ASSESSMENT OF THE COSTS AND ENHANCED POTENTIAL FOR CARBON SEQUESTRATION IN SOILS

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Background to the Study

The IEA Greenhouse Gas R&D Programme (IEA GHG) evaluates technologies that can be used to reduce greenhouse gas emissions. Much of IEA GHG's work so far has been on capture and storage of CO_2 from power stations. Alternative greenhouse gas abatement options are being assessed to put CO_2 capture and storage in context.

One of the greenhouse gas abatement techniques that has been widely promoted, and is recognised under the Kyoto Protocol, is enhanced sequestration of carbon in soils. When land is converted from native vegetation to modern agriculture, carbon stored within the soil is oxidised and released into the atmosphere. Because of this past depletion of carbon, arable soils have the capacity to store more carbon than they do at present.

There are many well-defined land use and management practices that can be adopted to increase the carbon content of agricultural soils. For example, a switch from conventional to conservation tillage reduces carbon oxidation and thus emissions of CO_2, and increasing crop or pasture biomass through increased mineral or organic fertiliser additions or the introduction of pasture legumes increases carbon inputs to soils. The potential for these practices to sequester additional carbon varies in that it is influenced by both the textural composition of soils and climatic conditions (i.e. temperature and moisture regime).

This study assesses the quantities of additional carbon that could be sequestered in a range of soils, and the costs of sequestration. The study was carried out by a consortium led by the Australian Cooperative Research Centre for Greenhouse Accounting, including experts from Australia, the USA, Sweden and Kazakhstan.

Study Description

Most of the published assessments of the costs of carbon sequestration in soils have focussed on one region, North America. This study therefore focuses on other regions of the world, to broaden the knowledge of the costs of sequestration. Within the resources of IEA GHG it was not possible to carry out a study which covered the whole world. Instead the study focussed on five regions:

- Australia - South Eastern region
- Central Asia – Northern Kazakhstan
- India - Indo-Gangetic plain
- Northern Europe - Sweden
- South America, South Eastern region - Uruguay

A number of essential criteria were considered in the selection of regions for this study:

- Agro-ecological regions with proven high technical potential for carbon sequestration.
- Proven history of adoption of management strategies which promote carbon sequestration.
- Broad coverage of management strategies for promoting soil carbon sequestration.
- Availability of quality bio-physical and economic data for accurate assessment and extrapolation.
- Diversity in agro-economies (from both the developing and developed world).
- Diversity in agro-climatology (between regions) to ensure wide range of carbon sequestration potentials.
- Provide basis for extrapolation to other world regions (not part of this study).
- Presence of local collaborators experienced in greenhouse gas issues and their impacts in agricultural systems.

The main sequestration techniques considered in this study are minimum or no-tillage cropping. Conversion of crop land to permanent grass or pasture is also considered for Uruguay and Sweden.

The calculation of the technical potential for soil carbon accumulations was based on the method employed in the Intergovernmental Panel on Climate Change (IPCC) 1996 revised guidelines for national greenhouse gas inventories, as updated in the IPCC 2004 Good Practice Guidance for Land Use, Land Use Change and Forestry. The basic methodology is described in the main study report. The estimation of costs included farm opportunity costs of changing practices, fixed costs of adoption and transaction and verification costs.

Changing agricultural practises to maximise carbon sequestration affects ancillary emissions of CO_2, for example from agricultural machinery, and emissions of non-CO_2 greenhouse gases from soils, particularly N_2O. This study assesses the gross soil carbon accumulations and the overall net greenhouse gas abatement taking into account the global warming potentials of the ancillary emissions.

Results and Discussion

Technical potential

Figure 1 shows the average quantities of carbon sequestered in soil for each of the study regions and management practices, and the overall quantities of greenhouse abatement, taking into account ancillary emissions.

The quantities of carbon sequestered differ substantially between and within the regions considered in this study. Up to 14.4 tonnes of carbon is capable of being sequestered per hectare over a 20 year period, taking into account the changes in ancillary emissions. The average quantity for any of the regions is up to 10.7 tonnes ha^{-1} but a more typical figure is around 5 tonnes ha^{-1}. The largest net quantities of carbon sequestered over 20 years were in the high activity soils with reasonably high clay contents. The quantities of additional carbon sequestered are a relatively small percentage, typically 5-20%, of the organic carbon already present in the top 30cm of soil.

To put the quantities of carbon sequestered in context, a 1000MW high efficiency coal fired power plant operating at base load emits about 5.5 million tonnes of CO_2 (1.5 million tonnes C) per year. The area required to sequester this quantity of carbon, at a sequestration rate of 5 $tC.ha^{-1}$ over a 20 year period, would be 60,000 km^2.

In all of the Uruguay and Australian cases and almost all of the Indian cases the sequestration techniques reduces ancillary emissions but in the Swedish and Kazakhstan cases the ancillary emissions increase.

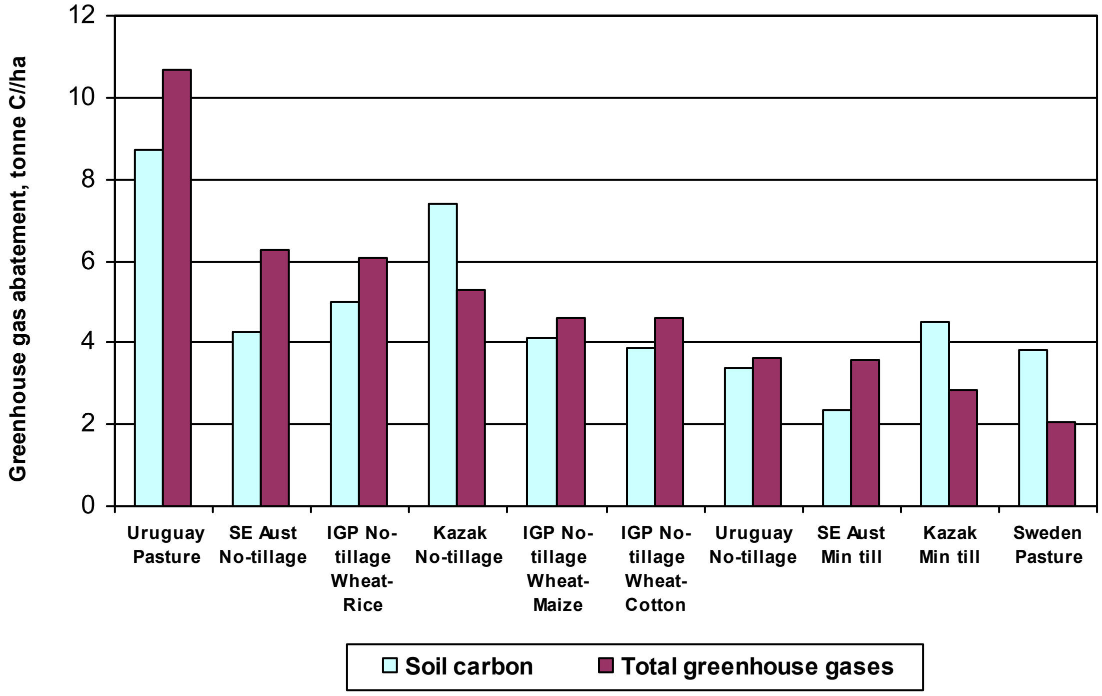

Figure 1 Soil carbon sequestration and net greenhouse gas abatement over 20 years

Costs

Costs of sequestration in soils depend on physical conditions (soils, climate, topography etc.) and socio-economic conditions. Figure 2 summarises the technical potential for sequestration for each of the regions and sequestration practices and the quantities of carbon that could be sequestration at 50, 100 and 200 \$/t C (equivalent to 14, 27 and 55 \$/t CO_2). Across all regions on average, 16% of the technical potential is achieved at \$50/t C and 61% of the potential is achieved at \$200/t C. Cost curves broken down into sub-regions and soil types are included in the main report.

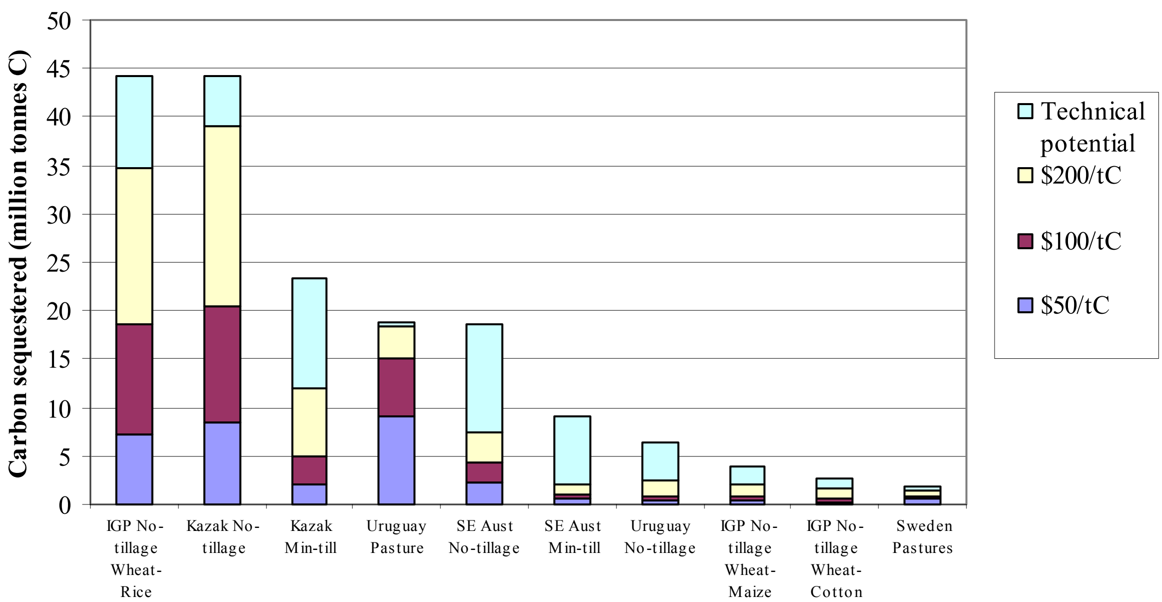

Figure 2 Quantities of carbon that could be sequestered at a range of prices

For comparison, the cost of capturing and storing CO_2 from a large power plant (post-combustion capture and aquifer storage) would typically be about \$150/tonne of carbon (\$40/t CO_2), based on current technology. This is approximately the average cost of soil carbon sequestration.

Additionality is an important issue for all greenhouse gas abatement practices. Carbon credits should only be paid to projects which would not otherwise have taken place. The practices that increase carbon sequestration such as low till agriculture are already widely practiced in some regions and in some cases are economically attractive without carbon sequestration credits. The quantities of carbon sequestration shown in figure 2 are those which would only be achieved with sequestration payments.

Long term permanence of sequestration

There is an attainable maximum stock of carbon in soil, which is highly dependent on the soil type, its land use history, the prevailing climate and ecosystem productivity. At that point in time, usually well in excess of the 20 year time frame defined in this analysis, the soil is said to become "saturated" and no further carbon is sequestered. In most of the cases considered in this study the carbon sequestration practices reduce ancillary emissions of greenhouse gases. In these cases there will be a continuing reduction in greenhouse gas emissions even when the carbon content of the soil becomes saturated. However, in some of the cases the sequestration practices increase ancillary emissions. In these cases there is a short/medium term reduction in overall greenhouse gases but in the longer term, when the soil carbon content becomes saturated, there will be a net increase.

Sequestered carbon can be released back to the atmosphere in a short period of time if farmers revert back to conventional practices. Published studies indicate that sequestration practices can result in increased risks of yield variations and reduced income in the early years after adoption but in later years the risks tend to decrease and profitability tends to increase. When sequestration payments stop, farmers would therefore not necessarily revert to their earlier practices. However, it is possible that changes in economic conditions could cause farmers to dis-adopt formerly profitable practices, resulting in loss of sequestered carbon.

Obstacles to adoption

Many factors could inhibit the participation of farmers in carbon credit markets. In many parts of the developing world land use rights can change over time and legal and financial institutions are less well developed. If contracts are not enforceable, buyers of carbon contracts will have less recourse if farmers are found to be not complying with the terms of the contract. In countries with a lack of financial institutions, farmers may not be able to borrow to make investments needed to adopt carbon sequestration practices. Another barrier in some countries is a low level of knowledge of farmers about long term effects of management practices on productivity.

Expert Reviewers' Comments

A draft version of the report was sent for review to experts on soils and carbon sequestration. The reviewers were generally pleased with the report. The authors took the reviewers' detailed comments into account, where possible, in the final version of the report. Many of the comments asked for further information which was beyond the scope of the study. The need for further information on transaction costs was highlighted and one of the reviewers thought that the treatment of long term permanence was too optimistic. It was pointed out that it may be regarded as unfair to pay farmers to rehabilitate degraded soils when such payments would not be available to farmers who had looked after their soils. However, this is an institutional and policy issue.

Major Conclusions

There are large regional and sub-regional variations in the technical and economic potential for carbon sequestration in soils.

For the cases considered in this study, up to 14.4 tonnes of carbon is capable of being sequestered per hectare over a 20 year period but a more typical figure is around 5t.ha^{-1}.

For carbon prices of less than \$50/t carbon (\$14/t CO_2) all regions show a relatively low economic potential for soil carbon sequestration; the overall economic potential is 16% of the technical potential. At \$200/t C (\$55/t CO_2) 61% of the technical potential could be achieved.

In most, but not all, cases the carbon sequestration practices reduce the overall net emissions of greenhouse gases, for example CO_2 from farm machinery and N_2O emissions from soils. These are taken into account in the assessment of sequestration potentials and economics.

Recommendations

Further work, including on-farm and institutional surveys, is needed to assess the economics of soil carbon sequestration techniques. Quantification of transaction costs and techniques for the accurate and consistent assessment of co-benefits are a priority. However, because of other commitments, no further work by IEA GHG on soil carbon sequestration is recommended at this time.

Assessment of the Costs and Enhanced Potential for Carbon Sequestration in Soils

A study commissioned by the International Energy Agency Greenhouse Gas Research and Development Programme

and completed by

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Executive Summary

In this analysis, soil carbon accumulation rates based on the Intergovernmental Panel on Climate Change (IPCC) methodology were combined with economic data to simulate the economic potential for agricultural soil carbon sequestration in regions of five countries (Australia, India, Kazakhstan, Sweden and Uruguay). The analysis assessed the economic potential for farmers to sequester additional carbon in the soil by changing land use and management practices in exchange for payments based on the tonnes of carbon they sequester over a 20 year time horizon.

Two types of changes in land use and management were considered, depending on what is feasible in each region: the adoption of minimum or no-tillage in cropping systems; and conversion of cropland to permanent grass or pasture. Rates of soil carbon sequestration were estimated in gross and net terms, where the latter adjusts for changes in greenhouse gas emissions of carbon dioxide, methane and nitrous oxide associated with changes in management (e.g. fuel use, nitrogen fertilizer application, grazing by animals).

In Uruguay, 14.4 Mg C ha^{-1} is capable of being sequestered under nominally managed pasture that has been previously cropped. Converting conventionally tilled systems to no-tillage on high activity soils was a consistent sequestering technology across most of the regions. In the High Rainfall region of South-Eastern Australia, 12.7 Mg C ha^{-1} was sequestered over 20 years. Other significant net carbon gains under no-tillage were simulated in the rice-wheat rotation of West Bengal of the Indo-Gangetic Plain (IGP) (9.6 Mg C ha^{-1}) and cropping systems of the Wimmera region of South-Eastern Australia (9 Mg C ha^{-1}).

The economic results of the analysis have been summarized in carbon supply curves for each region and sub-regions. These supply curves express the total additional soil carbon accumulated over 20 years that would be associated with a price per tonne of carbon ranging from zero to $200. For a relatively low carbon price (i.e., less than $50 per tonne), all regions show a relatively low economic potential for soil carbon sequestration, with the economic potential falling substantially below the technical potential simulated by the IPCC carbon model. On average, only 16% of the technical potential for carbon sequestration was achieved over 20 years. At $50 per tonne of carbon, farmers are willing to enter into carbon sequestration contracts on less than 34% of the land currently under the conventional (or baseline) technologies.

At $200 per tonne of carbon, 61% of the technical potential could be achieved, with farmers entering into contracts on less than 80% of the available land. In both cases, the conversion of cropping systems to nominally managed pastures in Uruguay was identified as a widely adopted strategy. Increased adoption of no-tillage in wheat-rice systems of the IGP and cereal systems of Kazakhstan is also favoured at higher prices.

The immaturity of the global carbon trading market makes it extremely difficult to adequately express the overall impact of institutional mechanisms involved in developing and coordinating carbon sequestration contracts. The accurate quantification of transaction costs, as well as the development of techniques for the accurate and consistent assessment of co-benefits and permanence of technologies needs to be considered a priority in future studies which specifically target the most profitable and sustainable management strategies identified in this study.

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1. Background to the study

The removal of CO_2 from the atmosphere through agricultural soil management has been widely promoted as a valid mechanism to reduce greenhouse house gas (GHG) emissions under the Kyoto Protocol (KP). The mass and long residence time of soil organic matter in the terrestrial ecosystems make it a major component of the global carbon cycle (Post *et al.*, 1990). Agricultural soils represent a potentially significant sink for the most prolific greenhouse gas, carbon dioxide. With CO_2 emissions from fossil fuel combustion increasing globally by over 116 million Mg C per annum (Marland *et al*., 2003), there is growing interest in the use of management strategies that promote carbon sequestration in soils and thus reduce the net concentration of atmospheric CO_2 and other GHGs (Lal *et al.,* 1998).

When land is converted from native vegetation to modern agriculture, the carbon stored within the soil is oxidized and released into the atmosphere. Because of this past depletion of soil carbon levels, arable soils have the capacity to store more carbon than they do at present (Lal *et al*., 1998). Soil carbon can be increased by adopting practices that reduce soil disturbance and/or by increasing the amount of biomass produced on an area.

There are many well-defined land use and management practices (IPCC, 2000) that can be adopted to increase soil carbon. For example, a switch from conventional to conservation tillage reduces carbon oxidation and thus emissions of CO_2; increasing crop or pasture biomass through increased mineral or organic fertiliser additions or the introduction of pasture legumes increases carbon inputs to soils. The potential for these practices to sequester additional carbon varies in that it is influenced by both the textural composition of soils and climatic conditions (i.e. temperature and moisture regime).

Long-term agronomic trials have provided the best evidence to data of the influence of management strategies to promote soil carbon storage (Rasmussen *et al*., 1998), however the presence of spatially heterogeneous bio-physical and economic conditions suggest that a single land use or management practice will not be equally efficient at sequestering carbon at different regions across the globe. Changes in management strategies must also be economically feasible for the producer of the agricultural product at hand, and, except for recent studies in North America (Antle *et al*., 2001; McCarl & Schneider, 2000) there are few (if any) estimates of the economic potential for soils in different agro-ecological zones of the globe to sequester additional carbon. The allocation of private and public financial resources to support carbon sequestration is dependent on the cost effectiveness of implementing technologies within a region whilst at least maintaining or improving productivity of the natural resource. The identification of high potential regions and management strategies for sequestration in soils is therefore an important policy issue (McCarl & Schneider, 2000).

There are a number of important factors that must be considered in a full cost economic assessment of the potential for soil carbon sequestration in agriculture.

First, producers must not be disadvantaged in terms of monetary reward by switching to alternative management strategies to rehabilitate degraded soils. Therefore, we must determine both the technical potential to store carbon and the economic returns to farmers who adopt practices that sequester carbon in soils.

Second, practices that sequester carbon often generate additional social benefits, sometimes referred to as "co-benefits", e.g. through a reduction in soil erosion and leaching of agricultural chemicals and sustaining productivity in the long-term. Thus, to determine socially efficient incentives for farmers, the full array of economic benefits and costs of soil carbon sequestration, both public and private, must be assessed.

Third, the evaluation of incentives or mechanisms required to ensure widespread adoption of management strategies for enhancing soil carbon storage i.e. what is the true (as opposed to the perceived) cost of actually bring these strategies into effect within an agro-ecological region. These incentive mechanisms may vary with respect to the numbers and size of farms involved and must be compatible with the legal and financial institutions in these countries. Finally, the assessment must take into account contractual arrangements and the barriers to fulfillment of any carbon contracts entered upon by the producer. This should take into account longevity issues (impermanence and saturation of soil carbon) as well as additionality discounts[1].

It is also important to note that whilst agriculture is both a sink for carbon as well as a major emitter of CO_2, the other two GHGs associated with agricultural systems, nitrous oxide (N_2O) and methane (CH_4), are of greater significance in terms of their contribution to the enhanced greenhouse effect and their emissions are also influenced by land use and management (Robertson et al., 2000). A comprehensive cost assessment of carbon sequestration must therefore take into account the total mixture of emissions when comparing strategies e.g. increases in carbon storage may actually be partially negated by the nitrous oxide emissions from the application of additional nitrogen fertilizers. To do this, one is able to convert the emissions to a standard carbon equivalent value by using the individual Global Warming Potential's (GWP) for each of the gases to provide a full cost accounting of GHGs in the analytical framework. While this generalization is straightforward, its implementation is still evolving as methods and models to quantify nitrous oxide and methane emissions are not as well developed as those for carbon. The full cost GHG accounting approach forms the basis of the Revised 1996 Guidelines for National Greenhouse Gas Inventories and provides a readily available, transparent and internationally acceptable framework for our methodology in assessing the relative impacts of alternative management strategies on carbon sequestration across agro-ecological zones of the world.

In anticipation of caps being imposed on emissions of GHGs through the KP of the United Nations Framework Convention on Climate Change (UNFCCC), and through domestic policies, various organizations have begun working towards the creation of markets for trading of GHG emissions. In addition to domestic reductions in GHGs, Article 12 of the KP allows developed countries (those listed in Annex 1 of the Convention) to purchase emissions reduction credits from projects in developing countries and use these credits to offset their obligations to reduce GHGs. Developed countries can also trade emissions reduction credits between themselves.

[1] International agreements such as the Kyoto Protocol are expected to give credit only for carbon sequestered above and beyond changes in carbon stocks that would have occurred in the absence of incentives for carbon sequestration. In this report we define an additionality discount as the additional amount of carbon that would have been sequestered over a period of time in the absence of incentives for carbon sequestration.

The International Energy Agency Greenhouse Gas Research and Development Program (IEA GHG) has commissioned a study to assess the costs and potential of enhanced sequestration of carbon in soil. While various estimates of technical potential to sequester soil carbon exist and are being further developed and refined, no comprehensive method exists to assess the economic feasibility of agricultural soil carbon sequestration across highly diverse agro-ecological regions and production systems of the world.

Our objective has been to develop a transportable and comprehensive assessment methodology and implement these procedures with the best available data for making a true and equitable assessment of soil carbon sequestration in agricultural systems around the globe.

2. Key concepts and issues

2.1 Agronomic

Soils can act as both a source and a sink of CO_2. The net exchange of carbon between soils and the atmosphere is mainly a function of organic carbon cycling and is determined by the net balance of carbon entering the soil through plant residues and CO_2 released from the mineralization of organic matter in soils. In most native ecosystems (i.e. those with minimal anthropogenic disturbance), soil organic carbon stocks tend towards an equilibrium or steady state, in which carbon inputs roughly balance carbon losses, and the soil is neither a sink nor a source for CO_2. The same can be true for managed ecosystems, that is, under a constant management regime, soil carbon stocks will over time tend towards an equilibrium state, and whether it is greater or less than the initial pre-management state is dependent on the balance between carbon inputs and outputs.

Changes in land use and management therefore alter the balance between inputs and outputs, leading to either a net uptake (sink) or release (source) of soil carbon as CO_2, which can persist for several years until the soil again approaches a new equilibrium state. These management practices may be a reduction in bare fallows in cropping rotations, crop residue retention, a reduction in tillage practices, a shift to pastures or ley farming, or a combination of all of these interventions.

Regardless of the actual management practice undertaken, the objective is to increase carbon stores by ensuring inputs of carbon (through introduction of organic matter) exceed outputs of CO_2. The fact that sequestration of carbon in the soil is highly correlated with more sustainable and profitable farming (i.e. production benefits alone) has provided the impetus to develop a greater understanding of the processes governing the dynamics of soil carbon in managed systems. The magnitude of these changes in soil organic carbon over time is both soil (type) and climate dependent, with heavier textured soils (e.g. clays) generally having a greater affinity to store carbon than coarser sands. Hot, wet climates also tend to decompose organic matter at faster rates than cool, dry environments, however the estimation of change in soil carbon stores requires a combination of these factors which are best described in dynamic simulation models such as CENTURY (Parton & Rasmussen, 1994), ICBM (Andren & Katterer, 1997), RothC (Coleman & Jenkinson, 1996) and SOCRATES (Grace *et al*., submitted). All of these models provide reliable estimate of changes in soil carbon in response to management, but each requires a detailed and time-consuming collection of input parameters and preparation which basically excludes them from a broader global assessment of soil carbon sequestration as required for the IEA GHG. The continued use and modification of these models has actually provided us with a greater understanding of the complexity of soil carbon turnover and they have played a major part in the development of more empirical methods similar to those which we have selected as part of our own methodology i.e. based on the IPCC guidelines.

We also recognize that whilst the focus on soil carbon sequestration has been useful for stimulating policy discussions, there are other potentials for mitigating greenhouse gas emissions that are commonly overlooked. These other potentials can possibly be as or more effective than soil carbon capture in many systems, and may be especially suitable for regions and cropping systems for which carbon management agriculture is agronomically unsuitable or economically prohibitive.

For example, changes in tillage practices may have unanticipated and unwanted effects on other sources or sinks of GHGs. If, for example, soil water conservation associated with no till were to provide more moisture for nitrifying and denitrifying bacteria as well as plants, then production of the nitrous oxide (N_2O) might increase, offsetting some or all of the mitigation potential of carbon storage (Robertson, 1999). Managing systems specifically for soil carbon storage by boosting the production of crop residues to enhance soil organic carbon inputs can be counter-productive. In particular, if greenhouse gas generating inputs (nitrogen fertilizers) are used to stimulate residue production, then the mitigation gained with such production can be more than offset by the greenhouse costs of that production (Schlesinger, 1999). Carbon dioxide released during the generation of power for irrigation pumps or running tractors for conventional tillage and harvesting are also examples of such offsetting practices (Izaurralde *et al*., 2000).

The need to include all sources of greenhouse warming potential in cropping systems is essential. Without a complete cost-benefit analysis with respect to a cropping system's capacity to affect the radiative forcing of the atmosphere, it is difficult to judge the appropriateness of one mitigation strategy over another. It is also otherwise easy to overlook additional mitigation options that may be particularly well suited to specific cropping systems or regions. Global Warming Potential (GWP) provides a means for comparing the relative effects of one source or sink of greenhouse gas against another. By placing all fluxes in common terms, one can directly evaluate the relative cost of, for example, increased carbon storage due to residue production (GWP mitigation) against increased N_2O from additional fertilizer application (GWP source).

By convention, GWP is measured in CO_2-equivalents (IPCC, 1997, 2001). Conversions from other gases to CO_2 are based on the effect of a particular gas on the radiative forcing of the atmosphere relative to CO_2's effect. GWP is largely a function of a molecule's ability to capture infrared radiation, its current concentration in the atmosphere, the concentration of other GHGs, and its atmospheric lifetime. All else being equal, a gas molecule with a greater atmospheric lifetime will have a higher GWP than one that cycles rapidly.

In general, only three GHGs are affected by agriculture: CO_2, N_2O, and methane (CH_4). Although CH_4 and especially N_2O are at far lower atmospheric concentrations than CO_2, their

GWPs are sufficiently high that small changes have a disproportionate effect on radiative forcing. Twenty years is the recognized period to assess soil carbon change, however we will use GWP's of 100 years for non-CO_2 gases. The GWP of methane is 23 and for nitrous oxide 296, meaning that a molecule of contemporary N_2O released to the atmosphere will have 296 times the radiative impact of a molecule of CO_2 released at the same time. Thus, an agronomic activity that reduces N_2O emissions by 1 kg ha^{-1} is equivalent to an activity that sequesters 296 kg CO_2 ha^{-1} as soil carbon.

Sources of GWP arise from a number of agronomic practices. Some, such as soil CO_2 emissions following clearing and tillage and CO_2 emitted by diesel farm machinery, are direct sources of CO_2. Others, such as CO_2 emitted during fertilizer and pesticide manufacture, are indirect and are not usually considered as on-site emissions. Still others, such as CH_4 emitted by livestock and N_2O emitted from soil bacteria following cropping, are non-CO_2 based. These latter emissions will be considered in our study when calculating the environmental and economic cost-benefit of region specific management practices for soil carbon sequestration in agro-ecosystems.

2.2 Economic

The economic feasibility of agricultural soil carbon sequestration can be assessed by constructing a marginal cost curve, or supply curve, for the quantity of carbon that can be permanently stored in agricultural soils. This supply curve is derived by estimating the number of tonnes of carbon that would be supplied by farmers for each price per tonne of carbon offered, if there is a market for carbon emissions reductions credits (in this case we shall say that farmers are participating in *per-tonne contracts* for soil carbon). If a well-functioning market does not exist, and carbon is being sequestered through a governmental or non-governmental program that pays farmers for the adoption of practices that sequester carbon (what we shall call *per-hectare contracts*), the supply curve is constructed by determining the correspondence between the quantity of carbon sequestered and the implicit marginal cost of the carbon. The economic logic utilized here has been presented in detail in Antle *et al*. (2001, 2003), and is similar to the economic approaches used to assess forestry sequestration (e.g. Stavins, 1999). In this analysis, we utilize the more efficient per-tonne contracts. The reader should keep in mind that actual implementation using per-hectare contracts would likely result in higher costs per tonne of carbon sequestered.

