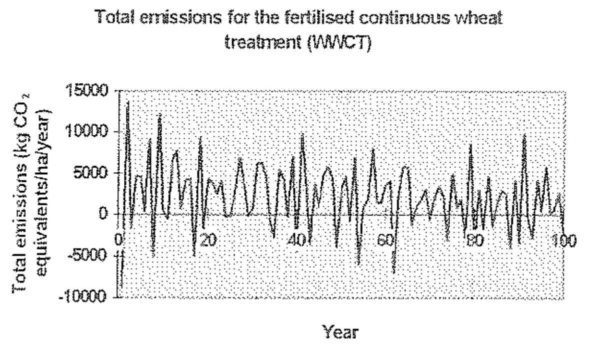

Fig. 1 Total annual emissions (kg CO_2 equivalents/ha/year) over the 100 year study period for the fertilised continuous wheat system (WWCT +N)

Stubble retention is a further agronomic practice that can conserve water. Two tillage systems where stubble from the previous wheat crop was retained (SR) were studied viz. SRCT and SRZT, whilst in the other treatments the crop stubble was removed through burning (WWCT and NSCT).

Conventional tillage practices (CT) were used in three treatments, consisting of up to 7 tillage passes with a scarifier/chisel plough for weed control during the period between crops. Zero-tillage (ZT) is where herbicides are used to control weeds without tillage, and this is normally used only in conjunction with stubble retention (i.e. SRZT).

3.1 Initial conditions

In the first year, the initial level of stubble was set at 4 t/ha with timing of tillage in both NSCT and SRCT fallows fixed in each fallow period on days 247, 310, 356, 64, 104, 110 and 155 regardless of weed growth, for simplicity. Fallows in the Wimmera may be tilled up to 12 times in some years. Where stubble was not to be retained it was burnt on Day 120, to coincide with when fire restrictions are usually lifted. Initial soil water, nitrogen and carbon levels were used as measured in a field experiment in the same tillage and rotation regimes at Dooen in 1987 and 1988 (O'Leary 1994).

4. RESULTS

Simulated net greenhouse gas emissions showed considerable variation between cropping cycles and between management treatments (Fig. 1). During wetter, more productive cropping cycles, the system was a significant net sink for greenhouse gases (often up to 5t CO_2 equivalents/ha) with this occurring more frequently in the conventional tillage systems than the zero-till systems. However, in most cropping cycles, the system was a significant net emitter (often more than 6t CO_2 equivalents/ha).

Average annual net emissions varied significantly across the different management treatments (Fig. 2). The treatments with no stubble retention (WWCT and NSCT) had emissions ranging from about 1940 to 2150 kg CO_2 equivalents/ha/year, whilst those with stubble retention (SRCT and SRZT) had lower emission rates ranging from 1350 to 1730 kg CO_2equivalents/ha/year.

The majority of the net emissions from the cropping systems were derived from the loss of carbon from the system in the form of CO_2 (Fig. 2). The size of this loss was significantly lower for the stubble retention treatments (SRCT and SRZT) than for the other treatments. Nitrous oxide was the next most significant gas emitted, comprising from 15% (SRCT -N) to 41% (SRZT +N) of the total emissions. Fertilisation increased N_2O emissions for all cropping systems but in the stubble retention treatments, there was a small compensatory reduction in carbon loss. Emissions of methane were small in all treatments with significant emissions (up to 5.6%) occurring only when burning was practiced.

There was significant variation in grain yields between the different treatments. This, combined with the variation in net emissions, resulted in almost four-fold variations in the ratio of grain yield to total emissions. This ratio ranged from 0.57 for the NSCT -N treatment to 2.21 for the SRCT +N treatment (Fig. 3). Fertiliser application had a smaller impact than tillage treatment but generally increased the ratio, with this effect being substantial only in the continuous wheat (WWCT) and stubble-retained/conventional tillage (SRCT) systems.

There were significant negative correlations between yield and net emissions for all treatments except NSCT -N, although for some treatments (WWCT -N, SRCT -N and the NSCT treatments) there was a positive correlation between yield and net emissions in the following year. This relationship being stronger than the unlagged relationship for the NSCT treatments and the WWCT -N treatment.