In order to increase the stock of carbon on a land unit, the farmer must make a change from production system *i* (e.g., producing a crop with conventional tillage) that had been followed over some previous period (i.e., the historical land-use baseline), to some alternative system *s* (e.g., producing a crop with minimum or no-tillage). We assume that utilization of management practice *i* up to the time the farmer adopts practice *s* results in a carbon level of C_i, and adoption of practice *s* causes the carbon level to increase to C_s after T years. At time T, the soil reaches the attainable maximum level of soil carbon until further changes in management occur. The "permanence" of soil carbon involves the question of whether the adoption of the conservation practice is permanent or not. Here we shall simply assume that adoption is permanent, but this is a question that would need to be addressed in designing programs or contracts for soil carbon sequestration.

In the case of a per-tonne contract, the farmer is paid \$P for each tonne of carbon sequestered, regardless of what practices are used. Given the difficulty in measuring the change in carbon each year, we assume that farmers are given credit for the average annual rate of carbon accumulation (as derived in equation 1).

$$\Delta c_{is} = (C_s - C_i)/T \qquad (1)$$

Thus if soil carbon is expected to increase by Δc_{is} tonnes ha^{-1} $annum^{-1}$, the farmer receives a payment of $\$P \cdot \Delta c_{is}$ tonne ha^{-1} $annum^{-1}$ for T years. In the case where the contract duration exceeds T years, additional payments could be made to compensate the farmer for maintaining the practice.

In economic terms, the decision to participate in a government program or a carbon contract is similar in many respects to a conventional investment decision. The present practice and the alternative practice each yield a flow of net benefits over time, and the farmer compares the capitalized value of the flow of net benefits under each alternative. For purposes of our discussion, it is useful to consider the special case where the net returns to the farmer's practices and the price of carbon are constant over time. In addition, we convert fixed costs of adopting the conservation practice into an annualized flow f_{is}, and we likewise convert transactions costs associated with the contracts into an annualized flow t_{is} (both measured per hectare of land under contract).

Under these simplifying assumptions, it follows that the farmer's decision to participate in a carbon contract depends simply on whether the net returns from the carbon-sequestering practices (NR_s) plus the carbon payment (g) less fixed costs and transactions costs, are greater than the net returns from the farmer's present practices (NR_i). Thus, the condition is to participate in the carbon contract if:

$$NR_s + g - f_{is} - t_{is} > NR_i \qquad (2)$$

Rearranging equation 2 we have:

$$g > (NR_i - NR_s) + f_{is} + t_{is} \qquad (3)$$

The first term in parentheses on the right-hand side of equation 4 measures the loss in returns from adopting the carbon-sequestering practice.

$$\Delta NR_{is} = (NR_i - NR_s) \qquad (4)$$

Thus, we can conclude that farmers will participate in carbon contracts when the payment per hectare is greater than the farm opportunity cost of sequestering carbon, less any fixed costs and transactions costs. We recognize that farmers do tend to be risk averse and highly conservative in their practices. Risk aversion and other costs of adjustment would add additional components to the farmers' perceived opportunity cost of switching practices. As we explain below, our methodology for estimating fixed costs captures all of these effects. In the case where the farmer receives a payment per tonne of carbon, the payment is expressed as:

$$g_{is} = P \cdot \Delta c_{is} \quad (5)$$

The condition for participating in the contract is therefore:

$$NR_s + P \cdot \Delta c_{is} - f_{is} - t_{is} > NR_i \quad (6)$$

Rearranging equation 6, we obtain the equivalent expression:

$$P > (\Delta NR_{is} + f_{is} + t_{is})/\Delta c_{is} \quad (7)$$

The right-hand side of equation 7 is the *opportunity cost per tonne of carbon sequestered*. Thus, we can conclude that farmers will participate in per-tonne carbon contracts when the price per tonne of carbon paid to them is greater than the farm opportunity cost per tonne carbon sequestered. Importantly, in this case the farmer's decision is determined by the price of carbon and the expected rate of carbon sequestration.

2.3 Carbon supply curves

Agricultural production systems are heterogeneous due to spatial and temporal variation in bio-physical conditions (soils, microclimate, topography, etc.) and in socio-economic conditions (prices, production technology, farm decision maker characteristics, financial constraints, etc.). Therefore, in a given agro-ecological zone, both the opportunity cost ΔNR_{is} and the carbon sequestration rates Δc_{is} are spatially heterogeneous. The goal of our methodology is to make the best possible approximation of this heterogeneity, given the available data.

Economists often use "representative farm" models to characterize agricultural production systems, and then extrapolate the result to a region. Under this simplifying assumption, if the price per tonne of carbon offered is greater than the opportunity cost per tonne, then no farmers participate in the contracts and the supply of carbon is zero. When the price per tonne of carbon rises to the opportunity cost per tonne, all agricultural land in the zone enters into contracts because the benefit exceeds the cost on all land units giving a kinked supply curve of the form illustrated in Figure 1, where a fixed quantity C_0 is supplied for all prices above the threshold opportunity cost.

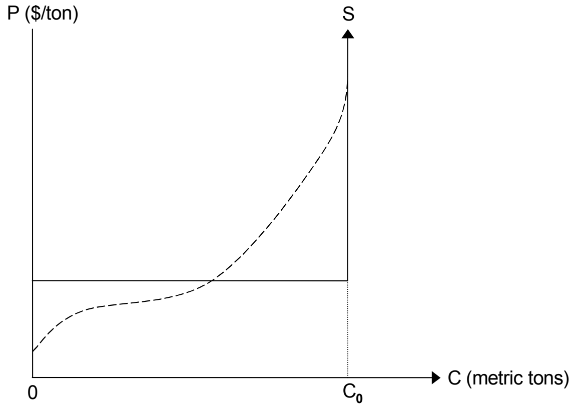

Figure 1. Carbon supply curves for homogeneous (solid) and heterogeneous (dashed) agro-ecozones.

We can interpret C_0 as the technical potential for carbon sequestration in the region. In this case, we can say that the technical potential is equal to the economic potential as long as the price per tonne of carbon is greater than the opportunity cost per tonne. In the case of a spatially heterogeneous region, we can represent the distribution of the opportunity cost per tonne as in Figure 2. When there is no market for carbon (i.e., the price per tonne of carbon is zero), the adopters of the conservation practice are represented by the land units corresponding to the area to the left of zero. For a positive price of carbon, the land units entering into contracts are represented by the area under the density function between zero and P. The result is a supply curve with the curvature represented by the dashed curve in Figure 1 (also see Antle & Capalbo, 2001). In this case, the economically feasible quantity of carbon in the region is generally less than the technically feasible quantity, and only approaches the technically feasible quantity (C_0) as the price per tonne increases to a sufficiently high level.

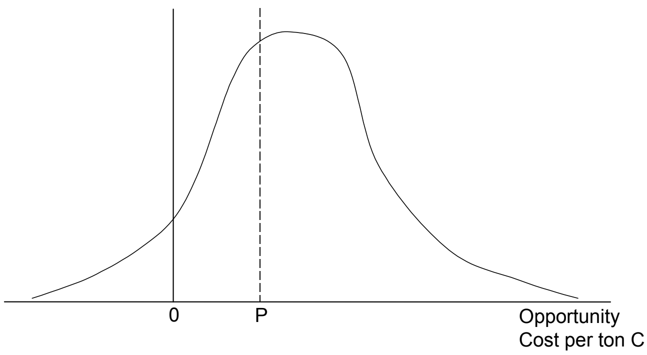

Figure 2. Spatial distribution of opportunity cost per tonne of carbon in a heterogeneous agro-ecozone.

The shape of this supply curve is determined by the properties of the spatial distribution shown in Figure 2. Clearly, the assumption of homogeneity (the step function in Figure 1) is likely to generate a poor approximation of the true supply curve (the dashed line in Figure 1) when the population is heterogeneous. At low prices, the homogeneity assumption will lead to the prediction that a zero quantity of carbon will be produced; then for higher prices, it will over-predict the amount of carbon.

3. Methodology for assessing soil carbon change

Our goal is to utilize existing data to approximate the spatial distribution of the opportunity cost of soil carbon sequestration for distinct agro-ecological zones within defined global study regions and construct carbon supply curves for each zone. A robust yet simple procedure which will provide a realistic comparison of technologies within and between regions from around the globe is a critical element of this assessment with the procedure both transportable and transparent for this and future assessments.

3.1 Technical potential

We chose the computational method employed in the IPCC 1996 Revised Guidelines for National Greenhouse Gas inventories, as updated in the IPCC Good Practice Guidance (GPG) for Land Use, Land Use Change and Forestry (IPCC, 2004) to provide estimates of soil carbon change to flow into the economic analysis. The IPCC Guidelines for National Greenhouse Gas Inventories are approved internationally. They have been developed through an international process which has included the dissemination of drafts and collection of comments from national experts; the testing of methods through development of preliminary inventories; country studies which ensure that methods are tested in a wide variety of national contexts; technical and regional workshops; and informal expert groups convened to recommend improvements on specific aspects of the methodology.

The improved IPCC Tier I model (using the default methodology and parameter values) has advantages in that it is easy to apply and requires a minimum of data requirements. Furthermore the parameters in the model are based on an extensive survey and statistical analysis of published studies and the method is well recognized and used internationally. This provides a sound and consistent basis for directly comparing outputs from our set of case studies with respect to the impact of agricultural management on soil carbon sequestration both between and within regions of the globe. Whilst its conceptual basis is the same as the IPCC 1996 Revised Guidelines, it differs in that reference soil carbon stocks and all the factor values have been statistically estimated, in a much more rigorous way than was possible in the original version. Thus, for example, it is now possible to estimate statistically valid uncertainty around particular estimates.

Specifically, the IPCC method estimates net changes in organic carbon stocks for mineral soils based on **relative** stock changes over a defined time interval (default of 20 years). There are three main kinds of information necessary:

- Stock change factors which relate to specific land use and management practices.
- Reference soil carbon stocks, which the stock change factors are applied.
- Activity data that records the changes in land use and management that occur over time.

These are combined in the following way:

$$\Delta C_i = [\ (C_{it} - C_{i(t-20)}\,) * LA_i] / 20 \qquad (8)$$

$$C_{it} = C_R * F_{LU} * F_{MG} * F_I \qquad (9)$$

Where C_i is soil organic carbon stock for the *i*th parcel of land at time t and t-20 years, LA_i is land area of each parcel, C_R is the reference carbon stock and F_{LU} , F_{MG} , F_I are stock change factors for land-use type, management regime (i.e. for annual croplands it represents different tillage alternatives) and carbon input level, respectively, which define the land use and management conditions on each parcel of land. The IPCC method classifies agricultural land management systems into categories based on their relative impact on soil organic carbon storage (IPCC 1997, 2004).

Cropland categories are based on the carbon input to the soil pools, and include low, medium, high and high w/amendment input categories, in addition to set-asides (Ogle et al. 2004a). Medium input cropping systems are defined as continuous cereal or row crop rotations with residues retained in the field. Low input systems have less carbon input relative to medium input, and include rotations with bare fallow or rest years, planting low residue crops such as vegetables, or due to practices that reduced residue cover such as burning or residue harvesting. High input systems have increased carbon input through the use of winter cover crops, green manures, high residue crop varieties, or fields with mixed systems that are managed with both periods of annual cropping and hay or pasture. Organic amendments also affect soil organic carbon storage by increasing carbon input to the soil and stimulating production.

In the IPCC classification, low input cropping systems are re-classified as medium input if amended with organic manures, which is a trade-off between low residue cropping practices and enhanced carbon input from the amendment. Similarly, medium input cropping systems are considered high input if they are amended. High input systems that receive organic amendments are classified as high input with amendment based on their high level of carbon input relative to other cropping management systems. Lands recently set-aside from agricultural production are placed in a separate category because of their low carbon storage relative to typical native conditions. These lands are often only temporarily set-aside and may be re-cultivated in a decade or two. However, if they remain in perennial cover after 20 years, then they are reclassified into a forest or grassland management category (Note: Forest management systems were not considered in this analysis).

Managed grassland are classified according to status and carbon input, similar to cropland, and include degraded, nominal, improved, and improved with high input catgories (Ogle et al. 2004b). Degraded grasslands have the lowest carbon balance relative to other categories have low productivity relative to native or nominally-managed grasslands and receive no inputs that could compensate for reduced productivity (e.g., fertilization or irrigation). Nominally managed grasslands are those in a native condition or are managed in a manner that does not lead to degradation. In addition, nominal grasslands are not improved with practices such as irrigation, fertilization, lime additions, seeding legumes, or planting more productive varieties of grasses.

Grasslands managed with these practices generally have relatively higher plant production and carbon input to the soil, and consequently are classified as improved grasslands. If a grassland is managed with multiple practices to enhance plant production (e.g., irrigation and organic amendments), those systems are considered improved with high input.

Land area parcels represent the areas associated with each type of land use/management system (as defined by the stock change factors) stratified by climate and soil type. The reference soil carbon stock values, as developed for the GPG are shown in Table 1. Stock change factor values for agricultural land uses, including land conversion to agricultural uses are given in Tables 2-4. Values for reference carbon stocks and management factors, including the base, tillage, grassland and cropland input factors, were based on estimates provided in the IPCC Good Practice Guidance Document for Land Use, Land Use Change and Forestry (IPCC, 2004). Additional information on the management factors and how they were derived is provided in Ogle *et al*. (2004a, 2004b).

Table 1. Default reference (under native vegetation) soil organic carbon stocks (SC_R) (tonnes C per ha for 0-30 cm depth).

Region	HAC soils[1]	LAC soils[2]	SAN soils[3]	Spodic soils[4]	Volcanic soils[5]	Wetland soils[6]
Boreal	68	NA	10	117	20	146
Cold temperate, dry	50	33	34	NA	20	87
Cold temperate, moist	95	85	71	115	130	
Warm temperate, dry	38	24	19	NA	70	88
Warm temperate, moist	88	63	34	NA	80	
Tropical, dry	38	35	31	NA	50	
Tropical, moist	65	47	39	NA	70	86
Tropical, wet	44	60	66	NA	130	

[1]Soils with high activity clay (HAC) minerals are lightly to moderately weathered soils, which are dominated by 2:1 silicate clay minerals (in the World Reference Base for Soil Resources (WRB) classification these include Leptosols, Vertisols, Kastanozems, Chernozems, Phaeozems, Luvisols, Alisols, Albeluvisols, Solonetz, Calcisols, Gypsisols, Umbrisols, Cambisols, Regosols; in USDA classification includes Mollisols, Vertisols, high-base status Alfisols, Aridisols, Inceptisols).

[2]Soils with low activity clay (LAC) minerals are highly weathered soils, dominated by 1:1 clay minerals and amorphous iron and aluminium oxides (in WRB classification includes Acrisols, Lixisols, Nitisols, Ferralsols, Durisols; in USDA classification includes Ultisols, Oxisols, acidic Alfisols).

[3]SAN includes all soils (regardless of taxonomic classification) having > 70% sand and < 8% clay, based on standard textural analyses (in WRB classification includes Arenosols,; in USDA classification includes Psamments).

[4]Soils exhibiting strong podzolization (in WRB classification includes Podzols; in USDA classification Spodosols)

[5]Soils derived from volcanic ash with allophanic mineralogy (in WRB classification Andosols; in USDA classification Andisols).

[6]Soils with restricted drainage leading to periodic flooding and anaerobic conditions (in WRB classification Gleysols; in USDA classification Aquic suborders).

Table 2. Relative stock change factors (F_{LU}, F_{MG}, F_I) for different management activities on cropland.

Factor value type	Level	Temperature regime	Moisture Regime	Factor value	Description
Land use (F_{LU})	Long-term cultivated	Temperate	Dry	0.82	Represents area that has been continuously managed for >20 yrs, to predominantly annual crops. Input and tillage factors are also applied to estimate carbon stock changes. Land use factor was estimated relative to use of intensive tillage and nominal ('medium") carbon input levels.
			Wet	0.71	
		Tropical	Dry	0.69	
			Wet	0.58	
Land use (F_{LU})	Paddy rice	Temperate and Tropical	Dry & Wet	1.1	Long-term (> 20 year) annual cropping of wetland (paddy rice). Can include double-cropping with non-flooded crops. For paddy rice, tillage & input factors are not used.
Land use (F_{LU})	Set aside (< 20 yrs)	Temperate and Tropical	Dry	0.93	Represents temporary set aside of annually cropland (e.g. conservation reserves) or other idle cropland that has been revegetated with perennial grasses.
			Wet	0.82	
Tillage (F_{MG})	Full	Temperate	Dry & Wet	1.0	Substantial soil disturbance with full inversion and/or frequent (within year) tillage operations. At planting time, little (e.g. <30%) of the surface is covered by residues.
		Tropical	Dry & Wet	1.0	
Tillage (F_{MG})	Reduced/ Minimum	Temperate	Dry	1.03	Primary and/or secondary tillage but with reduced soil disturbance (usually shallow and without full soil inversion). Normally leaves surface with >30% coverage by residues at planting.
			Wet	1.09	
		Tropical	Dry	1.10	
			Wet	1.16	
Tillage (F_{MG})	No-till	Temperate	Dry	1.10	Direct seeding without primary tillage, with only minimal soil disturbance in the seeding zone. Herbicides are typically used for weed control.
			Wet	1.16	
		Tropical	Dry	1.17	
			Wet	1.23	
Input (F_I)	Low	Temperate	Dry	0.92	Low residue return due to removal of residues (via collection or burning), frequent bare-fallowing or production of crops yielding low residues (e.g. vegetables, tobacco, cotton)
			Wet	0.91	
		Tropical	Dry	0.92	
			Wet	0.91	
Input (F_I)	Medium	Temperate	Dry & Wet	1.0	Representative for annual cropping with cereals where all crop residues are returned to the field. If residues are removed then supplemental organic matter (e.g. manure) is added.
		Tropical	Dry & Wet	1.0	
Input (F_I)	High – without manure	Temperate and Tropical	Dry	1.07	Represents significantly greater crop residue inputs due to production of high residue yielding crops, use of green manures, cover crops, improved vegetated fallows, frequent use of perennial grasses in annual crop rotations, but without manure applied (see row below)
			Wet	1.11	
Input (F_I)	High – with manure	Temperate and Tropical	Dry	1.34	Represents high input of crop residues together with regular addition of animal manure (see row above).
			Wet	1.38	

Table 3. Relative soil stock change factors (F_{LU}, F_{MG}, F_I) for native vegetation and shifting cultivation.

Factor value type	Level	Climate regime	Factor value	Definition
Land use (F_{LU})	Native forest or grassland (non-degraded)	Temperate	1	Represents native or long-term, non-degraded and sustainably managed forest and grasslands.
		Tropical	1	
Land use (F_{LU})	Shifting cultivation - Shortened fallow	Tropical	0.64	Permanent shifting cultivation, where tropical forest or woodland is cleared for planting of annual crops for a short time (e.g. 3-5 yr) period and then abandoned to regrowth.
	Shifting cultivation - Mature fallow	Tropical	0.8	

Table 4. Relative stock change factors for grassland management

Factor	Level	Climate regime	Factor value	Definition
Land use (F_{LU})	All	All	1.0	All permanent grassland is assigned a land use factor of 1.
Management (F_{MG})	Nominally managed (non –degraded)	All	1.0	Represents, non-degraded and sustainably managed grasslands, but without significant management improvements.
Management (F_{MG})	Moderately degraded grassland	Temperate/Boreal	0.95	Represents overgrazed or moderately degraded grasslands, with somewhat reduced productivity (relative to the native or nominally managed grasslands) and receiving no management inputs.
		Tropical	0.97	
Management (F_{MG})	Severely degraded	All	0.7	Implies major long-term loss of productivity and vegetation cover, due to severe mechanical damage to the vegetation and/or severe soil erosion.
Management (F_{MG})	Improved grassland	Temperate/Boreal	1.14	Represents grasslands which are sustainably managed with moderate grazing pressure and that receive at least one improvement (e.g. fertilization, species improvement, irrigation).
		Tropical	1.17	
Input (F_I) (applied only to improved grassland)	Nominal	All	1.0	Applies to improved grasslands where no additional management inputs have been used.
Input (F_I) (applied only to improved grassland)	High	Temperate/Boreal	1.11	Applies to improved grasslands where one or more additional management inputs/improvements have been used (beyond that required to be classified as improved grassland).
		Tropical	1.11	

To generate the soil carbon stock change estimates for the economic analysis, we applied a Geographic Information System (GIS) procedure to overlay climate, soil and land cover spatial databases to stratify the agricultural (cropland and grazing land) area of each of the study regions by agro-ecological zone.

Climate data in GIS coverages sufficient to support the IPCC methodology were obtained from UNEP-GRID (http://www.grid.unep.ch/data/grid/climate.php). Soils data, to determine the occurrence of major soil types within each study area, was obtained from the World Soils Reference data base (WRB, 1998) to map the occurrence of major soils within each study site, according to the IPCC categorization. In addition to the spatial soils information, we sought out country- and region-specific soil pedon data from the project collaborators in each of the study regions for verification.

The spatial data bases, together with information on the current and potential agricultural management regimes in each of the five study regions: South-Eastern Australia, Scandinavia (specifically Sweden), South-Eastern South America (specifically Uruguay), the Indo-Gangetic Plain of south Asia (specifically Northern India) and Central Asia (specifically Kazakhstan) were then used to generate a matrix of average annual soil carbon changes over 20 years for all current and potential land use and management changes within each study region or in most cases sub-regions. From the matrix we then identified the 2-3 principal management strategies within each sub-region, one of which was the current traditional practice (or baseline), and others which actually sequestered soil carbon and were considered both feasible and practical sequestration strategies as verified by local agronomists. The case study regions and sub-regions are detailed in Section 4.

For example, if a study region includes 6 major management alternatives/transitions for sequestering soil carbon and these can occur within 4 different climate regimes on 4 different soil types, then the matrix would include a total of 96 soil carbon change rates (6 x 4 x 4). An example of how a single such transition is estimated is given in the box below:

Example: For a Mollisol soil in a warm temperate moist climate, SC_R is 88 tonnes C ha^{-1}. On an area of land under long-term annual cropping, previously managed with intensive tillage and low carbon input level, the carbon stock at the beginning of the inventory period is calculated as ($SC_R \bullet F_{LU} \bullet F_{MG} \bullet F_{I}$,) = 88 tonnes C $ha^{-1} \bullet 0.71 \bullet 1 \bullet 0.91$ = 56.9 tonnes C ha^{-1}. Under the current management of annual cropping with no tillage and medium carbon input level the carbon stock is calculated as 88 tonnes C $ha^{-1} \bullet 0.71 \bullet 1.16 \bullet 1$ = 72.5 tonnes C ha^{-1}. Thus the average annual change in soil carbon stock for the area over the inventory period is calculated as (72.5 tonnes C ha^{-1} – 56.9 tonnes C ha^{-1}) / 20 yrs = 0.78 tonnes C ha^{-1} yr^{-1}.

An uncertainty analysis was conducted for each management scenario using a Monte Carlo Approach that was adapted from Ogle *et al*. (2003). Probability distribution functions (PDFs) were constructed for each reference carbon stock and management factor. PDFs for the management factors were based on their respective standard deviations as computed from linear mixed-effect models (IPCC 2004; Ogle *et al*. 2004a, 2004b). These ranges reflect error associated with estimating effects of management change from a global dataset, and it is likely that these uncertainties could be reduced in the future by estimating region-specific factors if there are sufficient experimental data available from the region of interest. PDFs for the reference carbon stocks were assumed to have a ∀50% normal distribution around the stock estimate, as a conservative estimate of the error since standard deviations were not provided with the reference stocks (IPCC, 2004).

Change in soil organic carbon storage was estimated 50,000 times using the Monte Carlo Approach for each management scenario by randomly selecting management factors and reference carbon stocks from the PDFs in an iterative process while accounting for dependencies among these inputs. Based on those results, a mean sequestration estimate and standard deviation was provided for each scenario and summarized into spreadsheet files for further analysis. After estimating average carbon rates for the changes in practices, they were adjusted to account for field based CO_2 and non-CO_2 emissions averaged over the defined time interval of 20 years.

The IPCC Tier 1 default values (IPCC, 1997) were used for calculating these emissions based on the inputs provided for each agro-ecological zone. Specifically, the additional emissions included in the full greenhouse gas account are:

- CO_2 from fuel used in farm machinery used in tillage, harvest or pumping operations, specifically 2.6 kg CO_2 per litre of combusted fuel (Robertson *et al*., 2000).
- N_2O from the burning of crop residues, manure application, nitrogen fertilizer addition, crop residue retention, nitrogen fixing crops, volatilization and leaching losses. Specifically, an emission factor of 1.25% from nitrogen applied as either fertilizer, biological nitrogen fixation or crop residue decomposition and 2.0% from nitrogen applied as animal manure. Emission factors of 1.0% and 2.5% respectively were applied to nitrogen assumed to have been lost through volatilization (10%) and leaching (30%) pathways.
- CH_4 and N_2O from the burning of crop residues, rice cultivation and from animals associated with grazing systems directly associated with sequestering technologies. Emission factors of 8 and 49 kg CH_4/head were applied to sheep and non-dairy cattle respectively and 100 kg CH_4/ha for rice.

Indirect, or off-site emissions, applicable to nitrogen fertilizer production were not included as they were considered off-site and not applicable to site specific carbon projects, and their inclusion at a project level is still a topic of contention in the international community. We do present limited data on the potential contribution of these emissions to net sequestration rates.

3.2 Economic potential

Having quantified the average carbon rates practices (on a full greenhouse accounting basis) for the changes that are feasible for the agro-ecological zones of each region, we then estimated three key components of the opportunity cost:

- The farm opportunity cost of changing practices, ΔNR_{is}. The ideal method for estimating farm opportunity costs is to collect data from a statistically representative sample of farms and land units. Cursory survey data is only available in many of our case study regions, in which case statistically representative distributions of farm opportunity costs were estimated. The methodology of Antle & Capalbo (2001) was utilized to construct economic models that simulate the net returns distributions under alternative price and technology scenarios. These models have previously been coupled with bio-physical models such as Century (as in Antle *et al*., 2001, 2003) to estimate the carbon supply curves for various price and technology scenarios. A simpler approach, as outlined herein, is to estimate the spatial distribution of opportunity costs for observed prices and technology to estimate a supply curve for observed prices and technology. When statistically representative data are not available, it has been necessary to construct synthetic estimates that represent the spatial heterogeneity in the population to the extent possible. We did this by utilizing sub-regional yields, prices, and cost of production data obtained from agricultural censuses and similar secondary data to estimate means of the net returns distributions. To estimate variability in returns, available reported data on yield variability was used. The most difficult part of this analysis was to obtain estimates of changes in yields and costs of production for the alternative production practices that sequester carbon but are not in widespread use (e.g., no-till practices). In this case, we used the expert judgement of our collaborators and local agronomists and agricultural economists to estimate the effects of these technologies.

- <u>The fixed costs of adoption, f_{is}.</u> It is possible to estimate the fixed costs of investing new capital associated with the conservation practice (e.g., the costs of new machinery and equipment needed for minimum tillage; or the costs of building terraces). Again, spatial variation in costs can be estimated to some degree (e.g., costs of terraces could vary with field slope or proximity to roads). However, in most cases, these costs of changing practices have not been measured in conventional production data and require estimation using engineering methods. This type of approach is beyond the scope of this project. As an alternative approach, we calibrated the economic models by adjusting the fixed adoption cost so that the model produced the observed allocation of land between conventional and alternative practices without carbon payments (i.e., so that the model reproduces the baseline land allocation). This procedure will incorporate all factors that constrain adoption, including physical capital costs as well as farmers' lack of information, financial constraints, risk perceptions, and so forth.

- The transaction costs of designing, negotiating, and verifying compliance with contracts, t_{is}. Until the actual implementation of carbon contracts occur, it is obviously difficult to estimate transactions costs associated with sequestration projects. Brokerage fees for similar kinds of financial transactions are considered to be reasonable first-order approximations to the costs of designing and negotiating contracts. Costs of verifying compliance with contracts also depends on the type of practices involved, the type of soil carbon measurement method used (e.g., field samples versus remote sensing) and the frequency and number of observations required (Mooney *et al*., 2002). Transaction costs depend on the size of the contract in terms of tonnes of carbon offset. Farm size actually plays a rather minor role, as it will be an aggregation of fields from a number of farms that will determine the marketable contract.

Using these data, a simulation model was then constructed to derive carbon supply curves for each spatial unit represented by the data. This simulation model draws multiple samples from the spatial distributions of net returns within each spatial unit, and computes the opportunity cost of changing from conventional to alternative practices for each activity in the spatial unit.

Next, for a range of given carbon prices, the model determines the proportion of hectares in the unit that participate in carbon contracts at each price, and then uses the carbon rate for that spatial unit to compute the total quantity of carbon sequestered in each spatial unit at each price.

Finally, the model constructs the supply curve for each sub-region and region by aggregating data across spatial units. Sensitivity analysis was performed on some of the key economic variables in combination with the changes in soil carbon changes to provide some estimates of uncertainty.

We have also provided a brief commentary on possible co-benefits and their impacts, but this would normally require large bio-physical modelling exercises not within the scope of this global cross-sectional study on soil carbon sequestration potential.

Instructions for completing the production data system data spreadsheet as distributed to cooperators are outlined in Appendix 1. Instructions for completing the transaction cost data spreadsheet as distributed to cooperators are outlined in Appendix 2.

4. Description of case studies

We considered a number of essential criteria in selecting regions for the soil carbon sequestration cost assessment study:

- Agro-ecological regions with proven high technical potential for carbon sequestration.
- Proven history of adoption of management strategies which promote carbon sequestration.
- Broad coverage of management strategies for promoting soil carbon sequestration - as identified in the IPCC Special Report on Land Use, Land Use Change and Forestry (IPCC, 2000).
- Availability of quality bio-physical and economic data for accurate assessment and extrapolation.
- Diversity in agro-economies (from both the developing and developed world).
- Diversity in agro-climatology (between regions) to ensure wide range of carbon sequestration potentials.
- Provide basis for extrapolation to other world regions (not part of this study).
- Presence of local collaborators experienced in greenhouse gas issues and their impacts in agricultural systems.