Emissions from fossil fuel usage were a relatively small proportion of the total emissions (Table 2). Fossil-fuel

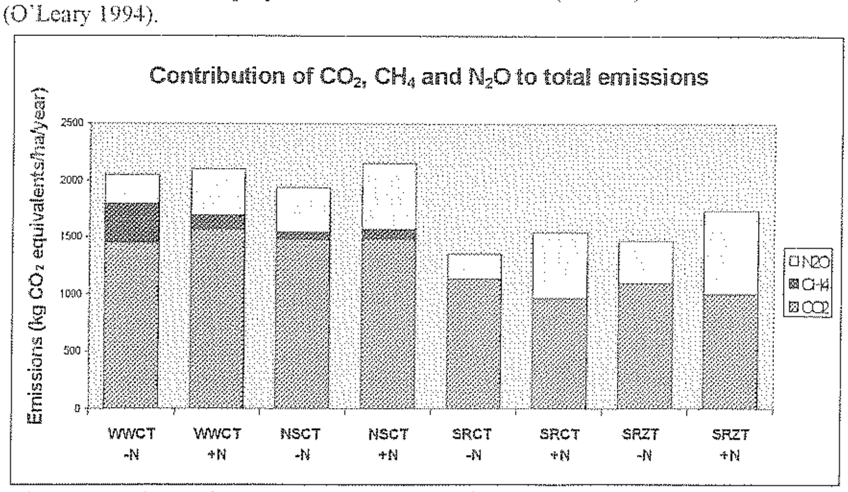

Fig. 2 Total greenhouse gas emissions (kg CO_2 equivalents/ha/year) and the CO_2, CH_4 and N_2O components of these for the eight cropping systems

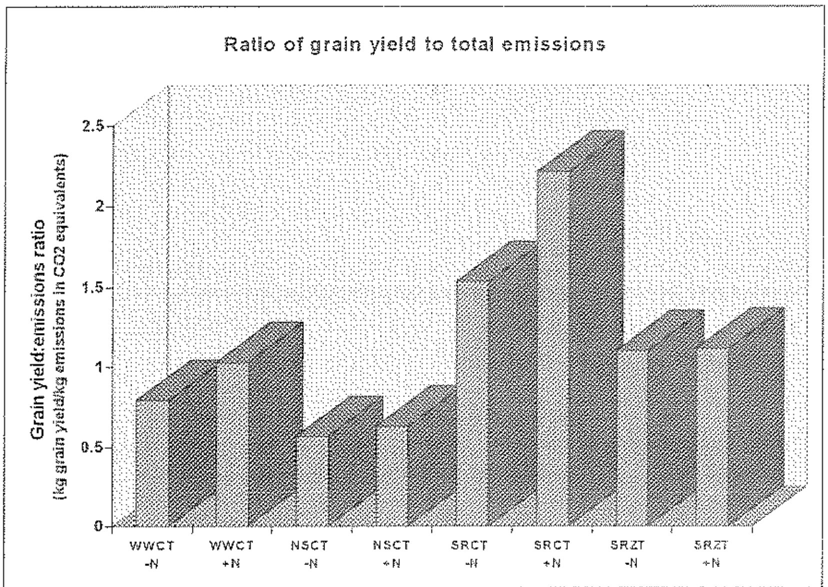

Fig. 3 The ratio of grain yield to total net emissions (kg grain yield/kg CO_2 equivalent emissions) for the eight cropping systems.

emissions ranged from less than 1% of total emissions in the zero-tillage systems (SRZT) to 8% in the SRCT treatment where stubble retention was practiced with conventional tillage and considerable effort is needed to incorporate stubbles. Direct emissions from burning (i.e. CH_4 and N_2O) were also a small proportion of the total emissions (7.1% to 20.6%) in those treatments where burning was practised (i.e. WWCT and NSCT).

Table 2 Fossil fuel and burning emissions expressed as a percentage of the total emissions for the eight cropping systems.