The case studies (i.e. regions) selected for the assessment of soil carbon sequestration potential represent a global cross-section of agro-climatologies and economies. One of the main considerations was also the access to reliable data through a network of qualified local collaborators.

4.1 South-Eastern South America - Uruguay

Uruguay has a subtropical to temperate climate with very marked seasonal fluctuations. The climate is classified as warm, temperate wet within the IPCC classification. Although there is no dry season, rainfall trends to be higher in the autumn and spring months going from south to north. The region is characterized by very high inter-annual rainfall variability, which is largely associated with El Niño/Southern Oscillation (ENSO) phases. The region is defined by the predominance of grasslands with rolling topography and a vegetation of grasses with other associated communities. The vast majority of the soils in the study region are Mollisols and Vertisols, with variable rooting depth (20-100 cm) and consequently, varying water holding capacity.

Production systems in this region include:

- Extensive livestock production: based on natural grasslands (similar to tall-grass prairies of the US Central Plains). An increasing area of these grasslands are being improved with the addition of legumes (no-tilled lotus, clovers) and/or the application of phosphorus fertilizers. The majority of the area is devoted to cow-calf operations, and a smaller proportion is used to finish steers. Usually these two production systems coexist in the same farm. This system covers abut 80% of the total land area in the country (more than 14 million ha).
- Annual crops in rotation with sown pastures: 3-4 years of annual crops (wheat and barley in the winter, maize, sunflower, soybeans, sorghum in the summer), alternating with 3-4 years of sown pastures (a mixture of fescue, ryegrass, red and white clover and birdsfoot trefoil). During the pasture stage of the rotation farmers raise cattle (mostly finishing steers, but also some cow-calf operations). Since the 1980's conventional tillage has been substituted by conservation (minimum) and no-tillage.

There are 7 major agro-ecological regions in Uruguay (Ferreira, 2001), with some sub-regionalization (Figure 3):

- Bassup (Basalt) – seasonal variation in climate limits the productivity and quality of natural pastures.
- Crsteste (East Sierras) - soils are mainly shallow or of medium depth with low fertility.
- Llaneste (East Plains) - large area under wetlands with rice the only significant crop.
- Crstcent (Granitic Centre) - medium to deep soils with 70% in natural pasture.
- Sierreste (East Lomadas) - natural pasture represents 80% of the area.

- Arenisc (Sandy soils) - deep soils of low fertility with potentially high productivity of low quality pastures.
- Noreste (Northeast) - soils with a high potential for increased productivity and suitable for both winter and summer crops and cultivated pasture.
- Basprof (Deep soils A) - natural pastures represent 90% of this zone, with irrigated rice has been increasing within the cropping systems.
- Litnort (Deep soils B) - main intensive livestock and crop production systems of the country which also supports rotational cropping.
- Litsur (Deep soils carbon) - main intensive livestock and crop production systems of the country, with the highest percentage of sown, improved and annual pastures.
- Lechsur (Deep soils) - dairying zone with vegetables and orchards.

There are over 14 Mha of natural grasslands in a varying state of degradation (often over-grazed) which are gradually being improved with the addition of leguminous species and/or application of P fertilizers. No-till farming is also increasing and whilst the case study will be centred on Uruguay, the outputs of this assessment are transportable to southern Brazil, Argentina and Paraguay.

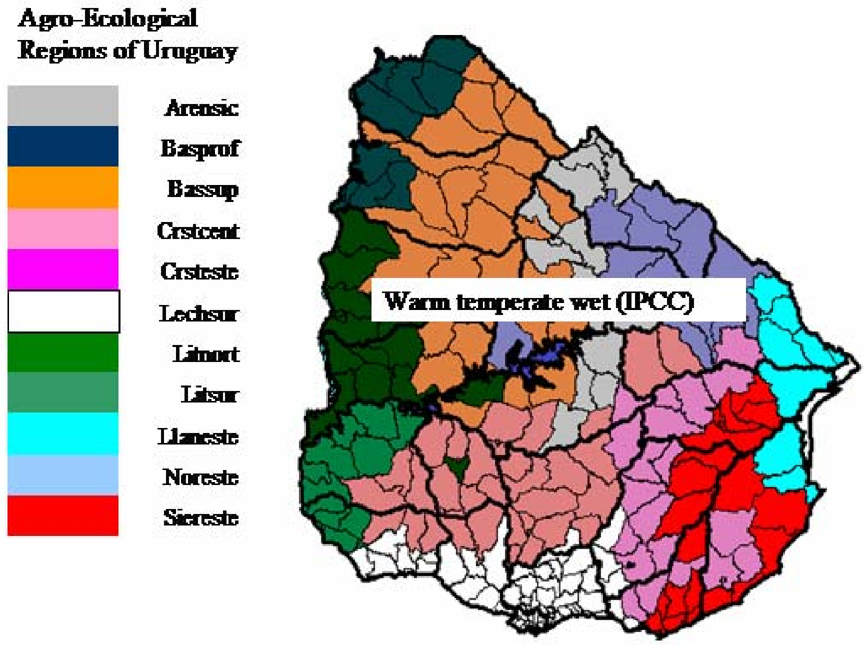

Figure 3. Location of agro-ecological regions of Uruguay.

4.2 The Indo-Gangetic Plain (IGP) of India

This region is considered one of the highest producing cereal production regions of the world and employs diverse fertilization management including organic manures. No-tillage is being successfully promoted across the region with soil carbon storage and fuel savings as major benefactors. The focus of this case study is the northern Indian systems which are monsoonal and comprise a mix of irrigated and non-irrigated systems in a sub-tropical environment within the states of Punjab, Haryana, Utter Pradesh, Bihar and West Bengal (Figure 4).

The region is characterized by fertile soils, favourable climate and abundant surface and groundwater and is the backbone of food security for the countries of the region. Rice and wheat, the major cereal crops of this region are grown in rotation on almost 12 million hectares. These crops are the principal source of food, nutrition and livelihood security for several hundred millions of people. The production of wheat has increased from 12.3 Mt in 1965 to 76 Mt in 2000 and the mean productivity has increased from 1 t ha^{-1} to 3.2 t ha^{-1} during that time. However, many long-term experiments in the region report significant declines in soil organic carbon in response to agronomic management (Duxbury et al., 2000).

It is also clear that the rice-wheat rotation over time has been removing more nutrients than the amount externally added through nitrogen fertilizers. Farmers, therefore, have to apply more fertilizers to get the same yields they were experiencing with less fertilizer 20-30 years ago. The fact the soils are now low in organic carbon but are in an environment which can sustain high levels of net primary production makes them particularly well suited to practices which can promote soil carbon sequestration.

The increased adoption and productivity of wheat and rice in rotation during last three decades has also resulted in a heavy usage of irrigation, fertilizer, electricity and diesel fuel. These have a direct impact on the emissions of all GHGs. It has been estimated that on an annual basis, rice-wheat system in IGP emits GHGs which has a global warming potential of 3 -8 Mg C ha^{-1} of carbon depending upon the management practices used (Grace et al., 2003).

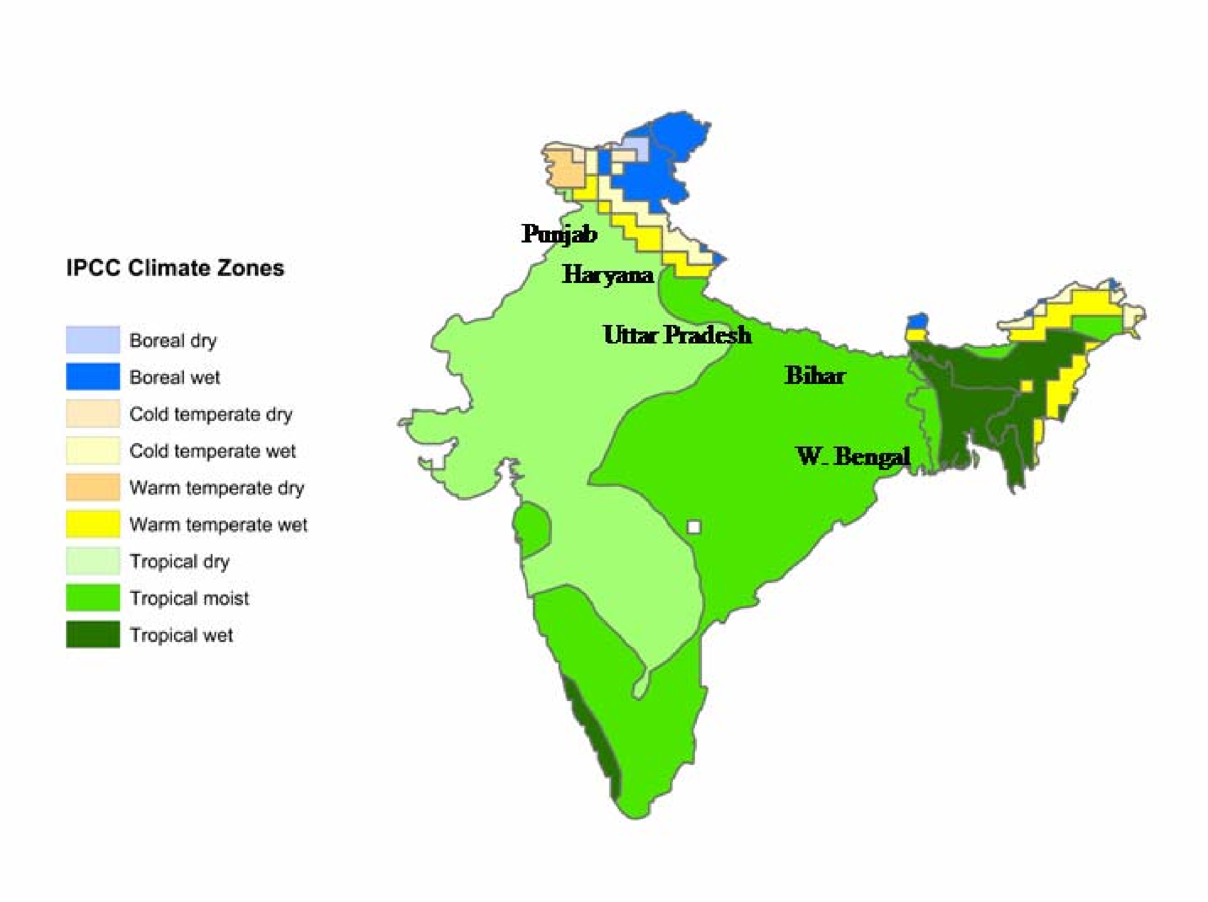

Figure 4. Location of case study states with the Indo-Gangetic Plain of India.

Opportunities for increasing carbon sequestration in agro-ecosystems of IGP and yet meet future food demands are of a high priority in this region. This requires analysis, monitoring and documentation of carbon, water and nutrient cycling in the region. Greater adoption of resource conservation technologies and diversification from rice-wheat are expected to sequester more carbon, enrich soil fertility and reduce other problems of agricultural sustainability. Recent research has shown that surface seeding or zero-tillage establishment of upland crops after rice gives similar yields to when planted under normal conventional tillage over a diverse set of soil conditions (Hobbs et al., 2000). This significantly reduces the costs of production, allows earlier planting and thus higher yields, results in less weed growth, reduces the use of natural resources such as fuel and steel for tractor parts, and shows improvements in efficiency of water and fertilizers. In addition, such resource conserving technologies restrict release of soil carbon thus mitigating increase of CO_2 in the atmosphere.

4.3 South-Eastern Australia

This region has a long history of mixed cereal and pasture systems, diversity in soil types and the promotion of conservation tillage and improved pasture systems. Two broadly defined agro-ecological zones exist representing both warm temperate wet and warm temperate dry agriculture as classified by the IPCC, similar to those found in Mediterranean regions of the world. The case study examines management options within the six distinct agro-ecological regions found in these two broader climatic zones (Figure 5).

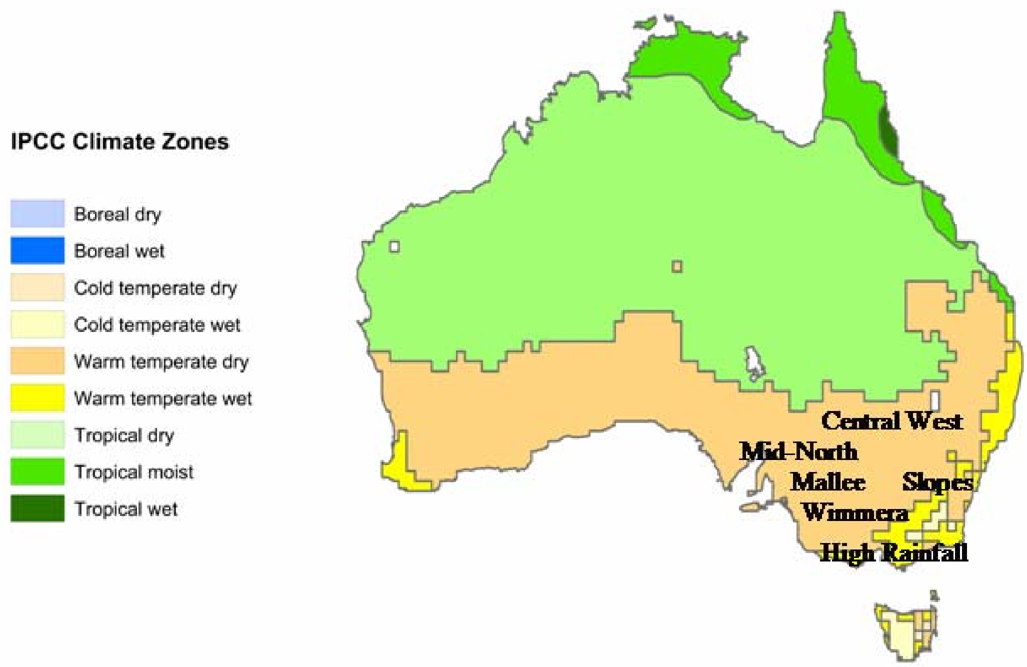

Figure 5. Location of case study regions within South-Eastern Australia.

The moist south-east zone, which includes the High Rainfall and Slopes regions, occurs south of the summer cropping zone and is considered the most reliable area of South-Eastern Australian for crop production, offering a high potential for soil carbon sequestration. Some summer rain does occur, sufficient to be an important source of stored water for winter crops but insufficient to regularly sustain summer crops. Wheat and barley are the dominant crops in the region, although smaller areas of oats and triticale are important. A considerable area is devoted to oats, grown as a grazing crop. The major rotation crop, within this zone is canola. Important grain legumes in the rotations are field peas, lupins, chick peas and faba beans (especially on alkaline soils in South Australia).

This zone also offers the greatest diversity of soils, ranging from podozolic and solodic soils on the eastern margins to grey clays and black earths. Cropping in much of the zone occurs on red earths and red-brown earths. Soil surface layers are usually sufficiently moist for a sufficient length of time for organic matter turnover to be fairly rapid. Crop and pasture rotations are relatively well developed within the region and farmers have traditionally relied on legume-based pastures to maintain soil carbon and improve nitrogen availability. As this is a livestock fattening region (both sheep and cattle, but predominantly sheep), special demands on pasture occur. Lucerne is an important rotation component in some areas. Many areas have a long history of pasture development based on subterranean clover and to a lesser extent on medics and other annual winter legumes.

The dry marginal south-east zone is normally considered the higher risk or marginal agricultural lands of South-Eastern Australia, apart from the Wimmera and its red clay soils which are on the fringe of wetter warm temperate wet zone (as classified by IPCC). The Mallee lands of Victoria, South Australia and south-west New South Wales form a large part of this zone with annual average rainfall are in the 300-350 mm range. Individual areas planted to crops are large, but not as a proportion of the duned landscape. Cultivated soils in the region are generally low in organic carbon (0.3-0.6%), with soils under virgin stands slightly greater than 1.0%. Problems occur due to the inability to generate sufficient organic matter to maintain soil structure, especially when long fallow phases are used. Residue loss through grazing plays a significant role in this environment, with wind erosion removing surface soil and problems of sand blasting of young crops.

Maintenance of soil fertility for production of high value wheat is a problem, especially in the more marginal areas of the Mallee, Mid-North and Central West regions where economic responses to nitrogen are limited. Changes in the organic carbon content of these sandy-loams are not usually as significant as the increases in plant carbon in response to nitrogen application, however with supplemental irrigation to boost production, changes in surface soil organic carbon are evident, even within the first growing season. This is usually negated by the decreased capacity of these coarse textured soils, which dominates the rainfed croplands in the semi-arid regions of southern Australia, to retain organic matter in the same proportion as heavy textured soils (Amato & Ladd, 1992).

Pastures here are generally more poorly developed, with the region generally being too dry or unsuitable (high pH) for subterranean clover. Medics are used in some areas as the basis for pastures together with volunteer annuals and native grasses. This is primarily a low stocking rate wool growing zone although some cattle do occur throughout the region. Cropping has become more intensive within this zone as the returns on wool growing have declined in recent years. The availability of large machinery enabling coverage of large areas in a short time has also facilitated the move toward increased cropping. With the use of few inputs and large economies of scale wheat cropping has tended to drift toward these areas.

4.4 Northern Europe - Sweden

This part of study is concentrated on Sweden (Figure 6), thus providing data for cold temperate moist agro-climatologies of Scandinavia which are not well represented in current studies. Arable land in Sweden covers about 3 Mha. Due to a favourable climate (moist, cold winters) young and fertile soils and well managed farms, the soils of the region have a high carbon content. In mineral soils (0-25 cm) there is approximately 80 Mg C ha^{-1}, which is believed to be close to steady state. On the other hand, there are about 0.3 Mha of cultivated organic soils, which on average contain 200 Mg C ha^{-1} and lose about 1 Mg C $annum^{-1}$.

Crops grown in southern Sweden are winter wheat, and rotated with barley in central Sweden. The proportion of pastures in southern Sweden is 12%, in central Sweden 24% and in northern

Sweden 60% (the same as in forest regions in central Sweden, Gsk). Winter wheat may yield up to 10 t ha^{-1} in southern Sweden, double that of the northern regions. Due to the long days during summer, the northern leys may still produce over 4 t dry matter ha^{-1}.

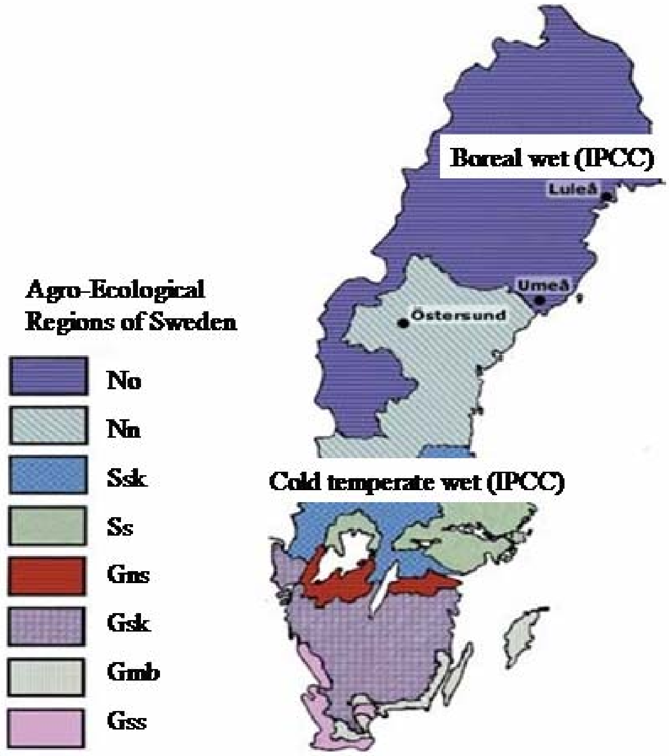

Figure 6. Agro-ecological regions of Sweden.

4.5 Central Asia - Northern Kazakhstan

The prime agricultural area in Kazakhstan is in the north of the country and covers 20 Mha with wheat, barley and oats the main crops, and some forages. Spring wheat covers over half of this area. Northern Kazakhstan has a continental climate very similar to the prairies of central Canada. The major cropping system in northern Kazakhstan is a wheat-fallow rotation, with one year of fallow followed by (an optimum) 3-4 years of wheat. Many decades under agrarian technologies promoted by the former Soviet Union have resulted in a general decline in the organic carbon stores for soils in this region of Central Asia. Representative soils are common chernozems with organic carbon contents (0-20 cm) of about 3.0%, southern chernozems about 2.5% and chestnut soils with organic carbon of 2%. These soils may be found in relatively distinct latitudinal bands and form the basis of the three major agro-ecological regions in this part of the country (Figure 7).

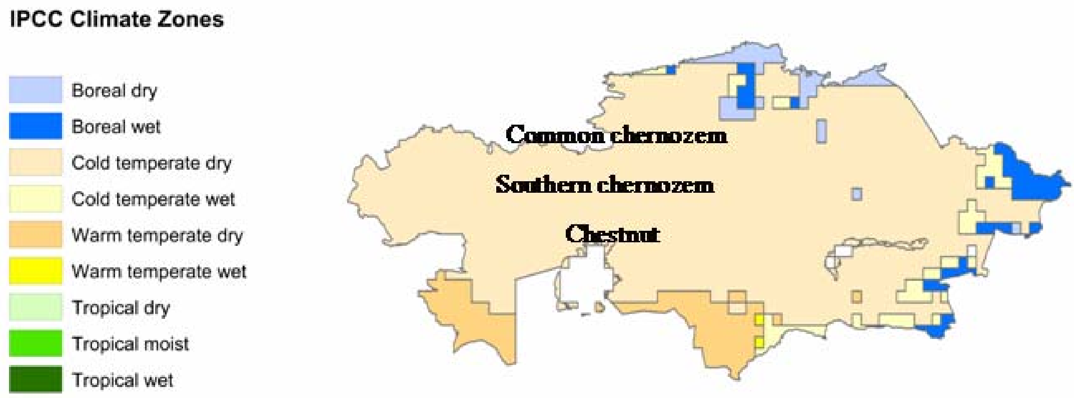

Figure 7. Agro-ecological regions of Northern Kazakhstan.

These soils have a high potential for increased soil carbon accumulation under improved management e.g. conservation tillage, reduced fallows and pastures. Legume crops are also now being introduced into common cereal rotations. In the rainfed semi-arid conditions of northern Kazakhstan, minimum and no-till are proving to be ideal for soil carbon storage as compared to general practice of deep tillage, provided adequate fertilization has been applied. In rainfed conditions of southern and south-eastern Kazakhstan, shallow and deep conservation tillage provides almost the same grain yield as that of conventional systems but minimum tillage has been generally found to be the most economical.

The replacement of worn-out agricultural machinery and equipment is a high priority for the government of Kazakhstan to promote improved agricultural management in this region. To effectively deal with the problem, the government has launched programs that encourage agricultural producers to lease machinery and equipment. A reduction in fertilizer usage has occurred in Kazakhstan due to their high cost. Increasing consumption will require investment in the mineral fertilizer production industry and the introduction of cost reducing technologies.

5. Results and Discussion

Results are presented as per the suggested protocol outlined in Annex A of the Technical specifications for IEA/CON/03/95.

5.1 Characteristics of regional agro-ecosystems

A total of ten country specific technologies were selected for the final analysis. A summary of the countries and practices is outlined in Table 5. Regional differences were also taken into account in each country, with up to 3 soil types (as per the IPCC classification) in each region. In all, 121 simulations were included in the global analysis, a small subset of the total number of soil carbon simulations actually performed to complete this study using the IPCC Tier 1 approach. The technologies identified as both practical and feasible as significant sequestering strategies for each country were selected for the final economic analysis.

The specific rotations and technologies for analysis within each of the nominated regions including the relevant IPCC soil, climate and system definitions required to complete the carbon simulations using the IPCC Tier 1 framework are outlined in Tables 6-10. Also included is a full listing of the associated GHG emission sources which partially offset simulated soil carbon change. The conventional technologies identified within each region were historically in wide use and deemed to be the baseline technology for the analysis.

In Uruguay (Table 6), conventional tillage has been superceded by minimum or reduced tillage systems over the past decade and the shift to mixed crop-pasture no-tillage rotations and grassland systems is considered optimal for carbon sequestration. Nitrogen fertilizers are applied to cereal crops at 45-70 kg ha^{-1} with yields for wheat, barley and soybean in the 2 t ha^{-1} range.

Maize yields average 4 t ha^{-1} with rice yielding close to 6 t ha^{-1}. Crop residues are generally retained, but some burning does occur every 3-4 years in conventional systems which are characterized by 3-4 tillage passes. In minimum tillage cropping systems, which are now the norm in Uruguay, crop residues are partially buried with the use of a broad spectrum herbicide to control weeds. In no-tillage systems, broad spectrum herbicides are typically applied before sowing. Sown pastures in rotation with crops are usually grazed (on average) with less than 1 steer ha^{-1}, nominally grasslands at about 0.65 steer ha^{-1}.

Table 5. Country and/or region specific technologies for assessing the potential magnitude and costs of soil carbon sequestration in a global market.

Country/Region	Current Practice	Future Practice	Regions	Sequence/Rotation
Uruguay	Minimum till	No-till	7	Crop
Uruguay	Minimum till	Pasture	7	Crop to Pasture
Indo-Gangetic Plain	Conventional till	No-till	5	Wheat – Rice
Indo-Gangetic Plain	Conventional till	No-till	1	Wheat – Maize
Indo-Gangetic Plain	Conventional till	No-till	2	Wheat – Cotton
Australia	Conventional till	Minimum till	6	Crop – pasture
Australia	Conventional till	No-till	6	Crop – pasture
Sweden	Cereal	Pasture	8	Crop to pasture
Kazakhstan	Conventional till	Minimum till	3	Crop – fallow
Kazakhstan	Conventional till	No-till	3	Crop – fallow

On the IGP of India (Table 7), multiple cropping is commonplace, with two crops per annum. The wheat-rice rotation dominates, with wheat-cotton and wheat-maize also common. Wheat and rice yields are in excess of 4 t ha^{-1} in the western extents of the IGP (Punjab and Haryana states) and tend to decrease heading east to W. Bengal. Maize and cotton are commonly found in Punjab and Uttar Pradesh with yields of 1-2 t ha^{-1}. A proportion of the wheat and maize residues are usually removed for animal feed or the production of fuel, whilst burning of rice straw is still the norm in conventional cropping systems. In minimum and no-tillage systems there is a tendency to retain higher levels of crop residue, but the effective sowing of seed into crop residues still poses problems, particularly after rice.

Nitrogen fertilizer applications range from 126-212 kg ha^{-1} applied to wheat, and 50-174 kg ha^{-1} to rice with a tendency for reduced applications in the lower yielding eastern states. Organic animal manures are applied as supplemental fertilizer sources to many of the crops, particularly rice. In the poorer eastern states, organic manures are generally the major source of nutrients, with 4-5 t ha^{-1} applied to both wheat and rice crops.

In Australia (Table 8), traditional crop-annual legume based pasture systems are generally being replaced by continuous cropping in combination with minimum or no-tillage in the high yield potential Wimmera region, and to a lesser extent in Mid-North South Australia. In contrast, in the High Rainfall region in the far south of the country, annual pastures offer the best returns, with long phases in the rotation. In both the Central West and the eastern Slopes regions, minimum and no-tillage systems are being favoured for increasing the cropping phases (replacing pastures) within a rotation sequence. In the lower rainfall Mallee, Central West and Slopes, 1-2 sheep ha^{-1} typically graze on crop residues left in the field. Grazing pressure is reduced to zero in no-tillage systems.

Pastures support higher grazing pressures than crop residues, ranging from 2.5 sheep ha^{-1} in the Mallee to 12 animals in the High Rainfall region. Yields for wheat and barley range from 2-2.5 t ha^{-1} on the semi-arid sandy-loam soils of the Mallee region to 4-4.5 t ha^{-1} on the heavy textured soils of the Wimmera region. Canola and grain legumes are common in the rotation sequence in most regions with yields of 2-2.5 t ha^{-1}. Nitrogen fertilizer applications of 50-100 kg ha^{-1} are normal for crops in all regions, except the Mallee, where little or no nitrogen fertilizers are applied. Nitrogen applications are generally at the lower end of this range when wheat is sown after a legume-based pasture.

In Sweden (Table 9), there is a distinct north-south gradient in wheat yields, ranging from 2.3-5.4 t ha^{-1}. Similarly, nitrogen fertilizer application is reduced in the northern regions, with only 26 kg ha^{-1} applied, compared to 88 kg ha^{-1} in the far south. Wheat is conventionally tilled and crop residues retained. There is no apparent move in the country towards minimum or no-tillage cropping. The alternative to cropping is continuous ley pastures for hay with significant carbon gains measured in these systems. Fuel consumption in the preparation and harvesting of these ungrazed leys is about 135 l ha-1, about double the consumption in the crop system. Nitrogen applications range from 82-136 kg ha^{-1}, again following the north-south climatic gradient.

In Kazakhstan (Table 10), crop residue removal is minimal in all systems in an attempt to control erosion. Wheat and barley yields in conventional tillage systems on the common chernozem soils range from 2-3 t ha^{-1} and may be as low as 1 t ha^{-1} on the chestnut soils further south. There is a tendency for slightly higher yields under minimum and no-tillage technologies but no consistent pattern as yet exists. Nitrogen fertilizers are not generally applied to conventional systems, however applications of 30 and 40 kg ha^{-1} are practiced in minimum and no-tillage systems respectively.