Treatment	Fossil fuel emissions as % of total emissions	Burning emissions as a % of total emissions
WWCT -N	5.4	20.6
WWCT +N	5.2	12.9
NSCT -N	2.8	7.1
NSCT +N	2.5	8.8
SRCT -N	8.0	-
SRCT +N	7.1	-
SRZT -N	0.9	-
SRZT +N	0.8	-

5. DISCUSSION

The wheat cropping systems studied are likely to be, on average, significant net emitters of greenhouse gases with emissions equivalent to 1350 to 2150 kg of carbon dioxide each year. However, the size of these emissions will vary greatly between years and in some years these systems can even be substantial net emission sinks.

Choice of wheat cropping systems could reduce the average net emissions per hectare by up to 37% depending on the systems used. More importantly though, the cropping systems which have lower emissions also tend to have greater yields, and thus may produce up to four times the grain yield per unit emissions than other systems. This indicates that there is significant potential to adapt wheat cropping systems to reduce greenhouse gas emissions in a cost effective way.

Stubble retention when combined with conventional cultivation gave the greatest yield per unit emissions, particularly where fertiliser was added. Stubble retention has been promoted through research and extension agencies, however, early reports of problems with Yellow leaf spot (*Pyrenophora tritici-repentis*), Eyespot (*Pseudocercosporella herpotrichoides*), Take-all (*G. graminis* var. *tritici*) and rhizoctonia root rot in some areas has limited adoption rates. Consistent disease control measures, such as rotation with canola, will need to be demonstrated before more widespread adoption occurs. Furthermore, stubble retention is not suitable for all soil types and environments. For example, Incerti *et al.* (1993) have suggested that in the Mallee it can only be justified to reduce wind erosion.

There was a consistent relationship across most cropping systems in which years with higher grain yields had lower emissions. These wetter, more productive years resulted in the soil becoming a substantial sink for carbon, although in some cropping systems there was a partially compensatory increase in emissions in the following year. These relationships suggest that tactical farm management could reduce emissions by deferring planting or by reducing fertiliser inputs in those years when either initial soil water is low, or when medium-term climate indicators such as the SOI suggest that an El Niño event may reduce rainfall during the growing season. Similarly, by increasing fertiliser inputs these systems could act as a carbon sink in those years with high initial soil moisture stores or expectations of above-average rainfall (La Niña years). The feasibility of this is supported by correlations between the SOI and wheat yield in Victoria (Rimmington and Nicholls 1993). There may be an economic incentive to adopt this approach as incorporation of the SOI into decisions on fertiliser application rates for wheat crops in Queensland has been shown to reduce the risks of negative gross margins in poor years, but makes the most of the opportunities provided by better seasons (Stone *et al.* 1993).

Loss of soil carbon was the most substantial component of the emissions budget for all cropping systems. Stubble retention reduced the size of this loss, although it did not prevent run-down of soil carbon. This is consistent with other analyses (e.g. Li *et al.* 1994). Nitrous oxide emissions also formed a significant component of the emissions budget. Given the empirical way in which denitrified N was partitioned into N_2O and N_2 in this study, there will be a need to incorporate suitable routines into the soil carbon-nitrogen model and to validate this model before the development of policies to reduce N_2O emissions from cropping systems.

Emissions from fossil fuel combustion and from burning crop stubble formed relatively small components of the emissions budget. Hence, whilst adoption of zero-tillage in the stubble retention system reduces fossil fuel inputs significantly (by about 6-7% of total net emissions, there are compensating factors that result in increased emissions over conventional cultivation. This is one example of the need for systematic analyses of emission-reduction options.

The Australian Government has international commitments relating to the stabilisation of greenhouse emissions and has an over-arching domestic policy of Ecologically Sustainable Development. Hence, agricultural activities promoted or supported by such policies should meet economic, ecological and emission-reduction criteria. This suggests the need for more analyses using validated simulation models that can integrate these issues, so that policies can be effectively directed and are not counterproductive (e.g. by reducing one source of emissions there is a net increase in emissions from the whole system as in the zero-till and fossil fuel example above). Where policies have been implemented, such as those in the NGRS and 21C packages, there will be a continuing need to verify that the desired activities are being adopted and that these are having the desired effects (in this case, increased soil carbon amongst other factors). It will be necessary to identify barriers to the adoption of desirable approaches (such as the issue of disease control in stubble retention) and to develop policies and strategies to remove these barriers. There will also be a need to investigate the economic implications of widespread adoption of specific practices at both the farm level and at the macro-economic level. These are all significant challenges.

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