Table 6. Rotation sequences and nominated carbon sequestering technologies for agro-ecological regions of Uruguay, including IPCC environmental classifications and associated greenhouse gas emission sources.

Region	Rotation[1]	Technology[2]	IPCC Climate[3]	IPCC Soil[4]	IPCC Carbon Input[5]	Other GHG Sources[6]					
						Burn	N Inputs	N Losses	Rice	Animal	Fuel
Basprof	RSoWMSyBSu3P	MIN*	wtw	lac/hac/san	high	X	X	X	X		X
	RSoWMSyBSu3P	NOT	wtw	lac/hac/san	high		X	X	X		X
	Gr	GRASS	wtw	lac/hac/san	nominal		X	X		X	
Crstcent	RSoWMSyBSu3P	MIN*	wtw	lac/hac/san	high	X	X	X	X		X
	RSoWMSyBSu3P	NOT	wtw	lac/hac/san	high		X	X	X		X
	Gr	GRASS	wtw	lac/hac/san	nominal		X	X		X	
Lechsur	RSoWMSyBSu3P	MIN*	wtw	lac/hac/san	high	X	X	X	X		X
	RSoWMSyBSu3P	NOT	wtw	lac/hac/san	high		X	X	X		X
	Gr	GRASS	wtw	lac/hac/san	nominal		X	X		X	
Litnort	RSoWMSyBSu3P	MIN*	wtw	lac/hac/san	high	X	X	X	X		X
	RSoWMSyBSu3P	NOT	wtw	lac/hac/san	high		X	X	X		X
	Gr	GRASS	wtw	lac/hac/san	nominal		X	X		X	
Litsur	RSoWMSyBSu3P	MIN*	wtw	lac/hac/san	high	X	X	X	X		X
	RSoWMSyBSu3P	NOT	wtw	lac/hac/san	high		X	X	X		X
	Gr	GRASS	wtw	lac/hac/san	nominal		X	X		X	
Llaneste	RSoWMSyBSu3P	MIN*	wtw	lac/hac/san	high	X	X	X	X		X
	RSoWMSyBSu3P	NOT	wtw	lac/hac/san	high		X	X	X		X
	Gr	GRASS	wtw	lac/hac/san	nominal		X	X		X	
Noreste	RSoWMSyBSu3P	MIN*	wtw	lac/hac/san	high	X	X	X	X		X
	RSoWMSyBSu3P	NOT	wtw	lac/hac/san	high		X	X	X		X
	Gr	GRASS	wtw	lac/hac/san	nominal		X	X		X	

*baseline system
X = emissions included from this source
[1]R = rice, So = sorghum, W = wheat, M = maize, Sy = soybean, B = barley, Su = sunflower, P = sown pasture, Gr = nominally managed grassland ; one crop every year but not all nominated crops may be included, usually 4-5 years of single crops followed by 3-4 years of pasture; numbers preceding abbreviation denote number of consecutive years.
[2]MIN = minimum tillage, NOT = no tillage, GRASS = nominally managed grassland
[3]wet temperate wet
[4]lac = low activity soils, hac = high activity soils, san= sandy soils. For more detail refer to Table 1.
[5]Relative carbon input into agro-ecosystem (low = crop + fallow; medium = crop + residues retained; high = crop+ pasture, nominal = native grass, no degradation).
[6]Burn = N_2O + CH_4 from crop residue burning, N inputs = N_2O from fertilizer, manure, biological nitrogen fixation and crop residue decomposition, N losses = N_2O from volatilization and leaching, Rice = CH_4 from flooded rice, Animal = CH_4 from sheep or cattle grazing, Fuel = CO_2 from fuel combusted during tillage, planting, harvesting and spraying operations.

Table 7. Rotation sequences and nominated carbon sequestering technologies for regional agro-ecosystems of the Indo-Gangetic Plain of India, including IPCC classifications and associated greenhouse gas emission sources.

Region	Rotation[1]	Technology[2]	IPCC Climate[3]	IPCC Soil[4]	IPCC Input System[5]	Other GHG Sources[6]					
						Burn	N Inputs	N Losses	Rice	Animal	Fuel
Haryana	WC	CONV*	trd	lac	medium	X	X	X			X
	WC	NOT	trd	lac	medium	X	X	X			X
	WC	CONV*	trd	san	medium	X	X	X			X
	WC	NOT	trd	san	medium	X	X	X			X
	WR	CONV*	trd	lac	medium	X	X	X	X		X
	WR	NOT	trd	lac	medium	X	X	X	X		X
	WR	CONV*	trd	san	medium	X	X	X	X		X
	WR	NOT	trd	san	medium	X	X	X	X		X
Punjab	WC	CONV*	trd	lac	medium	X	X	X			X
	WC	NOT	trd	lac	medium	X	X	X			X
	WC	CONV*	trd	san	medium	X	X	X			X
	WC	NOT	trd	san	medium	X	X	X			X
	WR	CONV*	trd	hac	medium	X	X	X	X		X
	WR	NOT	trd	hac	medium	X	X	X	X		X
	WR	CONV*	trd	lac	medium	X	X	X	X		X
	WR	NOT	trd	lac	medium	X	X	X	X		X
	WR	CONV*	trd	san	medium	X	X	X	X		X
	WR	NOT	trd	san	medium	X	X	X	X		X
Utter Pradesh	WM	CONV*	trd	lac	medium	X	X	X			X
	WM	NOT	trd	lac	medium	X	X	X			X
	WR	CONV*	trd	hac	medium	X	X	X	X		X
	WR	NOT	trd	hac	medium	X	X	X	X		X
	WR	CONV*	trd	lac	medium	X	X	X	X		X
	WR	NOT	trd	lac	medium	X	X	X	X		X
Bihar	WR	CONV*	trm	lac	medium	X	X	X	X		X
	WR	NOT	trm	lac	medium	X	X	X	X		X
W. Bengal	WR	CONV*	trm	hac	medium	X	X	X	X		X
	WR	NOT	trm	hac	medium	X	X	X	X		X
	WR	CONV*	trm	lac	medium	X	X	X	X		X
	WR	NOT	trm	lac	medium	X	X	X	X		X

Region	Rotation[1]	Technology[2]	IPCC Climate[3]	IPCC Soil[4]	IPCC Input System[5]	Other GHG Sources[6] Burn	N Inputs	N Losses	Rice	Animal	Fuel
Table 7. (cont)											
	WR	CONV*	trm	san	medium	X	X	X	X		X
	WR	NOT	trm	san	medium	X	X	X	X		X

* = baseline system
X = emissions included from this source
[1]W = wheat, C = cotton, R = rice. Two crops in rotation every year.
[2]CONV = conventional tillage, NOT = no tillage
[3]Refer to Figure 4.
[4] lac = low activity soils, hac = high activity soils, san= sandy soils. For more detail refer to Table 1.
[5]Relative carbon input into cropping or pasture system (e.g. low = crop + fallow; medium = crop + residues retained, or crop + residues removed + organic manures; high = crop + pasture).
[6]Burn = N_2O + CH_4 from crop residue burning, N inputs = N_2O from fertilizer, manure, biological nitrogen fixation and crop residue decomposition, N losses = N_2O from volatilization and leaching, Rice = CH_4 from flooded rice, Animal = CH_4 from sheep or cattle grazing, CO_2 from fuel combusted during tillage, planting, harvesting and spraying operations.

Table 8. Rotation sequences and nominated carbon sequestering technologies for agro-ecological regions of South-Eastern Australia, including IPCC classifications and associated greenhouse gas emission sources.

Region	Rotation[1]	Technology[2]	IPCC Climate[3]	IPCC Soil[4]	IPCC Input System[5]	Other GHG Sources[6]					
						Burn	N Inputs	N Losses	Rice	Animal	Fuel
Mallee	WPLf	CONV*	wtd	san	low		X	X		X	X
	WPLf	MIN	wtd	san	low		X	X		X	X
	WPLf	NOT	wtd	san	low		X	X		X	X
Wimmera	WWBCG	CONV*	wtd	hac	low		X	X		X	X
	WWBCG	MIN	wtd	hac	medium		X	X			X
	WWBCG	NOT	wtd	hac	medium		X	X			X
High Rainfall	WBCW10P	CONV*	wtw	hac	high		X	X		X	X
	WBCW10P	MIN	wtw	hac	high		X	X		X	X
	WBCW10P	NOT	wtw	hac	high		X	X		X	X
Mid-North	WCBG	CONV*	wtd	lac	low		X	X		X	X
	WCBG	MIN	wtd	lac	medium		X	X			X
	WCBG	NOT	wtd	lac	medium		X	X			X
Central West	WWC6PLf	CONV*	wtd	lac	low		X	X		X	X
	WWC6PLf	MIN	wtd	lac	medium		X	X		X	X
	WWBC5PLf	NOT	wtd	lac	medium		X	X		X	X
Slopes	WWB5PLf	CONV*	wtd	hac	medium		X	X		X	X
	WWBC4PLf	MIN	wtd	hac	medium		X	X		X	X
	WWBCG3PLf	NOT	wtd	hac	medium		X	X		X	X

* = baseline system

X = emissions included from this source

[1]W = wheat, B = barley, C = canola, G = grain legume, P = pasture, Lf = long fallow; one crop or pasture every year; numbers preceding abbreviation denote number of consecutive years.

[2]CONV = conventional tillage, MIN = minimum tillage, NOT = no tillage

[3]Refer to Figure 5.

[4] lac = low activity soils, hac = high activity soils, san= sandy soils. For more detail refer to Table 1.

[5]Relative carbon input into cropping or pasture system (e.g. low = crop + fallow; medium = crop + residues retained; high = crop+ pasture).

[6]Burn = N_2O + CH_4 from crop residue burning, N inputs = N_2O from fertilizer, manure, biological nitrogen fixation and crop residue decomposition, N losses = N_2O from volatilization and leaching, Rice = CH_4 from flooded rice, Animal = CH_4 from sheep or cattle grazing, CO_2 from fuel combusted during tillage, planting, harvesting and spraying operations.

Table 9. Rotation sequences and nominated carbon sequestering technologies for agro-ecological regions of Sweden, including IPCC classifications and associated greenhouse gas emission sources.

Region	Rotation[1]	Technology[2]	IPCC Climate[3]	IPCC Soil[4]	IPCC Input System[5]	Other GHG Sources[6]					
						Burn	N Inputs	N Losses	Rice	Animal	Fuel
Gss	W*	CONV*	ctm	hac	high		X	X			X
	P	n.a.	ctm	hac	nominal		X	X			X
Gmb	W*	CONV*	ctm	hac	High		X	X			X
	P	n.a.	ctm	hac	nominal		X	X			X
Gsk	W*	CONV*	ctm	hac	High		X	X			X
	P	n.a.	ctm	hac	nominal		X	X			X
Gns	W*	CONV*	ctm	hac	High		X	X			X
	P	n.a.	ctm	hac	nominal		X	X			X
Ss	W*	CONV*	ctm	hac	High		X	X			X
	P	n.a.	ctm	hac	nominal		X	X			X
Ssk	W*	CONV*	ctm	hac	High		X	X			X
	P	n.a.	ctm	hac	nominal		X	X			X
Nn	W*	CONV*	ctm	hac	High		X	X			X
	P	n.a.	ctm	hac	nominal		X	X			X
No	W*	CONV*	ctm	hac	High		X	X			X
	P	n.a.	ctm	hac	nominal		X	X			X

* = baseline system

X = emissions included from this source

[1]CONV = conventional tillage, n.a. not applicable

[2]W= spring wheat, P = pasture. One crop or pasture every year.

[3]Refer to Figure 6.

[4] lac = low activity soils, hac = high activity soils, san= sandy soils. For more detail refer to Table 1.

[5]Relative carbon input into cropping or pasture system (e.g. low = crop + fallow; medium = crop + residues retained; high = crop+ pasture, nominal = nominally managed grassland).

[6]Burn = N_2O + CH_4 from crop residue burning, N inputs = N_2O from fertilizer, manure, biological nitrogen fixation and crop residue decomposition, N losses = N_2O from volatilization and leaching, Rice = CH_4 from flooded rice, Animal = CH_4 from sheep or cattle grazing, CO_2 from fuel combusted during tillage, planting, harvesting and spraying operations.

Table 10. Rotation sequences and nominated carbon sequestering technologies for agro-ecosystems of Northern Kazakhstan, including IPCC classifications and associated greenhouse gas emission sources.

Region	Rotation[1]	Technology[2]	IPCC Climate[3]	IPCC Soil[4]	IPCC System[5]	Other GHG Sources[6] Burn	N Inputs	N Losses	Rice	Animal	Fuel
Common Chernozem	4WLf	CONV*	ctd	hac	low		X				X
	5W	MIN	ctd	hac	medium		X	X			X
	5W	NOT	ctd	hac	medium		X	X			X
Southern Chernozem	4WLf	CONV*	ctd	hac	low		X				X
	5W	MIN	ctd	hac	medium		X	X			X
	5W	NOT	ctd	hac	medium		X	X			X
Chestnut	3WLf	CONV*	ctd	hac	low		X				X
	4W	MIN	ctd	hac	medium		X	X			X
	4W	NOT	ctd	hac	medium		X	X			X

* = baseline system
X = emissions included from this source
[1]W = wheat, Lf = long fallow; One crop every year.
[2]CONV = conventional tillage, MIN = minimum tillage, NOT = no tillage
[3]Refer to Figure 7.
[4]lac = low activity soils, hac = high activity soils, san= sandy soils. For more detail refer to Table 1.
[5]Relative carbon input into cropping or pasture system (e.g. low = crop + fallow; medium = crop + residues retained; high = crop+ pasture).
[6]Burn = N_2O + CH_4 from crop residue burning, N inputs = N_2O from fertilizer, manure, biological nitrogen fixation and crop residue decomposition, N losses = N_2O from volatilization and leaching, Rice = CH_4 from flooded rice, Animal = CH_4 from sheep or cattle grazing, Fuel = CO_2 from fuel combusted during tillage, planting, harvesting and spraying operations.

5.2 Soil carbon change

The technical potential for soil organic carbon sequestration (in contrast to its economic potential) was calculated using the widely accepted IPCC Tier 1 approach. Ten country specific scenarios were simulated and the results of the 20 year simulations for each of the 5 regions are summarized. The reported carbon changes are relative to the nominated baseline technology. The reported unadjusted soil carbon values refer to gross carbon changes over 20 years without correcting for associated field emissions of GHGs. Adjusted soil carbon values are reported after taking these associated emissions (referred to as carbon offsets) into account.

5.2.1 Principal results

The largest gross, or unadjusted, changes in soil organic carbon after 20 years were found in the high activity soils with reasonably high clay contents. In Uruguay, 12.4 Mg C ha^{-1} was sequestered under nominally managed pasture which had been previously cropped. Converting conventionally tilled systems to no-tillage on high activity soils was also effective as a sequestering technology across most of the sub-regions of Uruguay.

In the High Rainfall region of South-Eastern Australia, 11.8 Mg C ha^{-1} was sequestered over 20 years. Other significant gains under no-tillage were simulated in the wheat-rice rotation of West Bengal of the IGP (8.7 Mg C ha^{-1}) and wheat systems of Kazakhstan (7.38 Mg C ha^{-1}). The smallest gains in soil organic carbon, 0.4 and 1.4 Mg C ha^{-1}, were found under minimum and no-tillage systems respectively, on the relatively infertile sandy soils of the Mallee region in South-Eastern Australia.

The implementation of minimum tillage is also considered an effective strategy, sequestering (on average) 3.5 Mg C ha^{-1} compared to conventional tillage across all regions and soil types of Australia and Kazakhstan. These gains over 20 years are comparable to those found when converting cereals to pastures in Sweden, and the conversion of minimum and conventional tillage systems respectively to no-tillage in both Uruguay and the IGP. In the regions were minimum and no-tillage systems were directly compared to conventional tillage as sequestering technologies (Kazakhstan and Australia), no-tillage returned (on average) an additional 72% more carbon than minimum tillage systems.

Gross changes in soil carbon may present a false impression of the full benefit in terms of greenhouse gas emissions. A full greenhouse gas accounting methodology is becoming the norm in the assessment of carbon sequestration projects. The adjusted values take into account field based emissions of CO_2 from fuel combustion and CH_4 and N_2O from burning or biological activities. The calculated emissions (or associated losses) of GHGs over 20 years ranged from as low as 1.2 Mg C (equivalents) ha^{-1} in the conventional cropping systems of Kazakhstan, to 34.8 Mg C ha^{-1} from the high input rice-wheat systems of the Punjab in the IGP.

Off-farm emissions (e.g. CO_2 produced in the production of nitrogenous fertilizers) were not specifically included in our carbon offset calculations. The Haber-Bosch process for producing fertilizer nitrogen results in the production of 0.375 moles of CO_2 per mole of nitrogen produced at 100% efficiency (Schlesinger, 1999). At normal efficiencies, a mole of nitrogen is manufactured at a cost of about 0.58 moles of carbon released as CO_2 (IPCC, 1997). Additional CO_2 produced during the processing, transport, and application of nitrogen fertilizer increases this value to around 1.4 moles of carbon released per mole of nitrogen applied (Schlesinger, 1999; Izaurralde *et al*., 2000).

For comparison, if we had included these off-farm emissions (using the conversion factor of 1.4 moles of carbon per mole of nitrogen applied), the emissions over 20 years from (e.g.) conventionally tilled rice-wheat systems of the Punjab of the IGP would have increased by 9.3 Mg C ha^{-1} to 44 Mg C ha^{-1}, an increase of 27%. However, in the IGP there is no difference in nitrogen application between technologies, so the overall change with no-tillage (with respect to conventional) would not have been affected. In the low input cropping systems of Kazakhstan, where conventionally tilled systems do not receive nitrogen fertilizer, a shift to reduced tillage does involve the addition of 30 kg N ha^{-1} $annum^{-1}$. This would increase N_2O emissions (relative to conventional tillage) by an amount equivalent to 0.7 Mg C ha^{-1} over 20 years. The average net gain in soil carbon as a result of implementing minimum tillage would in turn be reduced by 25% to 2.1 Mg C ha^{-1}.

Globally, there is little conclusive evidence of differential nitrogen fertilizer application with specific technologies, and it is not possible within the limited bounds of the current study to derive such information. Such information would only be derived through the use of highly detailed farm surveys. The assessment herein does include CO_2 emissions from the combustion of fuel in tractors associated with a wide range of on-farm operations, and it would be difficult to specifically nominate a fraction of the 1.4 conversion factor to the application of nitrogen fertilizer alone. Considering the fact that most technologies within the regions we have assayed do not receive different nitrogen fertilizer inputs, the inclusion of the off-farm data on emissions associated with nitrogen fertilizer production, processing and transport would not have affected the outputs to any great extent.

Except for Sweden and Kazakhstan, the new technologies tended to have slightly lower ancillary on-farm emissions compared to the baseline systems. Therefore the same basic trend existed with respect to the ranking of the most effective sequestering technologies. The largest net (i.e. adjusted) changes in soil carbon after 20 years were found in the high activity soils with reasonably high clay content.

In Uruguay, 14.4 Mg C ha^{-1} was sequestered under nominally managed pasture that had been previously cropped, nearly 2 Mg C ha^{-1} more than if we had just considered the gross carbon change in isolation. Converting conventionally tilled systems to no-tillage on high activity soils was a consistent sequestering technology across most of the regions except Kazakhstan where it had lost some of the gains due to the increased emissions of associated GHGs under no-tillage.

In the High Rainfall region of South-Eastern Australia, 12.7 Mg C ha^{-1} was sequestered over 20 years. Other significant gains under no-tillage were simulated in the rice-wheat rotation of West Bengal of the IGP (9.6 Mg C ha^{-1}) and cropping systems of the Wimmera region of South-Eastern Australia (9 Mg C ha^{-1}). Overall, the smallest gains in organic carbon, 0.6 and 1.6 Mg C ha^{-1}, were in soils under minimum and no-tillage systems on the sandy soils of the Mallee region in South-Eastern Australia.

The adjusted net gains in soil organic carbon over 20 years for the ten country specific technologies are ranked in Figure 8. The average carbon sequestration gain in the top 30 cm of soil over 20 years was 5 Mg C ha^{-1}, or 250 kg C ha^{-1} $annum^{-1}$ and ranged from 10.7 Mg C ha^{-1} under pasture in Uruguay, to 2.1 Mg C ha^{-1} under pastures in Sweden. It is interesting to note that technologies which performed best had also been adjusted for a wide array of ancillary emissions of significant magnitude (e.g. CH_4 from grazing animals in Uruguay and South Eastern Australia as well as from rice cultivation in the IGP). In Sweden, the only offsetting emissions were CO_2 from fuel combustion and N_2O from fertilizer application, emission sources common to all the technologies assessed. All of the tillage based technologies produced net carbon gains over 20 years in the mid range of our analysis i.e. 2.9 - 6.3 Mg C ha^{-1}. The country specific land areas required to sequester 10,000 Mg C $annum^{-1}$ for each of these technologies (based on the average soil carbon accumulation rates depicted in Figure 8) are reported in Figure 9. The land areas range from 18,750 ha under pasture in Uruguay to 96,400 ha under pasture in Sweden.

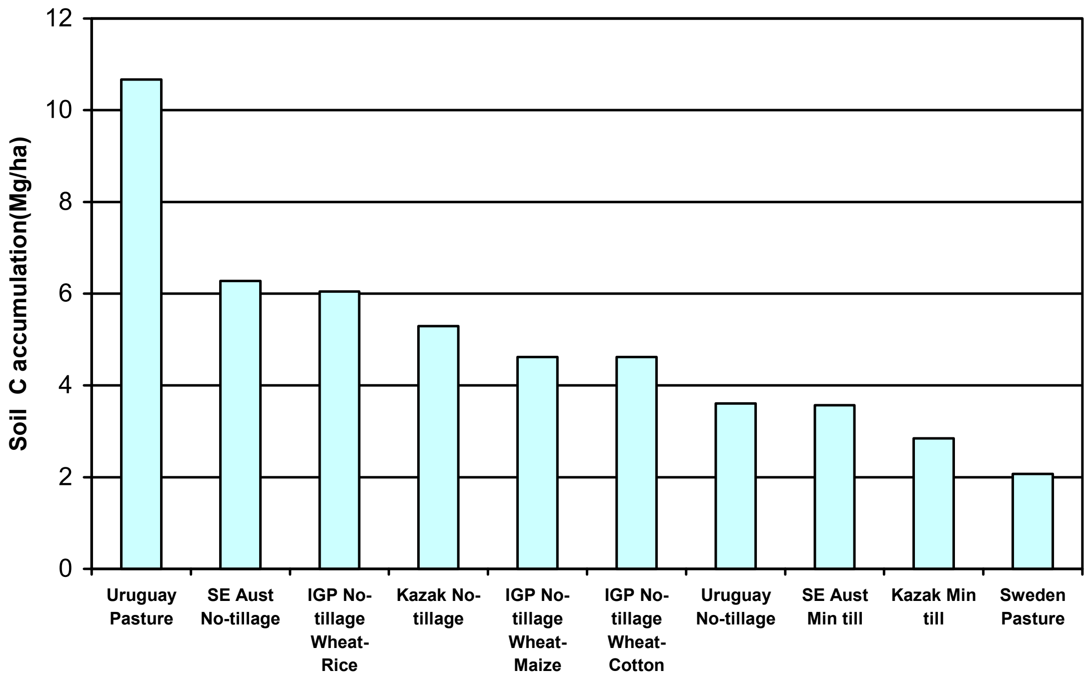

Figure 8. Rank order of simulated net gains in soil organic carbon (0-30 cm) after 20 years in response to technological changes (i.e. pasture or tillage) relative to conventional management and adjusted for on-field emissions of GHGs associated with implementing these practices.

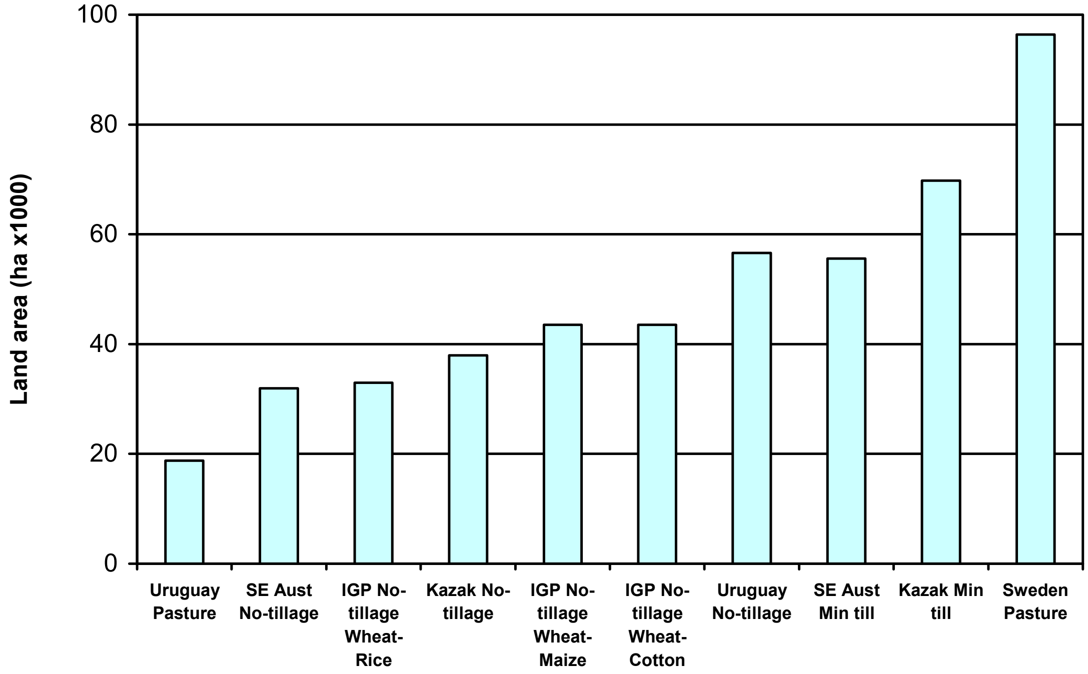

Figure 9. Land areas required for regional practices to sequester 10,000 Mg C per annum without considering economic constraints.

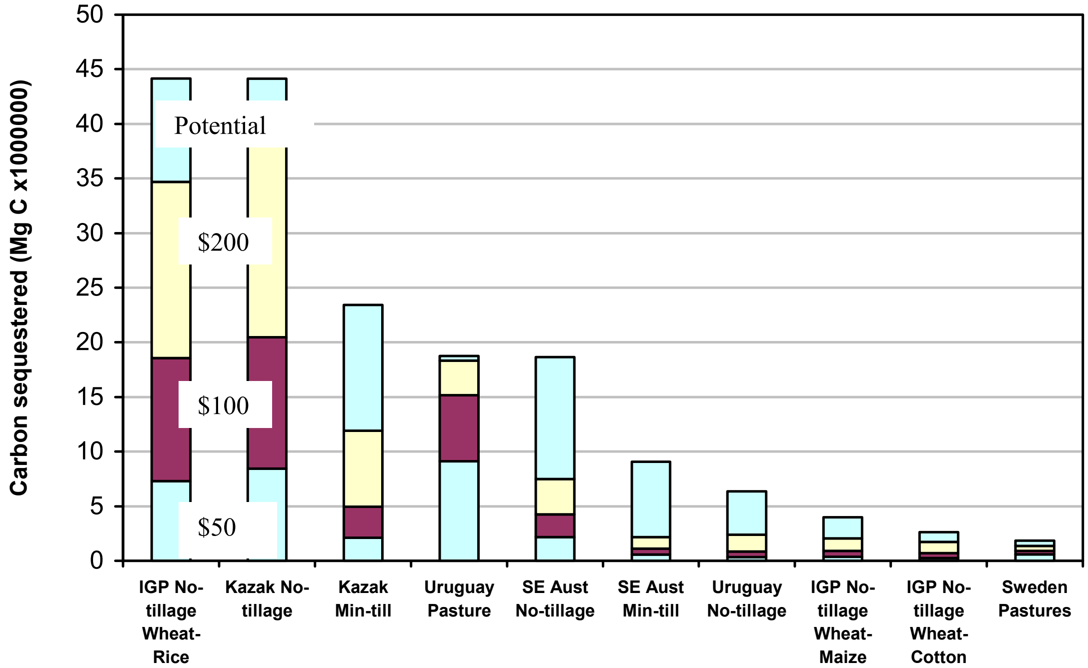

Figure 10. Rank order of total carbon potentially sequestered for region specific technologies relative to baseline technologies. Incremental changes in soil carbon (0-30 cm) after 20 years, for $50, $100, $200 Mg C ha^{-1} and no economic constraints (i.e., the technical potential).

Table 11. Impact of tillage on soil organic carbon (0-30 cm) and associated field based greenhouse gas emissions in agro-ecological regions of Uruguay.

Region	Soil type[1]	Unadjusted C Stock[2] Mg C ha^{-1}		Carbon Offsets[3] Mg C ha^{-1}		Adjusted C Stock[4] Mg C ha^{-1}		Carbon Change[5] Mg C ha^{-1}		Area[6] ha x1000
		*Minimum till**	*No-tillage*	*Minimum till**	*No-tillage*	*Minimum till**	*No-tillage*	*Unadjusted*	*Adjusted*	
Basprof	hac	75.57	80.42	7.65	7.44	67.92	72.98	4.85	5.06	40.0
Basprof	lac	54.10	57.57	7.65	7.44	46.45	50.13	3.47	3.68	55.6
Basprof	san	29.20	31.07	7.65	7.44	21.55	23.63	1.87	2.08	100.0
Crstcent	hac	75.57	80.42	7.65	7.44	67.92	72.98	4.85	5.06	40.0
Crstcent	lac	54.10	57.57	7.65	7.44	46.45	50.13	3.47	3.68	55.6
Crstcent	san	29.20	31.07	7.65	7.44	21.55	23.63	1.87	2.08	100.0
Lechsur	hac	75.57	80.42	7.65	7.44	67.92	72.98	4.85	5.06	40.0
Lechsur	lac	54.10	57.57	7.65	7.44	46.45	50.13	3.47	3.68	55.6
Lechsur	san	29.20	31.07	7.65	7.44	21.55	23.63	1.87	2.08	100.0
Litnort	hac	75.57	80.42	7.65	7.44	67.92	72.98	4.85	5.06	40.0
Litnort	lac	54.10	57.57	7.65	7.44	46.45	50.13	3.47	3.68	55.6
Litnort	san	29.20	31.07	7.65	7.44	21.55	23.63	1.87	2.08	100.0
Litsur	hac	75.57	80.42	7.65	7.44	67.92	72.98	4.85	5.06	40.0
Litsur	lac	54.10	57.57	7.65	7.44	46.45	50.13	3.47	3.68	55.6
Litsur	san	29.20	31.07	7.65	7.44	21.55	23.63	1.87	2.08	100.0
Llaneste	hac	75.57	80.42	7.65	7.44	67.92	72.98	4.85	5.06	40.0
Llaneste	lac	54.10	57.57	7.65	7.44	46.45	50.13	3.47	3.68	55.6
Llaneste	san	29.20	31.07	7.65	7.44	21.55	23.63	1.87	2.08	100.0
Noreste	hac	75.57	80.42	7.65	7.44	67.92	72.98	4.85	5.06	40.0
Noreste	lac	54.10	57.57	7.65	7.44	46.45	50.13	3.47	3.68	55.6
Noreste	san	29.20	31.07	7.65	7.44	21.55	23.63	1.87	2.08	100.0

*baseline technology
[1]lac = low activity soils, hac = high activity soils, san= sandy soils. For more detail refer to Table 1.
[2]Simulated soil organic carbon change (0-30cm) after 20 years.
[3]Associated on-field greenhouse gas emissions over 20 years (expressed as carbon equivalents) as outlined in Table 6
[4]Simulated soil organic carbon change (0-30 cm) after 20 years and adjusted for associated greenhouse gas emissions.
[5]Net soil organic carbon change (0-30 cm) under the new technology relative to the baseline practice after 20 years.
[6]Area required to sequester 10000 Mg C per annum under the new technology based on adjusted soil carbon change per annum.

Table 12. Impact of tillage and pasture technologies on soil organic carbon (0-30 cm) and associated field based greenhouse gas emissions in agro-ecological regions of Uruguay.

Region	Soil type[1]	Unadjusted C Stock[2] Mg C ha^{-1}		Carbon Offsets[3] Mg C ha^{-1}		Adjusted C Stock[4] Mg C ha^{-1}		Carbon Change[5] Mg C ha^{-1}		Area[6] ha x1000
		*Minimum till**	*Pasture*	*Minimum till*	*Pasture*	*Minimum till*	*Pasture*	*Unadjusted*	*Adjusted*	
Basprof	hac	75.57	87.98	7.65	5.68	67.92	82.30	12.41	14.38	13.9
Basprof	lac	54.10	62.99	7.65	5.68	46.45	57.31	8.89	10.86	18.5
Basprof	san	29.20	33.99	7.65	5.68	21.55	28.31	4.79	6.76	29.4
Crstcent	hac	75.57	87.98	7.65	5.68	67.92	82.30	12.41	14.38	13.9
Crstcent	lac	54.10	62.99	7.65	5.68	46.45	57.31	8.89	10.86	18.5
Crstcent	san	29.20	33.99	7.65	5.68	21.55	28.31	4.79	6.76	29.4
Lechsur	hac	75.57	87.98	7.65	5.68	67.92	82.30	12.41	14.38	13.9
Lechsur	lac	54.10	62.99	7.65	5.68	46.45	57.31	8.89	10.86	18.5
Lechsur	san	29.20	33.99	7.65	5.68	21.55	28.31	4.79	6.76	29.4
Litnort	hac	75.57	87.98	7.65	5.68	67.92	82.30	12.41	14.38	13.9
Litnort	lac	54.10	62.99	7.65	5.68	46.45	57.31	8.89	10.86	18.5
Litnort	san	29.20	33.99	7.65	5.68	21.55	28.31	4.79	6.76	29.4
Litsur	hac	75.57	87.98	7.65	5.68	67.92	82.30	12.41	14.38	13.9
Litsur	lac	54.10	62.99	7.65	5.68	46.45	57.31	8.89	10.86	18.5
Litsur	san	29.20	33.99	7.65	5.68	21.55	28.31	4.79	6.76	29.4
Llaneste	hac	75.57	87.98	7.65	5.68	67.92	82.30	12.41	14.38	13.9
Llaneste	lac	54.10	62.99	7.65	5.68	46.45	57.31	8.89	10.86	18.5
Llaneste	san	29.20	33.99	7.65	5.68	21.55	28.31	4.79	6.76	29.4
Noreste	sac	75.57	87.98	7.65	5.68	67.92	82.30	12.41	14.38	13.9
Noreste	lac	54.10	62.99	7.65	5.68	46.45	57.31	8.89	10.86	18.5
Noreste	san	29.20	33.99	7.65	5.68	21.55	28.31	4.79	6.76	29.4

*baseline technology
[1]lac = low activity soils, hac = high activity soils, san= sandy soils. For more detail refer to Table 1.
[2]Simulated soil organic carbon change (0-30cm) after 20 years.
[3]Associated on-field greenhouse gas emissions over 20 years (expressed as carbon equivalents) as outlined in Table 6.
[4]Simulated soil organic carbon change (0-30 cm) after 20 years and adjusted for associated greenhouse gas emissions.
[5]Net soil organic carbon change (0-30 cm) under the new technology relative to the baseline practice after 20 years.
[6]Area required to sequester 10000 Mg C $annum^{-1}$ under the new technology based on adjusted soil carbon change per annum.

Table 13. Distribution of crop and pasture management technologies and total soil carbon sequestration potential (after 20 years) in agro-ecological regions of Uruguay.

Region	Land area under system ha x1000				Proportion of area %			Sequestration Rate[1] Mg C ha^{-1}		Total C sequestered[2] Mg C x1000	
	*Min-till**	*No-till*	*Pasture*	*Total*[3]	*Min tillage**	*No-till*	*Pasture*	*No tillage*	*Pasture*	*No tillage*	*Pasture*
Basprof	54.9	0.0	18.5	73.4	74.8	0.0	25.2	3.61	10.67	198.0	585.3
Crstcent	461.7	0.0	324.3	786.0	58.7	0.0	41.3	3.61	10.67	1666.6	4926.0
Lechsur	312.8	0.0	116.7	429.5	72.8	0.0	27.2	3.61	10.67	1129.3	3337.8
Litnort	413.3	0.0	127.4	540.7	76.4	0.0	23.6	3.61	10.67	1491.9	4409.6
Litsur	324.9	0.0	92.6	417.5	77.8	0.0	22.2	3.61	10.67	1172.9	3466.8
Llaneste	73.8	0.0	29.4	103.2	71.5	0.0	28.5	3.61	10.67	266.4	787.5
Noreste	116.6	0.0	65.1	181.8	64.2	0.0	35.8	3.61	10.67	421.1	1244.5
TOTAL	1,758.0	0.0	774.2	2532.1	69.4	0.0	30.6	3.61	10.67	6346.3	18757.6

*baseline technology

[1]Average soil carbon sequestration gain per hectare for all soil types after 20 years in response to management and derived from the adjusted carbon change data presented in Tables 11 and 12. The areal distribution of soil types within a region is not taken into account.

[2]Total soil organic carbon potentially sequestered after 20 years without economic constraints and all cropping area currently available under minimum tillage converted to either no-till or nominally managed pasture.

[3]Total = min-till + pasture. System conversions are analyzed separately. Area for min-till to no-till conversion not shown as is equal to current area under min-till.

Table 14. Impact of tillage on soil organic carbon (0-30 cm) and associated field based greenhouse gas emissions in agro-ecosystems of the Indo-Gangetic Plain of India.

Region/State	Soil type[1]	Unadjusted C Stock[2] Mg C ha^{-1}		Carbon Offsets[3] Mg C ha^{-1}		Adjusted C Stock[4] Mg C ha^{-1}		Carbon Change[5] Mg C ha^{-1}		10000 MgC[6] ha x1000
WHEAT-RICE		*Conventional**	*No- tillage*	*Conventional**	*No tillage*	*Conventional**	*No tillage*	*Unadjusted*	*Adjusted*	
Bihar	lac	27.25	33.52	23.29	23.33	3.96	10.19	6.27	6.23	32.3
Haryana	lac	24.14	28.25	32.10	30.84	-7.96	-2.59	4.11	5.37	37.0
Haryana	san	21.39	25.03	32.10	30.84	-10.71	-5.81	3.64	4.9	40.0
Punjab	hac	26.22	30.68	34.76	33.52	-8.54	-2.84	4.46	5.7	34.5
Punjab	lac	24.15	28.25	34.76	33.52	-10.61	-5.26	4.1	5.35	37.0
Punjab	san	21.39	25.03	34.76	33.52	-13.37	-8.49	3.64	4.88	41.7
U. Pradesh	hac	26.22	30.68	26.52	25.17	-0.30	5.51	4.46	5.81	34.5
U. Pradesh	lac	24.15	28.25	26.52	25.17	-2.37	3.09	4.1	5.46	37.0
W. Bengal	hac	37.69	46.35	25.67	24.76	12.02	21.59	8.66	9.57	20.8
W. Bengal	lac	27.25	33.52	25.67	24.76	1.58	8.75	6.27	7.17	27.8
W. Bengal	san	22.61	27.81	25.67	24.76	-3.06	3.05	5.2	6.11	32.3
WHEAT-MAIZE		*Conventional**	*No- tillage*	*Conventional**	*No- tillage*	*Conventional**	*No- tillage*	*Unadjusted*	*Adjusted*	
U. Pradesh	lac	24.14	28.25	8.65	8.14	15.49	20.11	4.11	4.62	43.4
WHEAT-COTTON		*Conventional**	*No- tillage*	*Conventional**	*No- tillage*	*Conventional**	*No- tillage*	*Unadjusted*	*Adjusted*	
Haryana	lac	24.14	28.25	11.62	10.87	12.52	17.38	4.11	4.86	41.7
Haryana	san	21.39	25.03	11.62	10.87	9.77	14.16	3.64	4.39	45.5
Punjab	lac	24.14	28.25	13.16	12.42	10.98	15.83	4.11	4.85	41.7
Punjab	san	21.39	25.03	13.16	12.42	8.23	12.61	3.64	4.38	45.5

*baseline technology

[1]lac = low activity soils, hac = high activity soils, san= sandy soils. For more detail refer to Table 1.

[2]Simulated soil organic carbon change (0-30cm) after 20 years.

[3]Associated on-field greenhouse gas emissions over 20 years (expressed as carbon equivalents) as outlined in Table 7.

[4]Simulated soil organic carbon change (0-30 cm) after 20 years and adjusted for associated greenhouse gas emissions.

[5]Net soil organic carbon change (0-30 cm) under the new technology relative to the baseline practice after 20 years.

[6]Area required to sequester 10000 Mg C annum^{-1} under the new technology based on adjusted soil carbon change per annum.

Table 15. Distribution of tillage management and total soil carbon sequestration potential (after 20 years) for agro-ecosystems of of the Indo-Gangetic Plain of India.

Region/State	Land Area in System ha x1000			Proportion of Area %		Sequestration Rate[1] Mg C ha^{-1}	Total C Sequestered[2] Mg C x1000
WHEAT-RICE	*Conventional**	*No-till*	*Total*[3]	*Conventional**	*No-till*	*No-till*	*No-till*
Bihar	1493.0	18.0	1,511	98.8	1.2	6.23	9301.4
Haryana	517.0	350.0	867	59.6	40.4	5.14	2657.4
Punjab	1535.0	215.0	1,750	87.7	12.3	5.31	8150.9
Uttar Pradesh	3947.7	175.0	4,122.7	95.8	4.2	5.64	22265.0
W.Bengal	233.1	0.0	233.1	100.0	0.0	7.62	1776.2
TOTAL W-R	7725.8	758.0	8483.8	89.3	10.7	-	44150.9
WHEAT-MAIZE							
Uttar Pradesh	570.0	0.0	570.0	100.0	0.0	4.62	2633.4
WHEAT-COTTON							
Haryana	603.3	0.0	603.3	100.0	0.0	4.62	2787.2
Punjab	240.0	0.0	240.0	100.0	0.0	4.63	1111.2
TOTAL W-C	843.3	0.0	843.3	100.0	0.0	-	3989.4

*baseline technology

[1]Average soil carbon sequestration gain per hectare for all soil types after 20 years in response to management and derived from the adjusted carbon change data presented in Table 14. The areal distribution of soil types within a region is not taken into account.

[2]Total soil organic carbon potentially sequestered after 20 years without economic constraints and all cropping area currently available under conventional tillage converted to no-till cropping.

[3]Total = conventional + no-till.

Table 16. Impact of tillage on soil organic carbon (0-30 cm) and associated field based greenhouse gas emissions in agro-ecosystems of South-Eastern Australia.

Region	Soil type[1]	Unadjusted Carbon Stock[2] Mg C ha^{-1}		Carbon Offsets[3] Mg C ha^{-1}		Adjusted Carbon Stock[4] Mg C ha^{-1}		Carbon Change[5] Mg C ha^{-1}		10000 MgC [6] ha x1000
		*Conventional**	*Minimum till*	*Conventional**	*Minimum till*	*Conventional**	*Minimum till*	*Unadjusted*	*Adjusted*	
Mallee	san	14.33	14.76	3.15	3.02	11.18	11.74	0.43	0.56	333.3
Wimmera	hac	28.66	32.09	8.47	5.48	20.19	26.61	3.43	6.42	31.3
High Rainfall	hac	69.33	75.57	20.65	20.59	48.68	54.98	6.24	6.3	31.3
Mid-North	lac	18.10	19.68	8.00	5.02	10.10	14.66	1.58	4.56	43.5
Central West	lac	18.10	19.68	10.24	9.95	7.86	9.73	1.58	1.87	111.1
Slopes	hac	31.16	32.09	8.45	7.67	22.71	24.42	0.93	1.71	111.1
		*Conventional**	*No-tillage*	*Conventional**	*No-tillage*	*Conventional**	*No-tillage*	*Unadjusted*	*Adjusted*	
Mallee	san	14.33	15.77	3.15	2.95	11.18	12.82	1.44	1.64	125.0
Wimmera	hac	28.66	34.27	8.47	5.11	20.19	29.16	5.61	8.97	22.2
High Rainfall	hac	69.33	80.42	20.65	19.02	48.68	61.40	11.09	12.72	15.6
Mid-North	lac	18.10	20.27	8.00	4.76	10.10	15.51	2.17	5.41	37.0
Central West	lac	18.10	20.27	10.24	8.92	7.86	11.35	2.17	3.49	58.8
Slopes	hac	31.16	34.27	8.45	6.09	22.71	28.18	3.11	5.47	37.0

*baseline technology

[1]lac = low activity soils, hac = high activity soils, san= sandy soils. For more detail refer to Table 1.

[2]Simulated soil organic carbon change (0-30cm) after 20 years.

[3]Associated on-field greenhouse gas emissions over 20 years (expressed as carbon equivalents) as outlined in Table 8.

[4]Simulated soil organic carbon change (0-30 cm) after 20 years and adjusted for associated greenhouse gas emissions.

[5]Net soil organic carbon change (0-30 cm) under the new technology relative to the baseline practice after 20 years.

[6]Area required to sequester 10000 Mg C annum^{-1} under the new technology based on adjusted soil carbon change per annum.

Table 17. Distribution of tillage management and total soil carbon sequestration potential (after 20 years) in crop-pasture agro-ecosystems of South-Eastern Australia.

Region	Land area[1] under system ha x1000					Proportion of area %				Sequestration Rate[2] Mg C ha^{-1}		Total C seq'ed[3] Mg C x1000	
	*Conv**	*Min-till*	*No-till*	*Conv+ Min-till*[4]	*Conv+ No-till*[4]	*Conv**	*Min-till*	*Conv**	*No-till*	*Min-till*	*No-till*	*Min-till*	*No-till*
Mallee	1647.1	2433.9	806.4	4081.0	2453.5	40.4	59.6	67.1	32.9	0.56	1.64	922.4	2701.2
Wimmera	213.8	342.0	569.3	555.8	783.0	38.5	61.5	27.3	72.7	6.42	8.97	1372.3	1917.3
High Rainfall	98.0	94.8	169.0	192.8	267.0	50.8	49.2	36.7	63.3	6.3	12.72	617.7	1247.2
Mid-North	542.1	581.5	452.3	1123.7	994.5	48.2	51.8	54.5	45.5	4.56	5.41	2472.2	2933.0
Central West	782.2	839.0	652.6	1621.2	1434.8	48.2	51.8	54.5	45.5	1.87	3.49	1462.7	2729.8
Slopes	1299.2	498.4	1083.2	1797.6	2382.4	72.3	27.7	54.5	45.5	1.71	5.47	2221.7	7106.8
TOTAL	4582.4	4789.7	3732.7	9372.1	8315.1	48.9	51.1	55.1	44.9	-	-	9068.9	18635.4

*Conventional tillage is the baseline technology

[1]Total areas include crop and pastures (where applicable) at any time.

[2]Soil carbon sequestration gain per hectare after 20 years in response to management and derived from the adjusted carbon change data presented in Table 16.

[3]Total soil organic carbon potentially sequestered after 20 years without economic constraints and all cropping area currently available under conventional tillage and converted to either minimum or no-till cropping.

[4]Total areas differ between conversions from conventional to both min-till and no-till and analyzed separately.

Table 18. Impact of cereal and pasture technologies on soil organic carbon (0-30 cm) and associated field based greenhouse gas emissions for agro-ecological regions of Sweden.

Region	Soil type[1]	Unadjusted Carbon Stock[2] Mg C ha^{-1}		Carbon Offsets[3] Mg C ha^{-1}		Adjusted Carbon Stock[4] Mg C ha^{-1}		Carbon Change[5] Mg C ha^{-1}		10000 MgC[6] ha x1000
		*Cereal**	*Pasture*	*Cereal**	*Pasture*	*Cereal**	*Pasture*	*Unadjusted*	*Adjusted*	
Gss	hac	74.40	78.20	7.32	7.92	67.08	70.29	3.8	3.21	62.5
Gmb	hac	74.40	78.20	5.58	7.43	68.82	70.77	3.8	1.95	100.0
Gsk	hac	74.40	78.20	4.65	7.18	69.75	71.02	3.8	1.27	166.7
Gns	hac	74.40	78.20	6.25	7.75	68.15	70.45	3.8	2.3	90.9
Ss	hac	74.40	78.20	5.98	7.27	68.42	70.93	3.8	2.51	76.9
Ssk	hac	74.40	78.20	4.78	6.62	69.62	71.58	3.8	1.96	100.0
Nn	hac	74.40	78.20	3.31	5.48	71.09	72.72	3.8	1.63	125.0
No	hac	74.40	78.20	3.18	5.24	71.22	72.96	3.8	1.74	111.1

*baseline technology
[1]hac = high activity soils. For more detail refer to Table 1.
[2]Simulated soil organic carbon change (0-30 cm) after 20 years.
[3]Associated on-field greenhouse gas emissions over 20 years (expressed as carbon equivalents) as outlined in Table 9.
[4]Simulated soil organic carbon change (0-30 cm) after 20 years and adjusted for associated greenhouse gas emissions.
[5]Net soil organic carbon change (0-30 cm) under the new technology relative to the baseline practice after 20 years.
[6]Area required to sequester 10000 Mg C annum^{-1} under the new technology based on adjusted soil carbon change per annum.

Table 19. Distribution of cereal and pasture technologies and total soil carbon sequestration potential (after 20 years) for agro-ecological regions of Sweden.

Region	Land Area in System ha x1000			Proportion of Area %		Sequestration Rate[1] Mg C ha^{-1}	Total C Sequestered[2] Mg C x1000
	*Cereal**	*Pasture*	*Total*[3]	*Cereal**	*Pasture*	*Pasture*	*Pasture*
Gss	33.2	73.9	107.1	31.0	69.0	3.21	353.1
Gmb	44.4	106.40	150.8	29.5	70.5	1.95	158.1
Gsk	70.5	93.9	164.4	42.9	57.1	1.27	180.3
Gns	128.9	294.7	423.6	30.4	69.6	2.3	579.7
Ss	252.0	159.6	411.6	61.2	38.8	2.51	323.6
Ssk	141.9	89.1	231.1	61.4	38.6	1.96	138.2
Nn	81.1	112.5	193.5	41.9	58.1	1.63	72.4
No	110.0	41.0	150.9	72.9	27.1	1.74	57.8
TOTAL	862.1	971.0	1833.1	47.0	53.0	-	1863.2

*baseline technology
[1]Soil carbon sequestration gain per hectare after 20 years in response to management and derived from the adjusted carbon change data presented in Table 18.
[2]Total soil organic carbon potentially sequestered after 20 years without economic constraints and all cropping area currently available under cereal converted to pasture.
[3]Total area = cereal + pasture

Table 20. Impact of tillage technologies on soil organic carbon (0-30 cm) and associated field based greenhouse gas emissions in agro-ecosystems of Northern Kazakhstan.

Region	Soil type[1]	Unadjusted Carbon Stock[2] Mg C ha^{-1}		Carbon Offsets[3] Mg C ha^{-1}		Adjusted Carbon Stock[4] Mg C ha^{-1}		Carbon Change[5] Mg C ha^{-1}		10000 MgC[6] ha x1000
		*Conventional**	*Minimum till*	*Conventional**	*Minimum till*	*Conventional**	*Minimum till*	*Unadjusted*	*Adjusted*	
Common	hac	37.71	42.23	1.34	3.14	36.37	39.09	4.52	2.72	71.4
Southern	hac	37.71	42.23	1.33	3.04	36.38	39.18	4.52	2.8	71.4
Chestnut	hac	37.71	42.23	1.17	2.65	36.54	39.57	4.52	3.03	66.7
		*Conventional**	*No-tillage*	*Conventional**	*No-tillage*	*Conventional**	*No-tillage*	*Unadjusted*	*Adjusted*	
Common	hac	37.71	45.09	1.34	3.53	36.37	41.56	7.38	5.19	38.5
Southern	hac	37.71	45.09	1.33	3.43	36.38	41.67	7.38	5.29	38.5
Chestnut	hac	37.71	45.09	1.17	3.16	36.54	41.94	7.38	5.4	37.0

*baseline technology
[1]hac = high activity soils, san= sandy soils. For more detail refer to Table 1.
[2]Simulated soil organic carbon change (0-30 cm) after 20 years.
[3]Associated on-field greenhouse gas emissions over 20 years (expressed as carbon equivalents) as outlined in Table 10.
[4]Simulated soil organic carbon change (0-30 cm) after 20 years and adjusted for associated greenhouse gas emissions.
[5]Net soil organic carbon change (0-30 cm) under the new technology relative to the baseline practice after 20 years.
[6]Area required to sequester 10000 Mg C $annum^{-1}$ under the new technology based on adjusted soil carbon change per annum.

Table 21. Distribution of tillage management and total soil carbon sequestration potential (after 20 years) in agro-ecosystems of Northern Kazakhstan.

Region	Land area under system ha x1000					Proportion of area %				Sequestration Rate[1] Mg C ha^{-1}		Total C seq'ed[2] Mg C x1000	
	*Conv**	*Min-till*	*No-till*	*Conv+ Min-till*[3]	*Conv+ No-till*[3]	*Conv**	*Min-till*	*Conv**	*No-till*	*Min-till*	*No-till*	*Min-till*	*No-till*
Common Chernozem	4400.0	550.0	550.0	4950.0	4950.0	88.9	11.1	88.9	11.1	2.72	5.19	11968.0	22836.0
Southern Chernozem	2800.0	350.0	350.0	3150.0	3150.0	88.9	11.1	88.9	11.1	2.8	5.29	7840.0	14812.0
Chestnut	1200.0	150.0	150.0	1350.0	1350.0	88.9	11.1	88.9	11.1	3.03	5.4	3636.0	6480.0
TOTAL	8400.0	1050.0	1050.0	9450.0	9450.0	88.9	11.1	88.9	11.1	-	-	23444.0	44128.0

*Conventional tillage is the baseline technology.
[1]Soil carbon sequestration gain per hectare after 20 years in response to management and derived from the adjusted carbon change data presented in Table 20.
[2]Total soil organic carbon potentially sequestered after 20 years without economic constraints and all cropping area currently available under conventional tillage converted to either minimum or no-till cropping.
[3]Total areas differ between conversions from conventional to both min-till and no-till and analyzed separately.

5.2.2 Uruguay

In Uruguay, the relatively high input cropping systems receive fertilizers to boost production and with minimal burning of residues there is sufficient carbon inputs for significant gains in soil carbon. Management of crop and pasture systems throughout Uruguay is relatively consistent based on the assessment of associated on-farm emissions. Carbon offsets across tillage systems are similar, with on average 0.8 Mg C ha^{-1} $annum^{-1}$ being emitted (Table 11). Methane from grazing cattle and N_2O from cattle manures, fertilizers, biological fixation and crop residue decomposition contribute over half of these emissions. Grain legumes in the crop rotation such as soybean, whilst boosting the nitrogen economy of these systems, do contribute to increased emissions of N_2O. In the permanent pasture systems, the majority of ancillary emissions are directly from grazing cattle.

With the conversion from minimum to no-tillage cropping systems, the largest relative gains in (adjusted) soil carbon are on the sandier soils, increasing by 9.8% over 20 years, compared to an average gain of 7.7 % for the low and high activity soils (Table 11). However both the low and high activity soils can support higher levels of agricultural productivity, therefore in absolute terms, the gains in soil organic carbon over 20 years are respectively, 3.5 and 5.1 Mg C ha^{-1}, compared to only 2.1 Mg C ha^{-1} on the sands. When converting from minimum tilled cropping to nominally managed pastures, the same trend exists with respect to the relative gains in soil carbon on the different soil types, with the gains on the sandier soils in excess of 30% (Table 12).

The gains in soil organic carbon over 20 years on the low and high activity soils are 10.9 and 14.4 Mg C ha^{-1}, compared to 6.8 Mg C ha^{-1} on the sands. Based on these sequestration rates, it would require nearly 14,000 ha to be converted from crop to pasture on high activity soils to sequester 10 Mg C $annum^{-1}$ (Table 12). This is less than half the area that would be required to sequester the same amount on the sandy soils of this region.

Current land areas under tillage and pasture technologies in each of the agro-ecological regions of Uruguay are reported in Table 13. The annual gain in soil carbon by converting one-half of the minimum tillage systems currently available in Uruguay to pastures would be 9.4 million tonnes, equivalent to 32% of the country's annual fossil fuel emissions in 2000 (Marland *et al*., 2003).

5.2.3 Indo-Gangetic Plain

On the IGP, crop residue removal after harvest is a common practice and in turn limits the potential for major accumulations of soil carbon. The burning of large amounts of rice straw is also a common practice to ensure wheat planting is not hampered and this contributes to both CH_4 and N_2O emissions. (The burning of residues is not an accountable CO_2 source).

In the wheat-rice rotations, many of the simulated increases in soil organic carbon in both conventional and no-tillage systems are heavily discount due to the large quantities of ancillary GHGs (carbon offsets) generated in these relatively high inputs systems. Methane emissions from rice cropping contribute one-third of all emissions (Table 14). Nitrous oxides are also a major source with nitrogen fertilizer applications as high as 386 kg ha^{-1} $annum^{-1}$ in the more productive Haryana and Punjab states. Fresh organic manure applications of over 8.5 t ha^{-1} in West Bengal also contributes to N_2O emissions but these manures are generally considered poor sources of nitrogen. Wheat-rice systems in the States of Haryana and the Punjab produced some of the largest amounts of associated GHGs (Table 14), averaging 1.6 Mg C (equivalents) ha^{-1} $annum^{-1}$, 28% higher than emissions from wheat-rice systems of Uttar Pradesh and West Bengal.

Even though the discounting of gross soil carbon gains has resulted in negative rates of accumulation, it is the relative differences between conventional (baseline) systems and technologies that determine the actual sequestration potential. In this case, the conversion to no-till from conventional tillage in wheat-rice systems in West Bengal is the most productivity in terms of potential carbon gains. Whilst there is an average increase (across all soil types) of 7.6 Mg C after 20 years, the actual area under wheat-rice is small compared to the other States (Table 15).

Without considering economic constraints, the region offering the greatest potential gains in the absolute amount of soil carbon through no-tillage is the State of Uttar Pradesh. With nearly 4 million ha of conventionally tilled wheat-rice cropping available, this area could technically sequester 22 million tonnes over 20 years, half of the total sequestration potential of wheat-rice under no-tillage in the IGP. The total amount of carbon sequestered over 20 years through no-till wheat-rice cropping would be equivalent to 15% of India’s annual emissions from fossil fuels in 2000 (Marland et al., 2003).

5.2.4 South-Eastern Australia

Australian farming systems have historically been crop-pasture rotations, with an increased incidence of pastures in either the High Rainfall region, capable of supporting heavy grazing pressures, or the marginal semi-arid regions such as the Mallee and Central West. A shift away from pastures has been the case in recent years in the Wimmera and the Mid-North regions, as the price of wool remains depressed, and grain prices relatively buoyant.

Associated GHG emissions from crop-pasture rotations within the six regions is (on average) 8.8 Mg C ha^{-1}, with conventionally tilled systems emitting 14% more than those under minimum tillage, which in turn emit 10% more than no-till systems (Table 16). The largest carbon offset over 20 years can be found in the High Rainfall region (20.7 Mg C ha^{-1}) with grazing animals contributing 71% of the total emissions from these systems. Methane and N_2O from grazing animals also contribute heavily to emissions from the Central West region. In the regions where cropping plays a significant role (Wimmera, Mid-North and Slopes), the associated GHG emissions are all relatively similar, averaging 8.3 Mg C ha^{-1} from the conventional systems to 5.3 Mg C ha^{-1} from no-till systems. Nitrous oxide emissions from fertilizer consumption are the major contributors to emissions from these regions.

The highest net gains in carbon in Southern Australia can be realized through conversion from conventional to no-tillage systems in the high activity clay soils of the High Rainfall and Wimmera regions. In the former, the high levels of primary productivity, in concert with soils of relatively high clay content realize net gains of 12.7 Mg C ha^{-1} over 20 years, even after being heavily discounting due to associated GHG emissions. Conversion to minimum tillage realizes half the benefit of no-tillage in both these regions (6.3-6.4 Mg C ha^{-1}).

In the Mid-North region, relatively large gains in soil carbon (4.6 Mg C ha^{-1}) can be made on converting conventionally managed cropping systems to minimum tillage, with little additional benefit moving to no-tillage (5.4 Mg C ha^{-1}). This trend is reversed in the Slopes region, where carbon gains under minimum tillage (1.7 Mg C ha^{-1}) are one-third of that found under no-tillage

(5.5 Mg C ha^{-1}). Gains in soil carbon under minimum and no-tillage are minimal in the Mallee region (0.6 and 1.6 Mg C ha^{-1} respectively).

In terms of the absolute returns in soil carbon (i.e. accumulation rate of carbon by areal extent of technology), the Slopes region offers a relatively high rate of accumulation and a large area still under conventional tillage and potentially available for a change in technology (Table 17). With complete adoption of minimum or no-tillage across the six regions of South-Eastern Australia, the latter would yield an additional 18.6 million tonnes of carbon over 20 years (twice the return of minimum tillage). For comparison, this is equivalent to 20% of Australia's annual fossil fuel emissions for the year 2000 (Marland *et al*., 2003).

5.2.5 Sweden

Sweden is a country of relatively uniform agricultural soils with high organic carbon content. Productive crops and pasture provide sufficient biomass to support soil carbon sequestration. There is no grazing of crop residues or pastures, however some of the pasture is cut for feeding of animals off-site. The associated GHG emissions from the pasture technology (an average of 5.1 Mg C ha^{-1} across the 8 regions) exceed those from the traditional cereal cropping by 34% due to additional nitrogen fertilizer and fuel use. These inputs negate much of the sequestration benefit on conversion of cereal to pastures in this region of the world (Table 18).

Cereals and pastures are equally found on Swedish agricultural lands therefore scope does exist for continued conversion to pasture if sequestration gains are justified. The average carbon accumulation rate across the 8 regions is 2.1 Mg C ha^{-1}, relatively low compared to other countries, with the 1.9 million tonnes of additional carbon potentially sequestered if the pasture technology was completely adopted (Table 19).

5.2.6 Kazakhstan

The situation with respect to soil carbon sequestration in agricultural soils of Kazakhstan is similar to that of Sweden. New technologies beneficial for soil carbon storage, actually produce more associated GHG emissions than conventional systems and essentially offset much of the carbon actually sequestered in the soil matrix. The management of low input conventionally tilled cropping systems in Kazakhstan emits (on average) 1.3 Mg C ha^{-1} over 20 years, the lowest emissions of associated GHGs of any of the systems we studied (Table 20). The addition of nitrogen fertilizers required in the conversion to minimum and no-tillage systems increase these emissions to 2.9 and 3.4 Mg C ha^{-1}, respectively. Taking the associated GHG emissions into account effectively reduces the original (gross) carbon benefit in converting to minimum till by 37%. When converting from conventional to no-tillage, the original carbon gain in reduced by 28%.

Whilst the overall gains in carbon may be reduced, there are large areas in Kazakhstan currently under conventional cultivation and potentially available for a change in technology (Table 20). In total, an additional 44.1 million tonnes of carbon would be sequestered over 20 years if no-tillage was fully adopted across the 3 regions, with the Common Chernozem region providing one-half of this carbon store.

5.3 Economic analysis

The economic results are for all combinations of countries and practices for gross and net carbon sequestration rates. Note that in the economic analysis (Figures 11 - 24), the horizontal axis represents the total amount of carbon accumulated over the 20 year contract period in thousands of Mg C. These quantities of carbon are net of an additionality discount, but have not been discounted for impermanence or leakage (due to the lack of data). The vertical axis represents either the participation rate, or the price (US$) per Mg C sequestered. The participation rate is the proportion of hectares where the carbon sequestering practice has not yet been adopted and would not have been adopted in the absence of a carbon contract.

All of the outputs incorporate transaction costs. Collaborators from Australia and India provided sufficient data to estimate transaction costs for those regions. For other regions, a similar transaction cost was assumed. Transaction costs were estimated to be a relatively small percent of the price of carbon, therefore, our results are not sensitive to these assumptions. The threshold effects are less significant because in revising the estimated transaction costs, the costs are smaller, therefore, we have not presented supply curves without and with transaction costs, as the two sets of curves are not very different.

It should be emphasized, however, that these estimates of transaction costs are from informal surveys carried out by qualified collaborators within each region. More reliable estimates of transaction costs can only be obtained through detailed case studies within each region. Even then, transaction costs in a mature market are likely to be very different (specifically, lower) than when the market is first being developed.

Collaborators were generally not able to reliably estimate fixed costs of changing practices (the term denoted f_{is} in Section 2.2). To address this limitation of the data, the net returns distributions for each alternative practice in each region were calibrated by adjusting the mean net returns for the alternative practice so that the model produced the observed allocation of land between the conventional and alternative practice in the base case (no carbon payment). This adjustment was interpreted as the fixed cost of adoption of the carbon sequestering practice, which would generally include the costs of physical capital (e.g., no-till machinery) as well as any other costs of adjustment associated with changing practices, including farmers' perceptions of risk. These fixed costs are presented in Table 22 on an annual basis and capitalized over a 20-year period at 5% and 10% as specified in Annex A of the Technical specifications for this project. This procedure is also described in the methodology (Section 2.2). While it is difficult to compare these estimated fixed adoption costs to observable costs, we can note that cost of a no-till seed drill in the United States is in the range of \$20,000 to \$40,000, whereas an animal-drawn implement for no-till in India might cost \$300 (Rice Wheat Consortium). Converting these figures into "representative" annual fixed costs is difficult to do, but rough estimates for large-scale mechanized agriculture appear to be in the range of \$100 ha^{-1} (assuming that farmers already own tractors and other implements and only need to purchase certain implements required for no-till). This fixed cost is at the lower end of the capitalized fixed costs estimated for Australia where similar production practices are used. This comparison suggests that the estimate of fixed adoption costs in Table 22 includes other adoption and adjustment costs, such as the effects of uncertainty and risk aversion, above and beyond the costs of the additional machinery required to use reduced tillage.

It is notable that the fixed costs of adoption in the IGP appear to be lower than in most other areas, consistent with the adoption of relatively low-cost implements and the continued use of large amounts of animal and human labor rather than machinery. The highest adoption cost area is Kazakhstan, a result consistent with the idea that there are likely to be significant costs of adjustment associated with moving from the Soviet system to a system based on private ownership. The high adjustment costs in Sweden reflect the fact that grains are highly subsidized crops, therefore farmers have to forgo a large subsidy payment to switch to pasture.

Table 22. Additionality discount and fixed cost of adoption by region and practice.

Country/Region	Future Practice	Additionality Discount	Annual Fixed Adoption Cost	Capitalized Fixed Adoption Cost	
				5%	10%
		%	$ ha^{-1} annum^{-1}	$ ha^{-1} annum^{-1}	
Uruguay	No-till	31-32	30	374	255
Uruguay	Pasture	0	0	0	0
Indo-Gangetic Plain	No-till (WR)*	13-55	5-40	62-499	43-340
Indo-Gangetic Plain	No-till (WM)*	34	20	249	170
Indo-Gangetic Plain	No-till (WC)*	35-51	30-50	374-624	255-426
Australia	Minimum till	0-28	0-65	0-811	0-553
Australia	No-till	0-41	0-95	0-1185	0-808
Sweden	Pasture	29-70	85-120	1060-1496	723-1021
Kazakhstan	Minimum till	82-85	90-72	898-1122	613-766
Kazakhstan	No-till	85-88	110-115	1372-1434	936-979

*W = wheat, R = rice, M = maize, C = cotton

In interpreting the economic results, the aggregate carbon supply curve for a given spatial unit is derived from three forms of information:

- The average carbon rate estimated for that spatial unit. The carbon rates are based on the application of the IPCC method for estimating carbon rates (Section 5.2).
- The number of hectares in that spatial unit on which the carbon-sequestering practice could be adopted. These data were reported to us by collaborators in each region based on census data, and are equal to the total number of hectares in production less the number of hectares on which the practice has already been adopted.
- The number of hectares on which farmers would adopt carbon-sequestering practices (the rate of participation in carbon contracts). This participation rate is estimated with the economic simulation model, and is based on the estimated net returns distributions for each practice in each region, estimated transactions costs, and estimated fixed adoption costs.

Therefore, the differences in the total quantities of carbon sequestered in each region at each price reflect regional differences in all three of these factors.

5.3.1 Principal results

A general observation is that the economic potential for soil carbon sequestration in these regions is generally quite low, relative to the technical potential, at carbon prices in the zero to \$200 Mg C^{-1} range that we have used in this study. The incremental values reported in Figure 10 are the additive differences in soil carbon storage in moving from \$50 to \$100 to \$200 Mg C^{-1} and their relationship to the total additional carbon that can technically be sequestered if there was complete adoption of the technology.

For example, in wheat-rice systems of the IGP, the technical potential for carbon sequestration, if cropping lands currently under conventional tillage were all converted to no-till, is 44.2 million Mg (tonnes) C. The economic potential is 7.3 million tonnes C at a contract price of \$50 Mg C^{-1}, and 18.5 million tonnes C at \$100 Mg C^{-1}, an incremental increase of 11.3 million tonnes C in moving from the \$50 to \$100 contract price.

In all regions, the economic potential for carbon sequestration for each of the sequestering technologies is lower than the technical potential for sequestration over 20 years. In the wheat-rice systems of the IGP, at a carbon price of \$50 Mg C^{-1}, only 17% of the full technical potential is realized. At \$200 Mg C^{-1}, the economic return increases to 79% of the technical potential. The average economic return (across all regional technologies) at \$50 and \$200 Mg C^{-1}, is 17% and 61%, respectively. The highest economic returns (in relation to the technical potential), are when converting cropping systems in Uruguay to nominally managed pasture (49% and 98% at \$50 and \$200 Mg C^{-1}, respectively), and the lowest are found when converting to minimum tillage in South-Eastern Australia (6% and 24% at \$50 and \$200 Mg C^{-1}, respectively)

The simulated carbon contract participation rates for each of the countries in the study are presented in Figure 11. This figure shows that at a carbon price of \$200 Mg C^{-1}, participation rates range from 13 to 80%, and are reduced for lower carbon prices. However, the economic potential increases with the price of carbon and approaches the technical potential at sufficiently high prices (in other words, at a sufficiently high carbon price, the participation rate approaches 100%). Participation rates were generally plateauing at a carbon price in excess of \$200 Mg C^{-1}, except in regions where the adoption of the stated technology was already high (e.g. Australia) or the potential of the technology to store additional C was low (e.g. converting from minimum to no-till in Uruguay).

The carbon supply curves for the regional technologies for carbon prices in the range relevant to policy analysis (\$0 - \$200 Mg C^{-1}) are presented in Figure 12. If we were to run the carbon price to a high enough level, the supply curves would all become vertical where the economic potential approaches the technical potential. Normally, supply curves are concave upward. These supply curves have an S-shape, becoming concave upward at higher prices. However, they can be concave downward at lower prices (as illustrated in Figure 1). A number of our supply curves have this property for carbon prices less than \$200 Mg C^{-1}, but they become concave upward at higher prices.

The finding of relatively low economic potential for soil carbon sequestration in some of the countries is explained by several factors:

- In some regions such as Australia, conservation tillage practices that sequester carbon have already been widely adopted by farmers because it is already recognized as profitable. Thus, additional adoption to sequester carbon will occur only if carbon incentives are high enough to offset the costs of adoption.
- In some regions where actual adoption rates are presently low, yet potential returns to carbon sequestering practices (such as no-tillage) are estimated to be high, we estimate a relatively high additionality discount. That is, our analysis suggests that a large proportion of current non-adopters would eventually adopt no-till or permanent pasture without carbon incentives. Our analysis includes only the amount of carbon estimated to be additional, i.e. above and beyond what farmers would have accumulated without carbon payments. If this additionality discount were not included, then you would scale up the supply curves by the amount of the additionality discount. For example, Table 22 shows that the additionality discount for Sweden ranges from 29-70%. If we take an average additionality discount of 49%, this means that 49% of the cropland in the Sweden analysis was estimated to change practices without carbon incentives. The adjusted Sweden supply curve shows that at a price of \$100 Mg C^{-1} about 925,000 Mg C would be sequestered. Without the additionality discount, this figure would be adjusted upward to be 925,000/(1 - 0.49) = 1,813,000 Mg C.
- In some sub-regions in our study, the technical potential for carbon sequestration is quite low, even though it may be higher in other sub-regions. In some cases, these low rates apply to sub-regions that are economically marginal but represent a large share of total cropland.

An additional general observation concerns the comparison of the supply curves based on the gross (unadjusted) and net (adjusted) soil organic carbon accumulation rates. In most cases, the adjustments for associated field emissions shift the supply curves to the right (i.e. in a positive direction), increasing the net amount of carbon sequestered at each price. However, the importance of this effect varies substantially across regions, reflecting the much higher energy usage in, for example, Australia agricultural systems as compared to India (Figure 13).

Also note that in some cases the net carbon rates are lower than the gross rates (Sweden, Kazakhstan). This is due to the fact that the technologies employed for carbon sequestration in these regions actually require additional external inputs (e.g. nitrogen fertilizer and fuel) and greenhouse gas emissions associated with these technologies have actually increased relative to the baseline (or conventional systems). For example, nitrogen fertilizers are not normally applied in Kazakhstan unless minimum of no-tillage management is employed. This resultant increase in N_2O production associated with this technology which to offsets a significant fraction of the gross carbon gain.

Another general observation is that there are substantial differences in the economic potential among the sub-regions within countries, due to differences in profitability of carbon-sequestering practices and differences in carbon sequestration rates. The sub-regional data for each country illustrates this spatial variation in economic potential. This fact has important implications for policy. For example, even though some or most areas of a country may have low economic potential to participate in carbon markets, other areas may have a much higher potential. Similarly, economic benefits from participating in carbon markets will not be uniformly distributed.

The regional and sub-regional outputs from the economic simulation model used to produce Figures 10-24 are reported in Appendix 3.

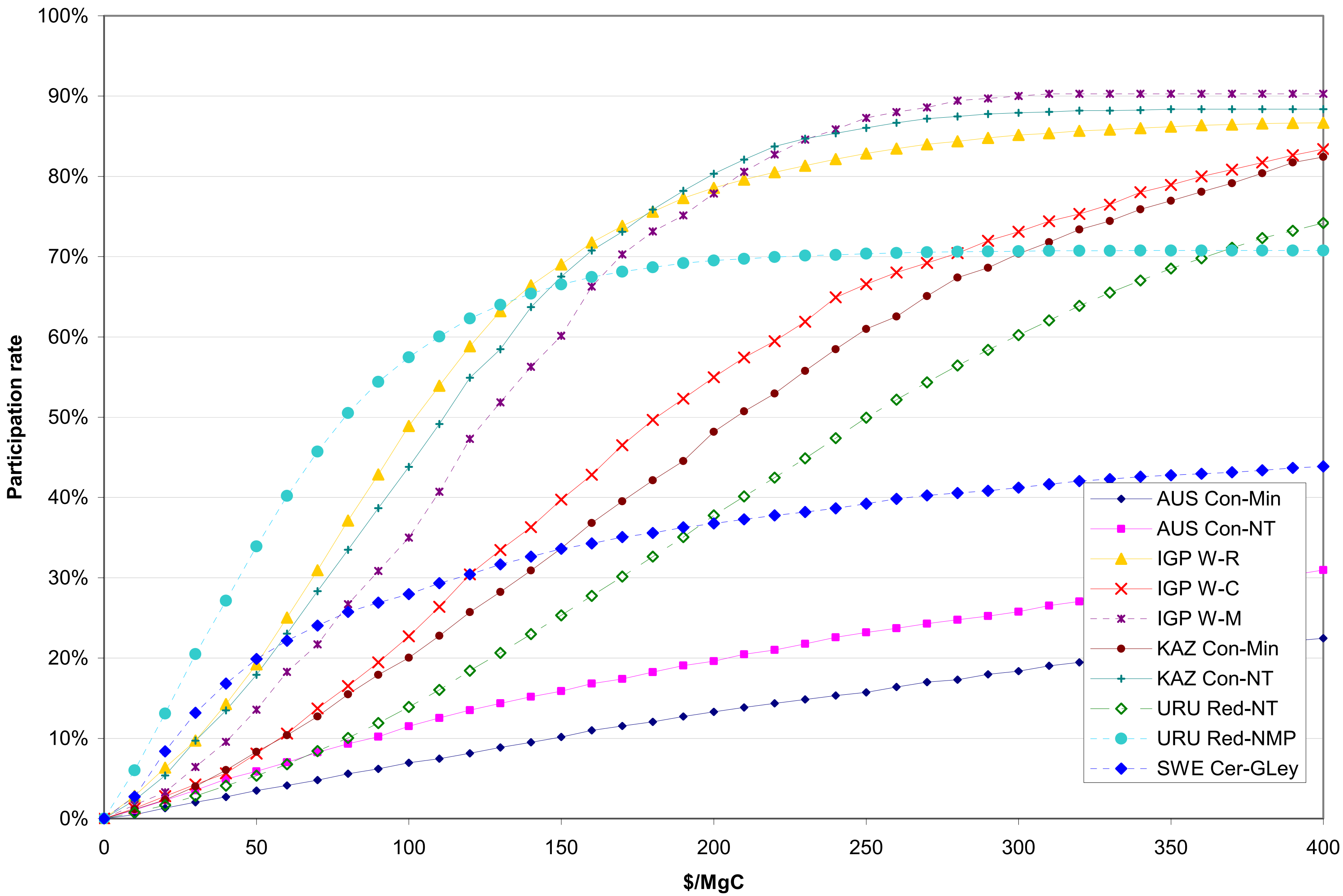

Figure 11. Regional participation rates of adopters to new technologies for sequestering soil organic carbon and their relationship to the market price of carbon.

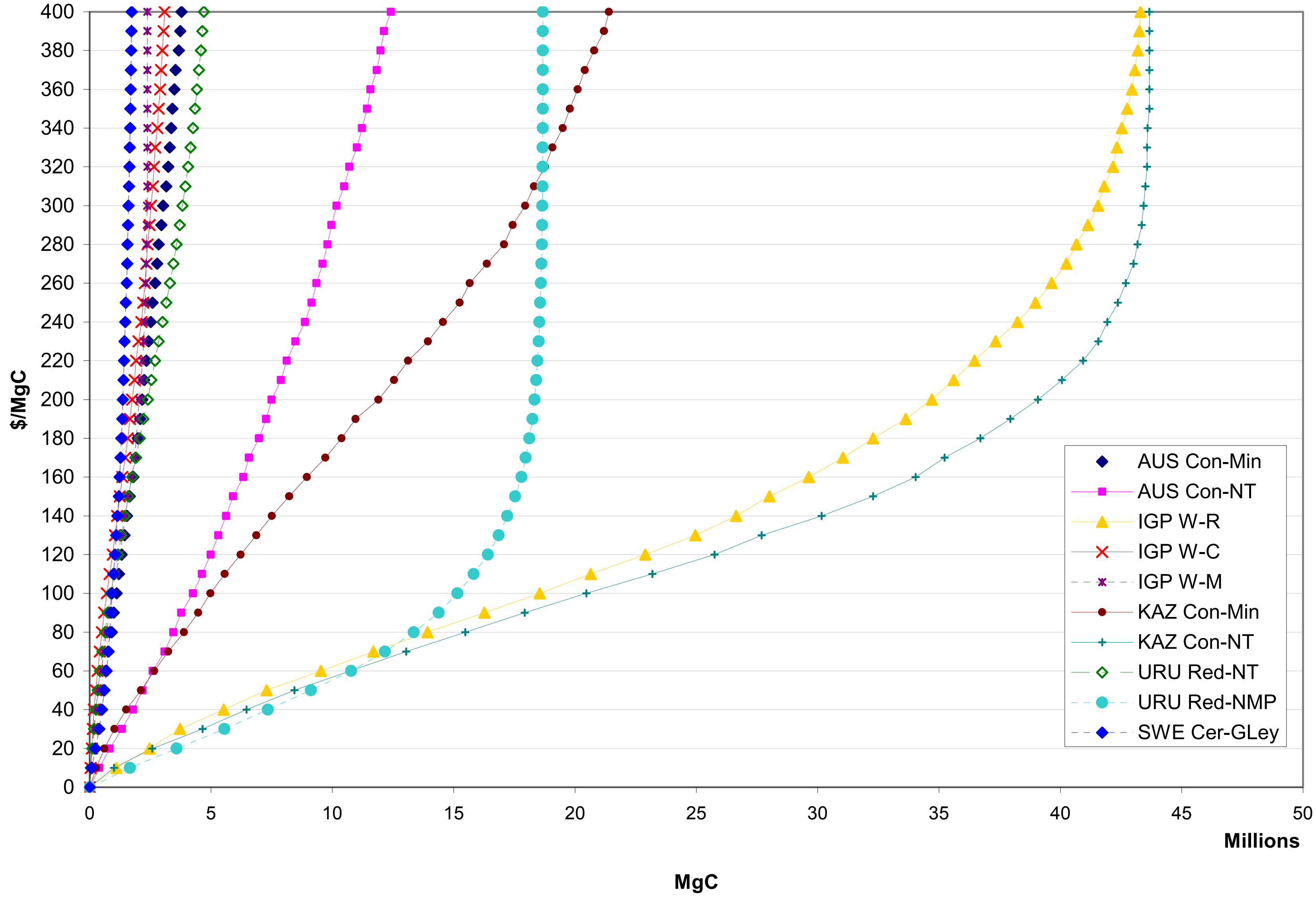

Figure 12. Carbon supply curves on implementation of regional technologies for sequestering soil organic carbon.

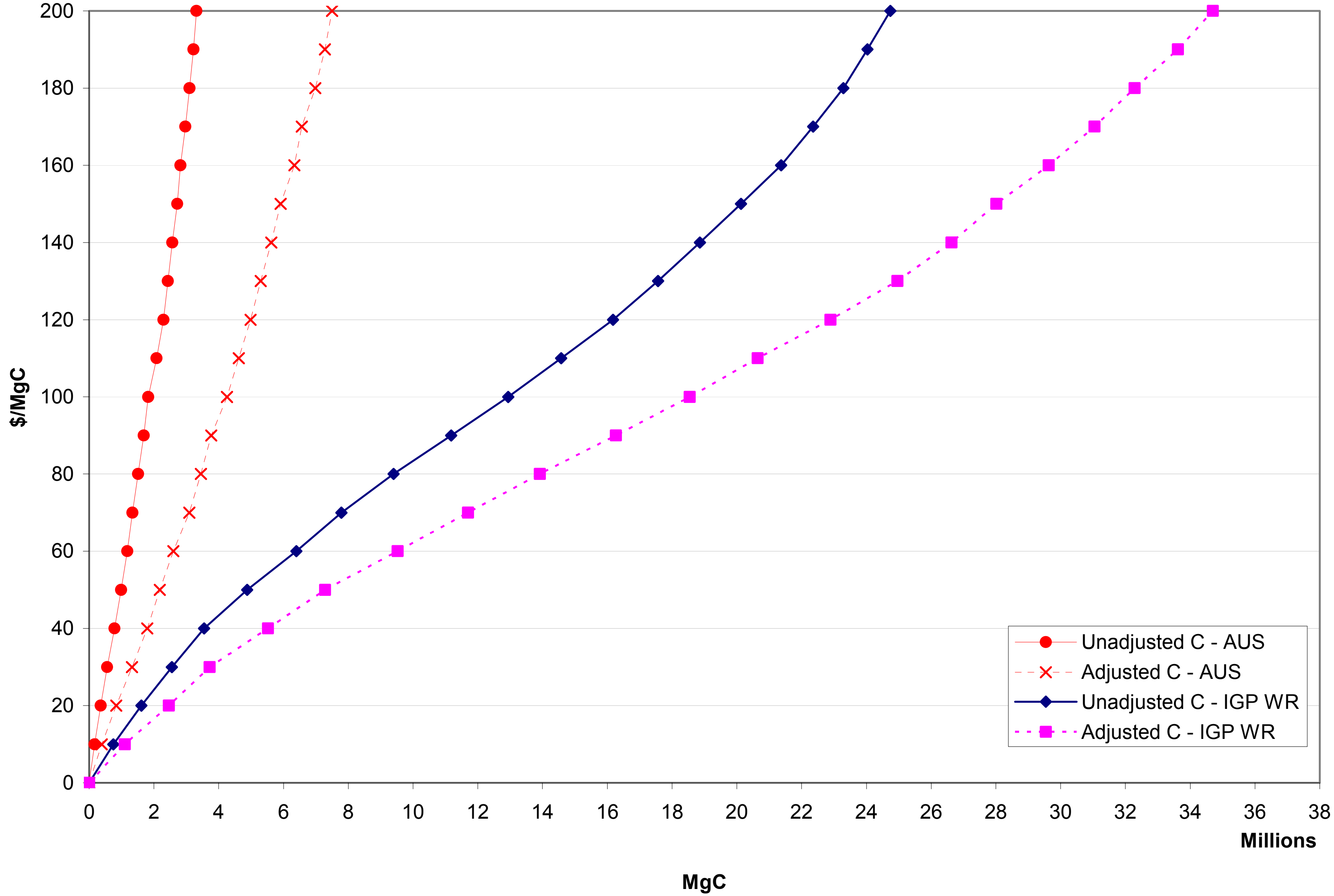

Figure 13. Comparison of carbon supply curves on conversion of conventional tillage systems to no-till from wheat-rice systems of the Indo-Gangetic Plain (wheat-rice) and crop-pastures systems of South-Eastern Australia. Calculated with both gross (unadjusted) and net (adjusted) carbon data. Transaction costs are included.

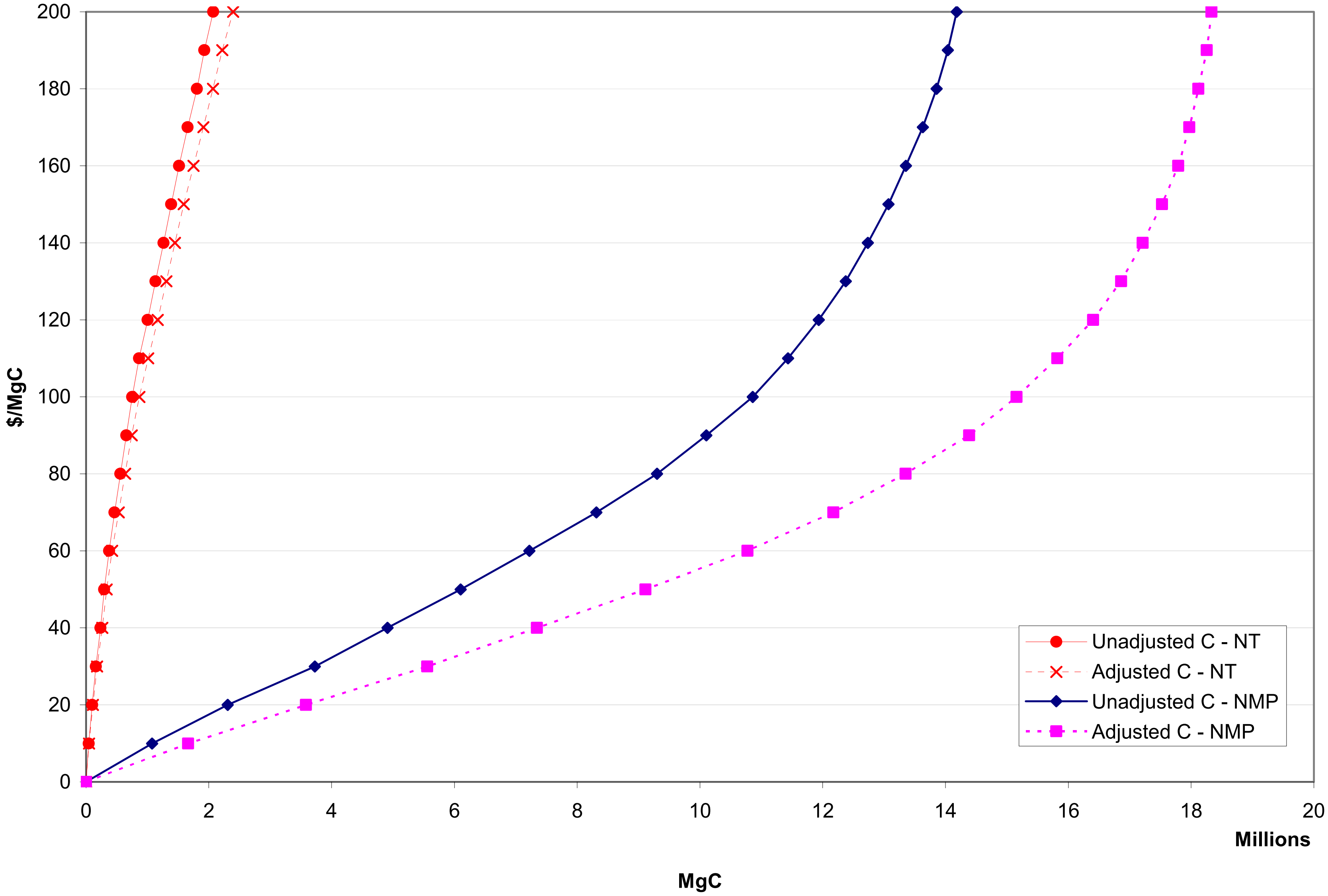

Figure 14. Comparison of carbon supply curves on conversion of reduced tillage systems to no-till (NT) and nominally managed pasture (NMP) of Uruguay and calculated with both gross (unadjusted) and net (adjusted) carbon data. Transaction costs are included.

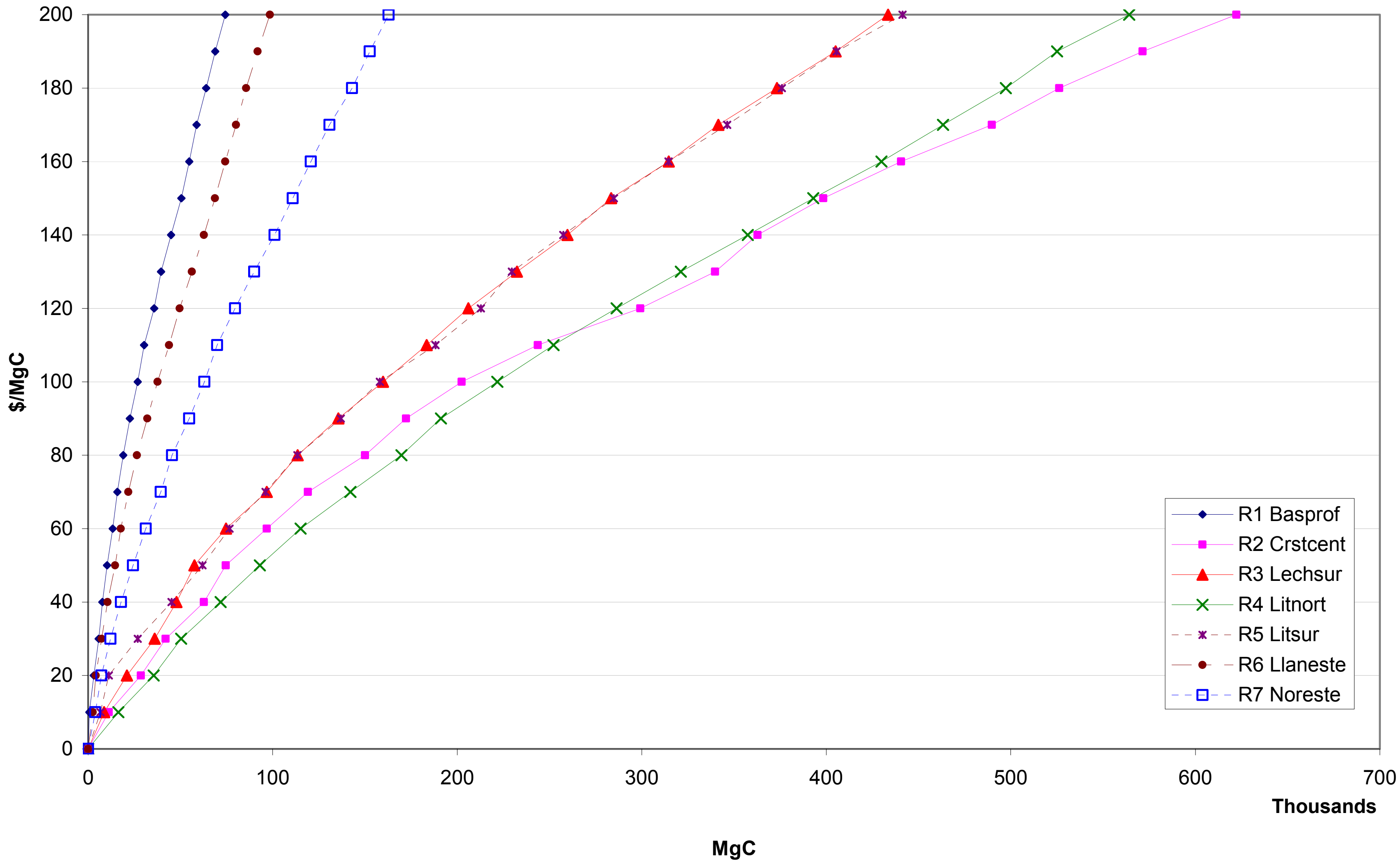

Figure 15. Sub-regional carbon supply curves when converting from reduced tillage to no till cropping systems in Uruguay.

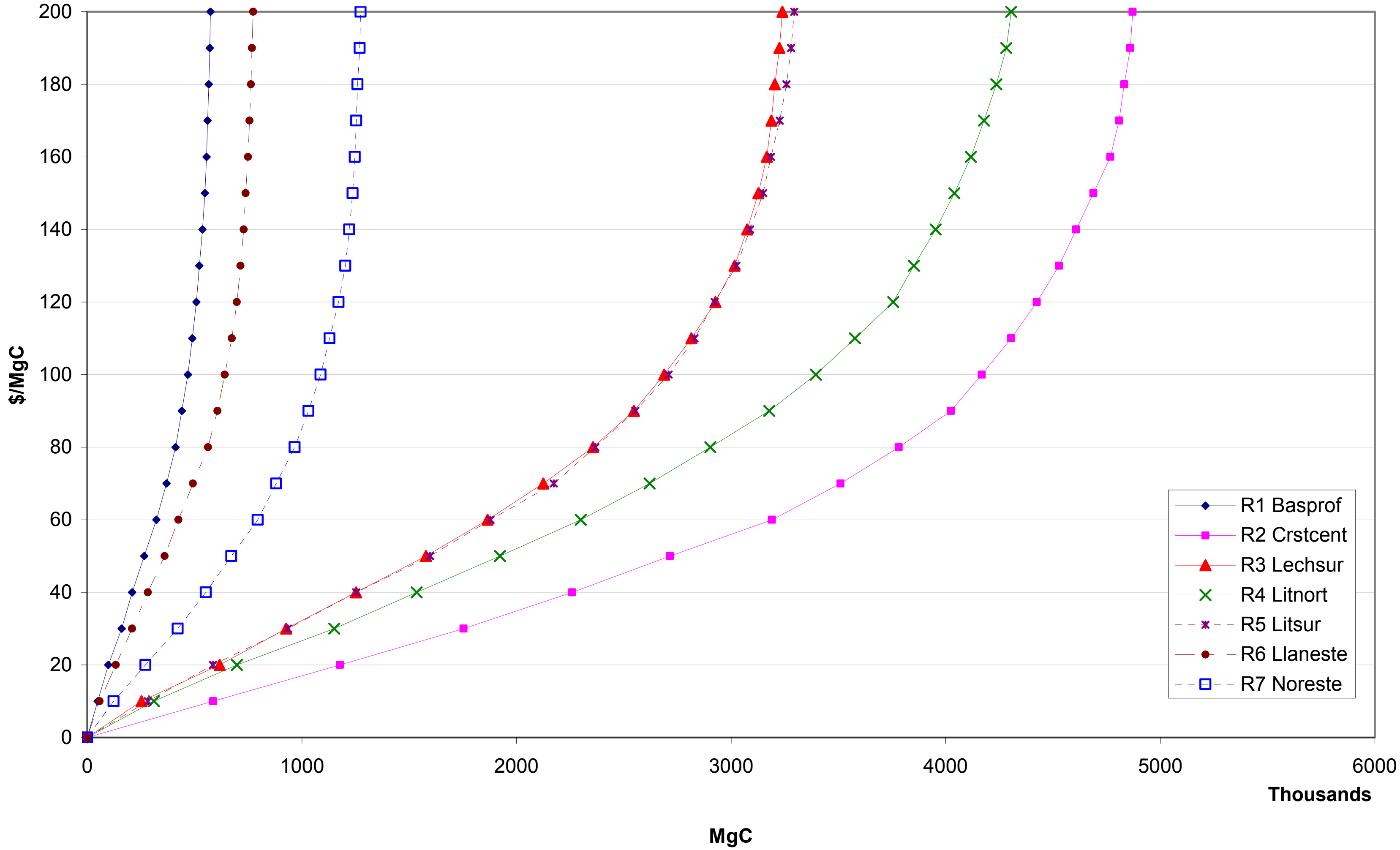

Figure 16. Sub-regional carbon supply curves when converting from minimum tillage to nominally managed pasture systems in Uruguay.

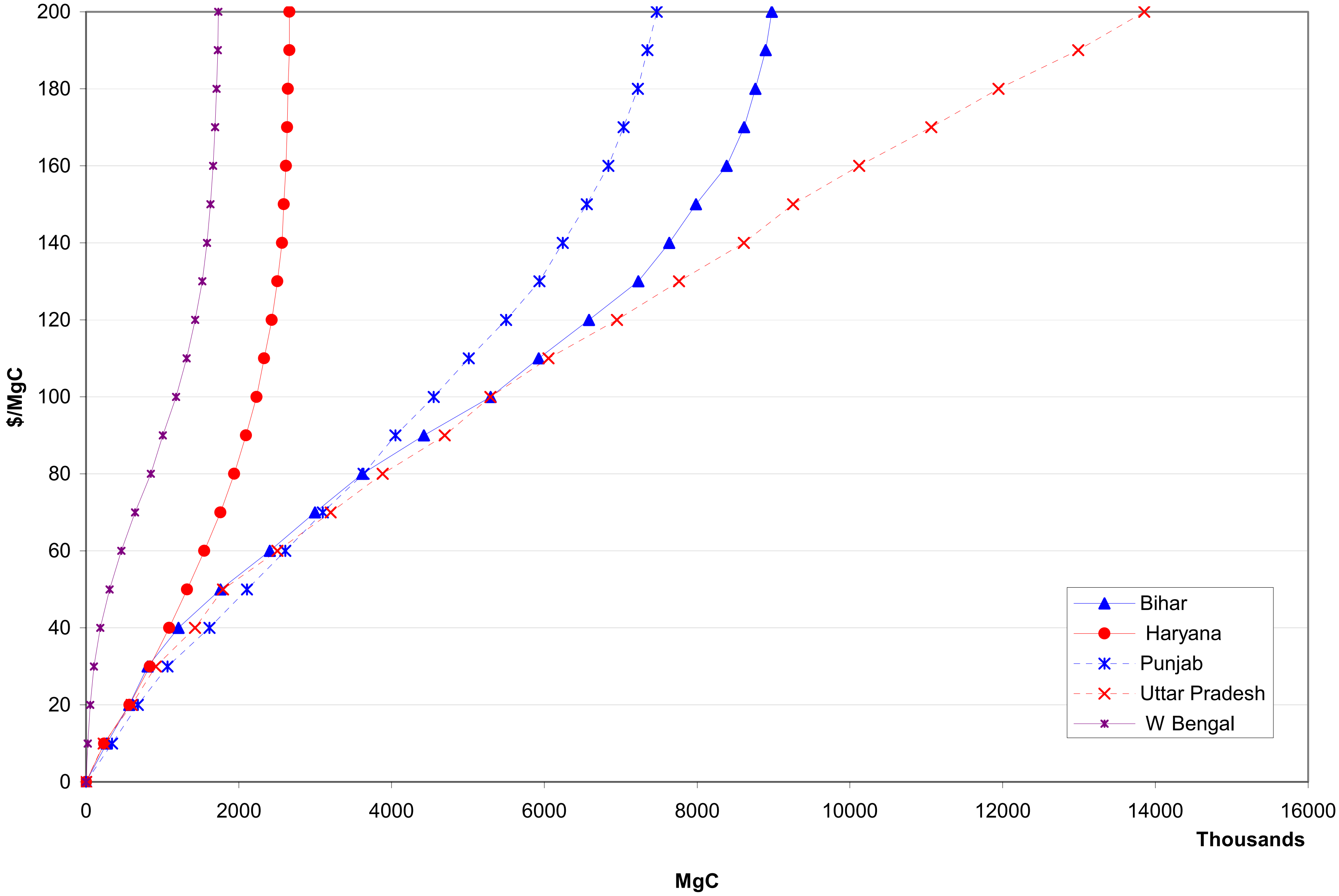

Figure 17. Sub-regional carbon supply curves when converting from conventional to no-till wheat-rice rotation systems in the Indo-Gangetic Plain of India.

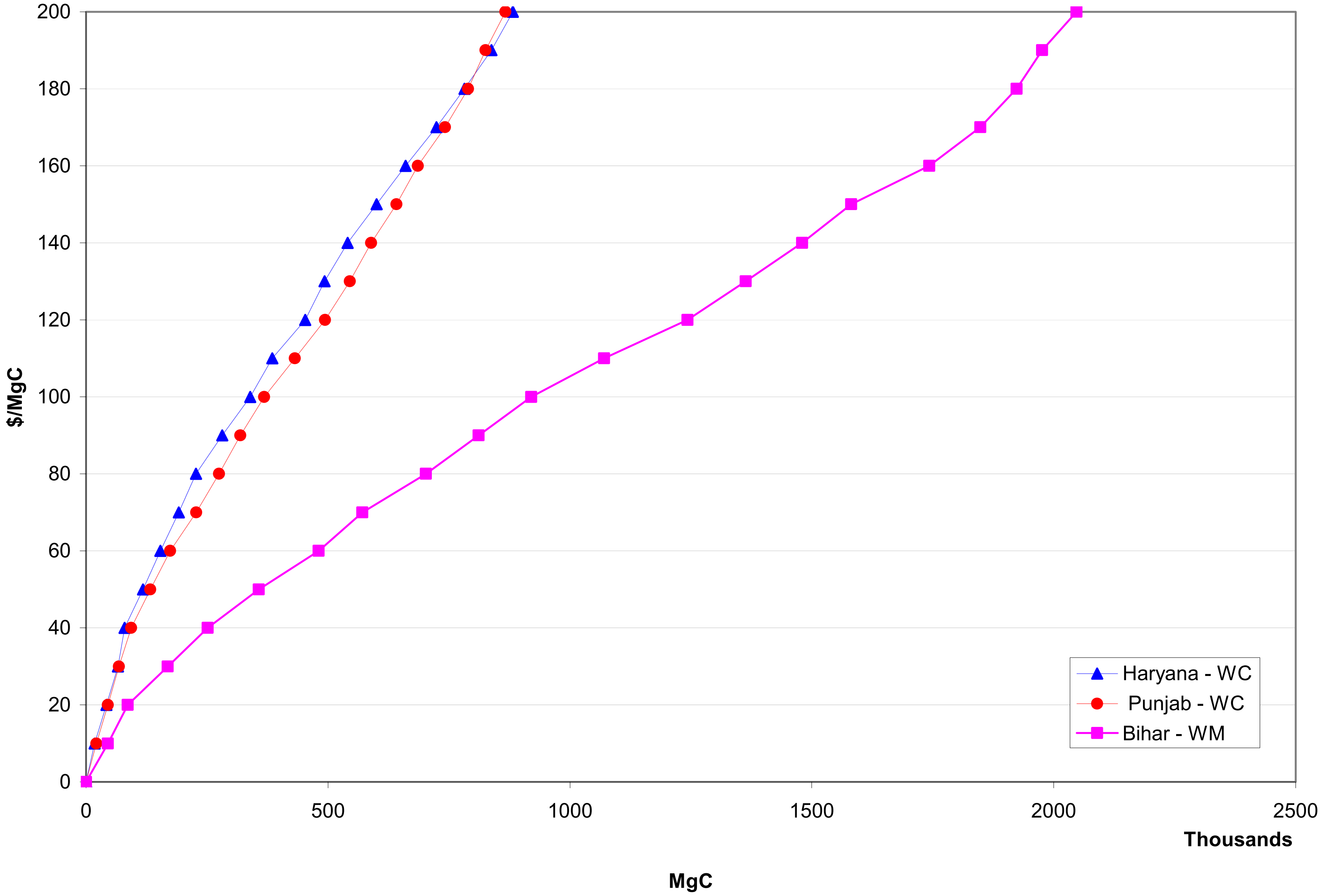

Figure 18. Sub-regional carbon supply curves when converting from conventional to no-till wheat-cotton (WC) and wheat-maize (WM) rotation systems in the Indo-Gangetic Plain of India.

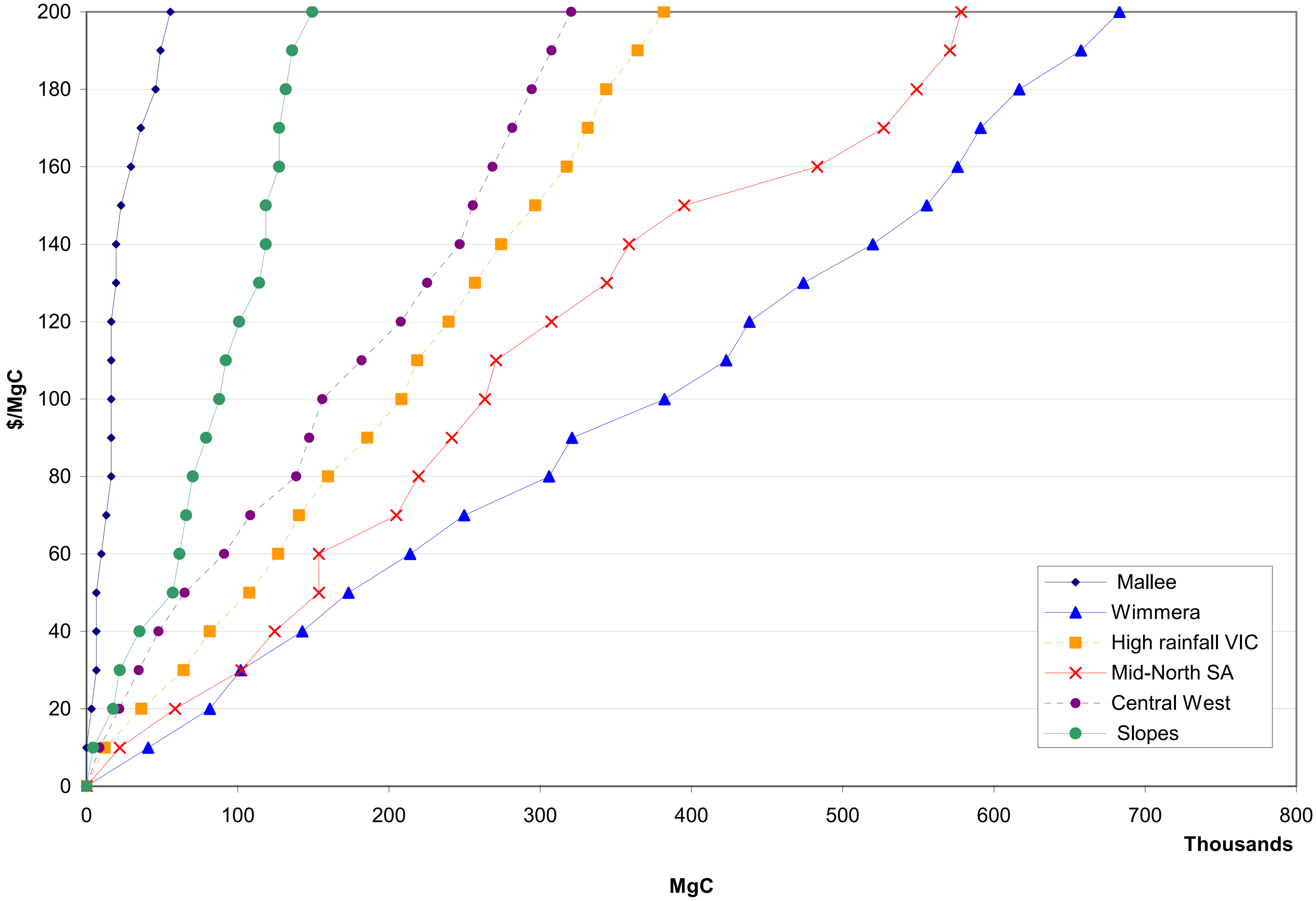

Figure 19. Sub-regional carbon supply curves for when converting from conventional to minimum tillage crop-pasture systems of South-Eastern Australia.

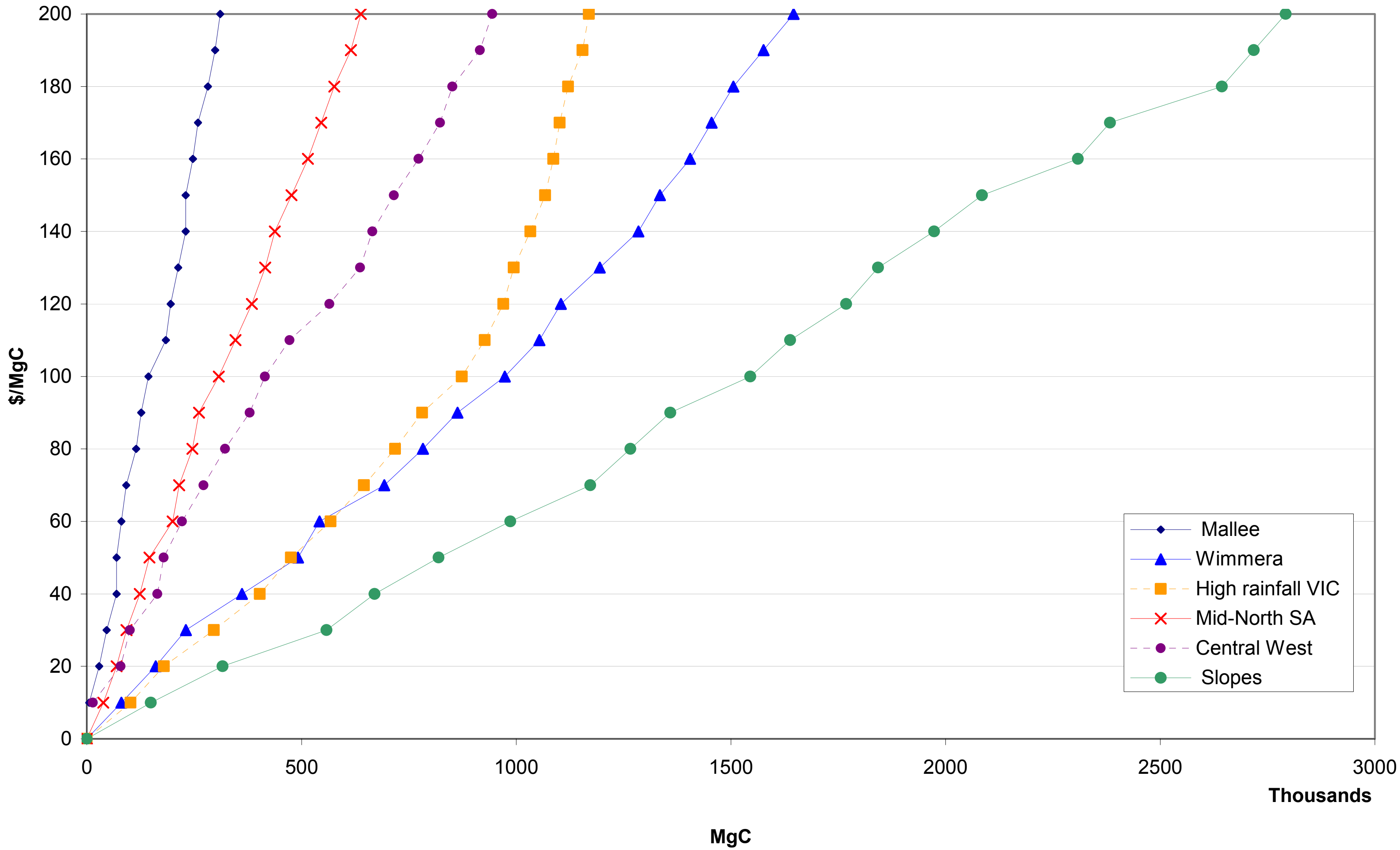

Figure 20. Sub-regional carbon supply curves when converting from conventional to no-tillage crop-pasture systems of South-Eastern Australia.

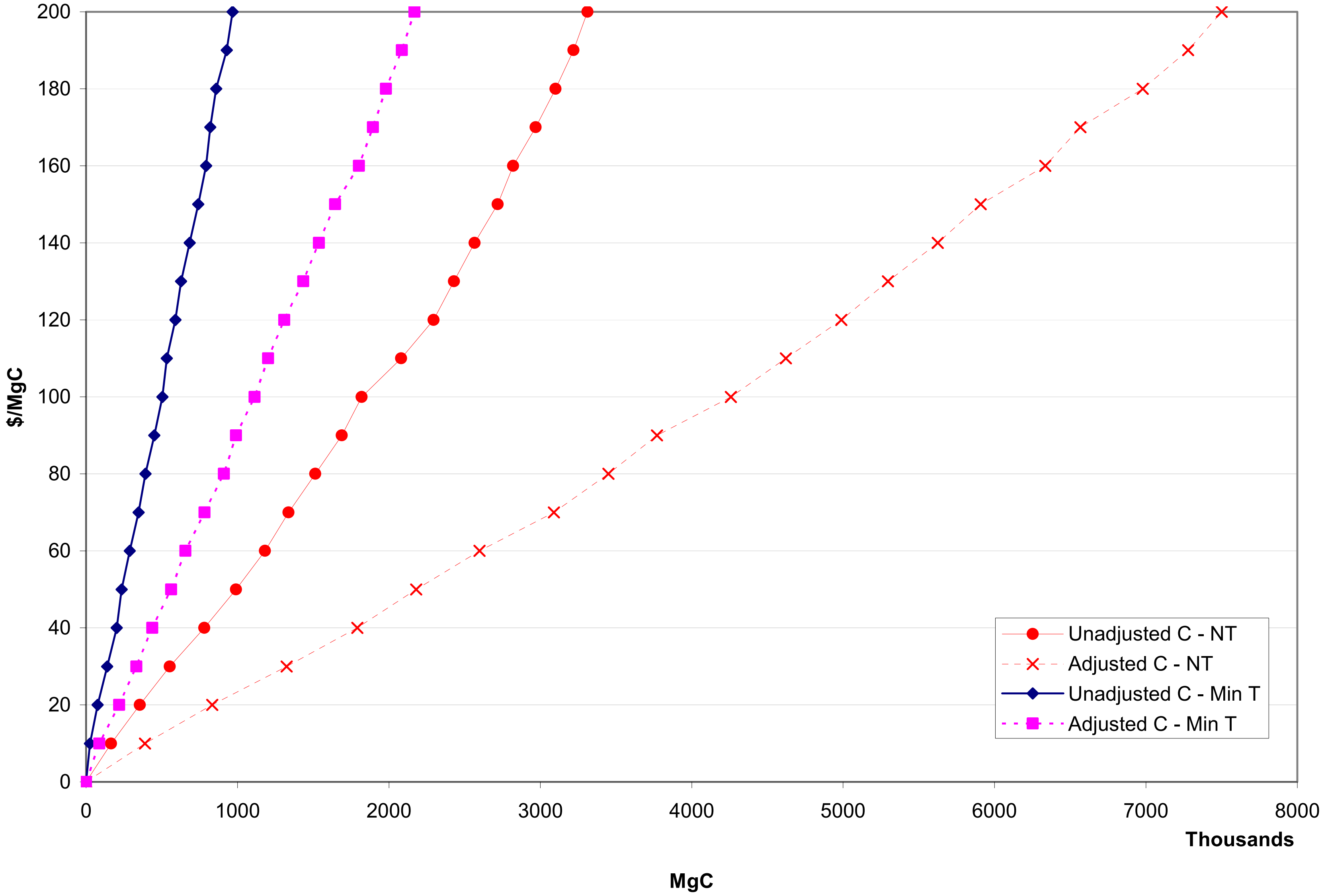

Figure 21. Comparison of carbon supply curves on conversion of conventional tillage systems minimum (Min T) and no-till (NT) in South-Eastern Australia and calculated with both gross (unadjusted) and net (adjusted) carbon data. Transaction costs are included.

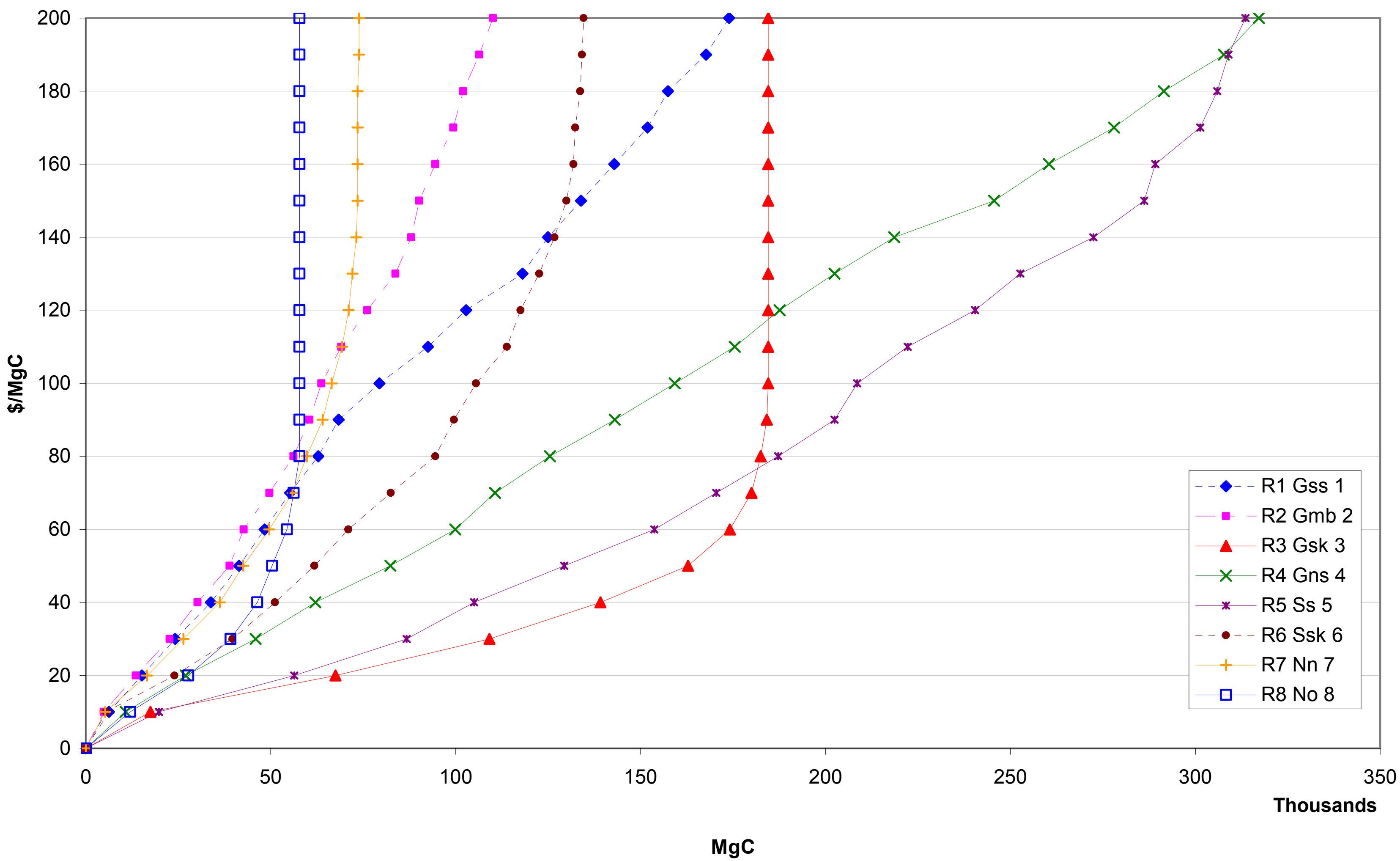

Figure 22. Sub-regional carbon supply curves when converting from conventional cropping to pastures systems in Sweden.

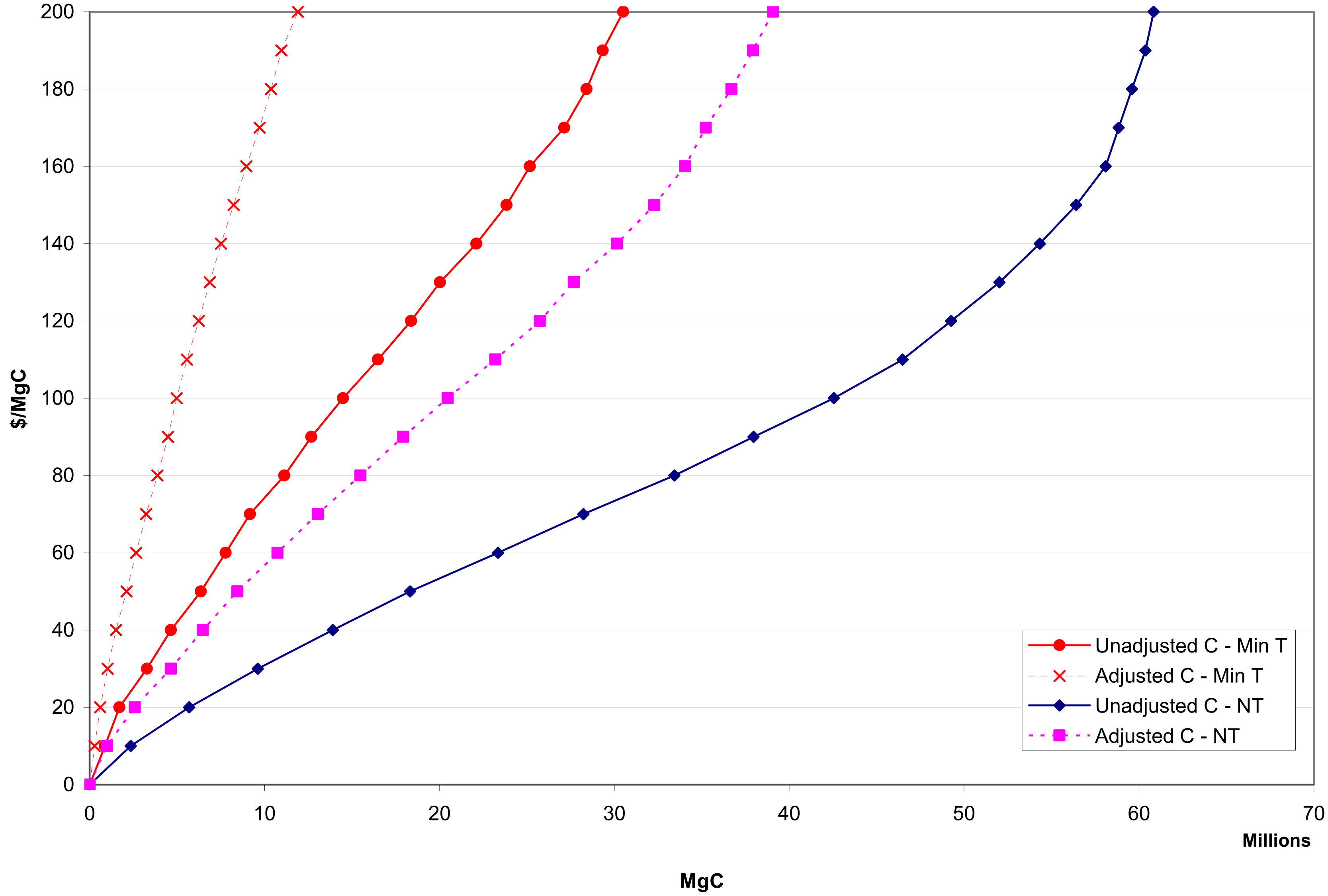

Figure 23. Comparison of carbon supply curves on conversion of conventional tillage systems to minimum (Min T) or no-till (NT) in Kazakhstan and calculated with both gross (unadjusted) and net (adjusted) carbon data. Transaction costs are included.

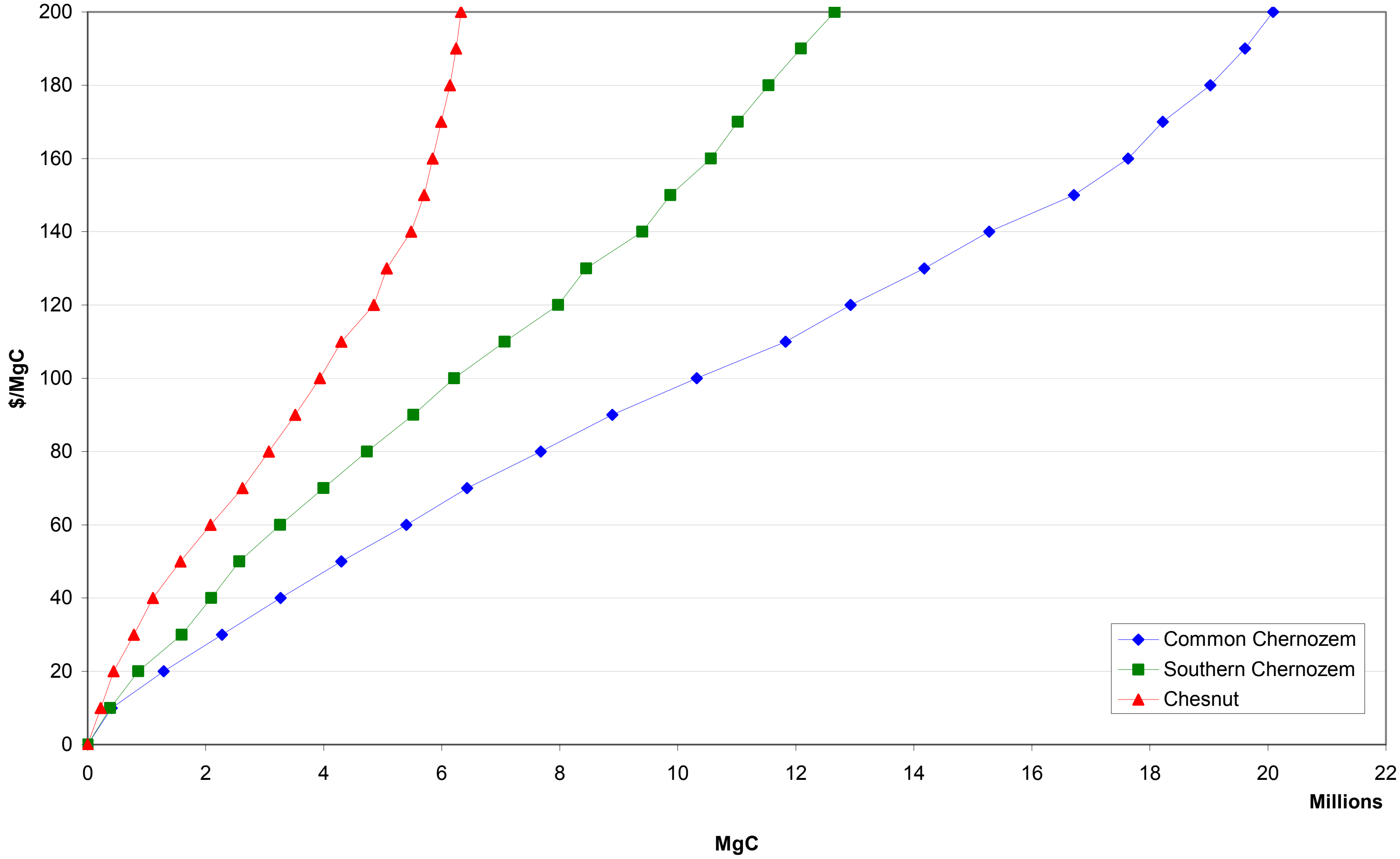

Figure 24. Sub-regional carbon supply curves when converting from conventional to no-tillage cropping systems in Kazakhstan.

5.3.2 Uruguay

The Uruguay analysis considers the adoption of no-till in a mixed cropping system where minimum tillage is already widely practiced. The conversion of cropland to permanent pasture is also evaluated. Because minimum tillage is the normal practice, there are relatively minor differences between unadjusted and adjusted carbon rates (Figure 14) for adoption of no-till, and returns to the two practices are similar (with returns to no-till slightly lower). However, for the analysis of conversion of crop land to permanent pasture, returns to pasture are lower than for no-till but carbon rates are substantially higher. Thus, it would appear that conversion of cropland to pasture represents the more likely scenario for carbon sequestration in Uruguay. This conclusion is reinforced by the fact that there does not appear to be a fixed cost for adoption of permanent pastures (Table 22). Moreover, the net carbon rates are higher than the gross rates, further reinforcing the significance of this management alternative.

The sub-regional carbon supply curves for Uruguay (Figures 15 and 16) show distinct regionalization (essentially into 2 categories), with the major livestock and crop production area of the country (Litnort and Litsur), being more effective in terms of economic efficiency in sequestering soil organic carbon.

5.3.3 Indo-Gangetic Plain

Analysis of this region considers adoption of no-till in three systems: wheat-rice (the most widespread system); wheat-maize; and wheat-cotton. Currently, a significant level of adoption has occurred only in one state, Haryana (approaching 45%), whereas adoption is low (10% or less) in the other regions. It is worth noting, however, that the technology is relatively new in this region and is in the process of being promoted for adoption more widely. This is through the support of a research program know as the Rice Wheat Consortium and government programs, so additional future adoption can be expected without carbon incentives. The estimated additionality discount (Table 22) indicates that farmers would adopt no-tillage on up to 13 - 51% of the cropland without carbon incentives. However, we caution that adoption in this region may likely be limited by market imperfections and other constraints.

Transaction costs are estimated to be relatively low (about \$3 ha^{-1}) (Section 5.4.2), and do not have a significant effect on the analysis. However, there are good reasons to believe that transaction costs may actually be quite high in developing countries where institutions needed to implement carbon sequestration are lacking or do not function efficiently. In the case of India, such institutions may in fact exist and function effectively, but caution is in order on this point. Carbon rates expected in the IGP region are in the mid-range of 0.2 - 0.4 Mg C ha^{-1} $annum^{-1}$, and the adjustments for net emissions are relatively small, presumably because relatively small quantities of fuels are used.

The IGP results also illustrate important sub-regional differences. For example, the highest potential for carbon sequestration in the wheat-rice system appears to be in Uttar Pradesh and Bihar, followed by the Punjab (Figure 17). Potential for additional adoption of no-till in Haryana, where adoption rates are already high, appears to be quite low. Total potential supply in West Bengal is relatively small simply because the area cultivated there is small. For wheat-cotton, both Haryana and the Punjab exhibit similar trends in carbon supply, whilst wheat-maize is more profitable in terms of its economic potential to sequester carbon compared to wheat-cotton (Figure 18).

5.3.4 South-Eastern Australia

The analysis for Australia considers adoption of either minimum tillage or no-till in a mixed grain and oilseed system. Unadjusted carbon rates were generally quite low (0.1 - 0.2 Mg C ha^{-1} $annum^{-1}$) in several larger regions and higher in two smaller regions. Economic returns to no-till were estimated to be higher on average than for minimum tillage. Therefore, expected returns (inclusive of carbon payments) would be larger for no-till than for minimum tillage, so the no-till case is likely to be the most relevant one to consider for carbon sequestration analysis.

There are substantial differences in economic potential for soil carbon sequestration across the sub-regions of Australia (Figures 19 and 20). The Wimmera, High Rainfall and Slopes regions have the highest carbon gains under no-tillage, but they are substantially smaller than some of the other regions. Nevertheless, they are among the sub-regions with the highest total potential for carbon sequestration, whereas other much larger regions have much lower technical and economic potential. The same regional pattern for investment is not evident for minimum tillage systems, but overall the Wimmera region would appear to be the most favourable when considering tillage based returns on investment.

It must be noted that in some of the larger Australia regions where crop-pasture systems are in predominance (Mallee and Central West), the total areas reported available for adoption may be slightly inflated. Data reporting in these areas is not detailed enough to differentiate long-term pasture from crop-pasture systems, so they are all considered available for technological change.

Note that the adjustment of the carbon rates for reductions in input use shift the supply curves significantly to the right, in this case doubling the estimated quantities of carbon sequestered (Figure 21). In Australian systems, particularly no-tillage, there are significant reductions in external inputs (e.g. fuel) with subsequent impacts on the associated field emissions. Animals are also removed, thus reducing CH_4 emissions and also allowing crop residues to decompose and aid in he maintenance of the soil carbon pool.

5.3.5 Sweden

The analysis for Sweden considers the conversion of grain crops to permanent grass pasture. Carbon rates are relatively low, and are even lower after adjustments are made because of the relatively high external inputs in these systems. The pasture systems actually receive more nitrogen fertilizers and require more fuel use for maintenance than the cropping system. However, given the relative returns to grains and grass, the opportunity cost per tonne of carbon is not exceptionally high, and participation in carbon contracts is in the low-middle range compared to other countries (Figure 11). Total economic potential for soil carbon sequestration in Sweden is low relative to other countries because technical potential is low and the areas in production are small (Figure 12). Sub-regional differences are relatively minor (Figure 22), with only two regions (Ss and Gns), showing some degrees of differentiation in cost effectiveness.

5.3.6 Kazakhstan

The analysis for Kazakhstan is for a dryland wheat/barley system with long fallows every 3-4 years Two options were considered, the conversion of conventional tillage to minimum tillage and no-till, as in the Australia case. Also like Australia, both expected returns and carbon rates are higher for no-till than minimum till, so the no-till option is the more relevant case for carbon sequestration, assuming there are not significantly larger fixed costs of adoption. In fact, our estimates of the fixed costs of adoption are about 30% higher for no-till, but this difference is offset by substantially higher carbon rates for no-till.

The analysis suggests that no-till would be profitable for many farmers without carbon incentives, and the average additionality discount estimated for this region (85%) is consequently the highest of all the regions studied (Table 22). However, as with IGP, we expect that capital market imperfections and other institutional constraints associated with the transition from the former collective farming system are likely to limit actual adoption, so this additionality discount should be interpreted as an upper-bound estimate.

Estimates of transaction costs were not available for Kazakhstan, these costs were assumed to be in between the values estimated for Australia and IGP. These values were sufficiently low that the results are not sensitive to this assumption. However, caution is in order here, given the difficulty in knowing whether institutions capable of implementing carbon trading exist.

The adjustments for net carbon rates in Kazakhstan indicate that the gross rates exceed the net rates, in contrast to most other regions where the net carbon rates are greater than the gross carbon rates. The input of nitrogen fertilizers in these systems is generally increased when shifting to reduced and no-tillage from conventional, and in these low input systems, this causes a substantial increase in associated greenhouse gas offsets. The results show that the adjustments reduce the estimated economic potential in the region by almost 50% (Figure 23). Nevertheless, the economic potential for all of the regions within Kazakhstan is quite high (Figure 24) due to the large areas in production and the moderately high technical potential. Investment in the Common Chernozem region is clearly favoured.

5.4 Additional information (from IEA Technical Specifications)

5.4.1 Estimation of costs of adopting local practices

It should be noted that collaborators were able to provide estimates of differences in operating costs of capital (e.g., changes in fuel use and machinery operation or human labor requirements), but were not able to estimate costs of any changes in capital needed (e.g., the costs of modifying tillage equipment to implement no-till). As explained in our methodology, we have estimated a fixed cost of adoption through a model calibration process. These fixed costs are summarized in Table 22.

5.4.2 Transaction costs for 10,000 Mg C contracts

The following elements were specified in Annex A of the technical specifications for IEA/CON/03/95:

- Assembly of parties
- Measurement & monitoring
- Payment dispersal costs
- Administration costs

Transaction cost information was requested from collaborators. Collaborators for Kazakhstan, Sweden and Uruguay did not provide useable information. For Australia and IGP, the data provided are summarized as follows.

Australia

- Brokerage fee (assembly of parties) = 1% of value of contract
- Measuring & Monitoring: sampling at 5 year intervals, cost = $100 per farmer per contract
- Payment Dispersal: included in admin cost.

- Costs of Administration: 1% of value of contract.

These values were estimated to be upper limits, and likely to be lower in a mature market. If we assume that the average carbon accumulation rate is 0.2 Mg C $ha^{-1}annum^{-1}$, then about 2500 ha will be required for a 10,000 Mg C contract (where the carbon is accumulated over 20 years). Assuming 100 ha per farm under contract, and 4 samples over a 20 year contract, then the total measuring and monitoring costs are estimated to be \$4 ha^{-1}, or \$10,000 for a contract of 10,000 Mg C. If brokerage and administration costs are in proportion to the value of the contract, then they will depend on the assumed price per Mg C of carbon. For example, for a price of \$30 Mg C^{-1} these costs would be \$6,000 per contract. Total transaction costs for a 10,000 Mg C contract would then be about \$16,000. Note this implies a per hectare transaction cost of about \$6.40 ha^{-1} for the entire contract. Converting this to a per-tonne basis and amortizing it over the life of the contract at 10%, the transaction cost is about \$3.50 Mg C^{-1} $annum^{-1}$.

IGP

- Brokerage fee (assembly of parties) = 1% of the value of the contract.
- Measuring & Monitoring:
    - SOC sampling twice $annum^{-1}$, cost = 1,000,000 rupees $anum^{-1}$ for IGP
    - Remote sensing every 2 years with 400,000 rupees per event for IGP
- Payment Dispersal: included in administration cost
- Costs of Administration: 10,000,000 rupees $annum^{-1}$ for the IGP region

To estimate the cost for a 10,000 tonne contract (defined as 10,000 Mg C accumulated over 20 years), we assume an average carbon rate of 0.25 Mg C ha^{-1} $annum^{-1}$, implying that 2000 ha would be under contract (2000 = 10,000/20/.25). Assuming a total carbon sequestration of 4 million Mg C over 20 years, this would give 400 contracts of 10,000 Mg C per contract. Total measuring and monitoring costs for the region over 20 years is estimated to be 24 million rupees, equal to \$534,000 or \$1,335 per contract. Administrative fees are estimated to be \$1800 per contract. Thus total transaction costs per 10,000 Mg C contract are estimated to be about \$3,135. Note that this implies a transaction cost ha^{-1} of about \$1.60. If we assume a brokerage fee of 1%

as for Australia, and assume a price of \$30 Mg C^{-1}, then the brokerage fee is \$3,000. The transaction cost ha^{-1} would then be about \$3. Converting to an annual per-tonne basis, the transaction cost is about \$1.20 Mg C^{-1} $annum^{-1}$.

5.4.3 Transaction costs used in carbon supply curves

Transaction costs are charged several ways in the financial industry: as a percent of the value of the transaction; a fixed fee per transaction; or per unit of traded commodity. In the case of soil carbon, transaction costs will vary with respect to the number of hectares under contract (or equivalently, with the number of tonnes of carbon traded) rather than by the value of the contract. We estimated some components of transaction costs as a percent of value and some on a per hectare basis and some as fixed per contract. Because data were not available for all of the study areas, we have made a set of uniform assumptions based on the data provided for Australia and India as well as using our judgment based on other studies. For estimation of supply curves we have translated these data into two components: (1) measuring and monitoring costs are estimated to be \$2 per hectare of land under contract; (2) brokerage and administrative costs are calculated as 2 percent of the value of the contract. In addition, we have assumed that there is a minimum brokerage and administrative cost of \$5 per hectare. However, regardless of these assumptions, the estimated transaction costs are low (less than 10% of the price except for prices below \$20 Mg C^{-1}) relative to the price total cost of the contract so our results are not sensitive to these assumptions.

5.4.4 Leakage

With the exception of Sweden and Uruguay, our analysis is based on the adoption of conservation tillage. This should not change production significantly, hence there will be no discernable leakage effects (which is very different from forestry where growing more trees lowers the price of wood products). In the case of Sweden, there could be some market effects, if farmers substantially reduced grain production, however, in that case prices are largely set by external market forces so we would not expect much leakage effects. Moreover, Sweden is a relatively high cost producer of carbon so the issue is probably moot in any case. Substantial conversion of crops to pasture in Uruguay could have leakage effects if crop prices increased and pasture rental values declined with the allocation of land to pasture in response to carbon incentives. Our analysis shows that carbon incentives could lead to about 60% of cropland being converted to pasture at a carbon price of \$100 Mg C^{-1} and about 70% if the carbon price were \$200 Mg C^{-1}. However, it is unclear how much long-term leakage would occur given that grain crop prices are substantially determined by trade within the region and the world.

5.4.5 Saturation and impermanence effects

There is an attainable maximum stock of carbon in soil (Six et al., 2002). It is highly dependent on the soil type, its land use history, the prevailing climate and ecosystem productivity. At that point in time, usually well in excess of 20 year time frame defined within this analysis, the soil is said to become "saturated". However, sequestered carbon can be released back in to the atmosphere in a short period of time if farmers revert back to conventional practices.

A simple way to address this permanence issue is to view farmers who enter into soil carbon contracts as providing a service in the form of accumulating and storing soil carbon. In effect, buyers of carbon contracts are paying for the service, and when the service is discontinued the buyer would be responsible for a corresponding liability (Marland *et al.*, 2001). Once the soil carbon level reaches the saturation point, the farmer provides only storage services. The key point, is that both accumulation and storage services depend on the farmer continuing to maintain the land use or management practices that make the accumulation possible. Therefore, if the practices that store carbon are not more profitable than the conventional practices that release carbon for the duration of the contract, farmers will have to be provided an incentive for the full duration of the time that the carbon sequestering and storing practices are to be maintained.

The economic model of Antle and Diagana (2002) shows that once productivity increases and the conservation practices become more profitable, farmers are likely to maintain the conservation practice indefinitely without additional financial incentives for carbon sequestration. Therefore, we can conclude that if a carbon sequestration practice becomes profitable at some point before the contract expires, the carbon sequestered through adoption and maintenance of these practices is likely to be permanent as long as the practices remain profitable. Thus, when conservation practices enhance the productivity of the production system so as to eventually make the practices profitable, carbon permanence may be an emergent property of the system. The model presented by Antle and Diagana (2002) also shows that the incentives for farmers to maintain a practice depend on all of the economic factors that affect profitability. Therefore, it is possible that changes in economic conditions could cause farmers to dis-adopt formerly profitable practices.

We have no additional information on which to base an estimate of these costs within this study, and they would require detailed targeted surveys beyond the scope of the original project.

5.4.6 Additionality discount

To estimate an additionality discount we have used the economic simulation model to estimate the proportion of land units that would have adopted carbon-sequestering practices, above and beyond the existing level of adoption, without carbon incentives. The carbon supply curves incorporate these discounts by calibrating the model's fixed cost term so that, without carbon payments, the model's baseline matches the observed land allocation between conventional practices and carbon-sequestering practices. Table 22 summarizes the additionality discount estimates implied by our analysis. We emphasize that these should be considered upper-bound estimates of additionality discounts because we are assuming that eventually all farmers who could potentially benefit from adopting the conservation practice would in fact adopt. Constraints such as imperfect capital markets, however, might actually prevent some farmers from adopting, especially in countries such as India and Kazakhstan.

In our analysis, two types of practices have been analyzed, conversion of conventional tillage to minimum or no-till practices, and conversion of crop land to permanent grass or pasture (in Uruguay and Sweden). In the case of converting crops to pasture, in Uruguay, our analysis does not indicate therefore there is likely to be any substantial change from the observed land allocation without additional incentives. In Sweden, our data suggest that farmers could abandon grain crops and replace them with permanent grass to a substantial degree, as indicated by a substantial (49%) average additionality discount.

In the case of minimum tillage there is the real possibility that farmers could significantly adopt minimum or no-till practices in the absence of carbon incentives, as they have already done in many parts of the world. In the countries in our study, Australia has already substantially adopted minimum and no tillage practices, and we would not expect substantial additional adoption in the absence of additional incentives from carbon payments. However, our analysis suggests that there would be some additional adoption of no-till (13%) without carbon incentives. In the other cases we have analyzed, our analysis suggests that there would be substantial additional adoption without carbon incentives, with additionality discounts ranging from 32% in Uruguay to 85% in Kazakhstan.

5.4.7 Obstacles to adoption

A great variety of factors influence farmers' land use and management decisions that ultimately result in soil conservation (or degradation) and consequently the amount of carbon that can be stored in their soils. Farmers in developed countries such as Australia, Sweden and Uruguay tend to have a greater understanding on how to maintain productivity and the need to prevent (for example) erosion and clearly have an incentive to manage their land, so as to maintain it as a valuable form of capital (Antle & Diagana, 2003). Also, local institutions are in existence to support construction and implementation of carbon contracts, including the adequate enforcement of property rights, compliance. In these countries, transaction costs should not be excessive and financial liquidity can not be considered a major constraint to investments due to presence of existing governmental and non-governmental financial institutions.

On the other hand, farmers with insecure rights, operating small plots of marginal land, lacking education and knowledge of how their management degrades productivity, may take actions, albeit unintentionally, that degrade soil resources. Therefore, in developing countries such as India and Kazakhstan, many factors would be likely to inhibit the participation of small-scale farmers in a carbon credit market. The transactions costs associated with aggregating land units to create a marketable contract would tend to be larger because of the smaller scale of production (i.e. more individual farms required for sequestering a set amount of carbon). In addition, verifying compliance with contracts could be more costly for a number of small farms.

Problems would also potentially arise where land property rights are not formalized. It is not clear at this stage how contracts would work if farmers did not hold legal title to the land they manage. For example, in many parts of the developing world, farmers have land use rights given to them by local village authorities, and these land use rights can change over time. Many parts of the developing world also lack well-functioning legal and financial institutions. If contracts are not enforceable, buyers of carbon contracts will have little recourse if farmers are found not to be complying with the terms of the contract. Likewise, in countries that lack financial markets, farmers may not be able to borrow to make investments needed to adopt practices that sequester carbon. The carbon market could function as a form of financing of these investments, by paying in advance all or part of the capitalized value of the carbon expected to be sequestered. For example, a "carbon loan" program could provide financing for conservation investments, to be paid back through generation of carbon credits.

5.4.8 Co-benefits

Practices that contribute to carbon sequestration are also likely to have significant impacts on the level and stability of farm production, food consumption and ecosystems services. In the developed world, these impacts direct translate to increased profitability and sustainability (Plantinga & Wu, 2003). In the developing world, these impacts translate into improvements in health and nutrition of rural households and ultimately to improvements in rural economic development. In the developing world, however, the impacts of carbon payments and other payments for environmental services on income distribution are not clear. On one hand, relatively poor farmers tend to manage degraded lands; on the other hand, carbon payments based on land ownership might benefit relatively wealthy landowners, and would not benefit the landless, except possibly indirectly.

Measuring possible co-benefits of carbon sequestration requires analysis that goes beyond economic models of agricultural production. Antle & Capalbo (2001) presented an integrated assessment framework that was used to address the on-farm and immediate off-farm environmental consequences of adoption of management practices that sequester soil carbon. To account for regional economic impacts, additional data is needed to characterize both on-farm and non-farm rural households, and to analyze market and non-market effects of improvements in agricultural production. Partial or general equilibrium economic models are also needed to assess rural development impacts.

Reducing atmospheric concentrations of GHGs produces a global benefit by reducing the risk of climate change, whereas most other environmental and social impacts are local. A market for GHG emissions reductions would not normally take into account the local co-benefits produced by farmers. This means that the incentives provided to farmers through a GHG emissions trading system will not be as large as they would be, if they incorporated the social value of other environmental and social co-benefits. Exceptions do exist, and e.g., in South-Eastern Australia, where dryland salinity is a major issue, management strategies that promote more efficient use of water (i.e., conservation tillage) have a potential win-win outcome on both salinity and carbon management. An important topic for further research is to assess how appropriate incentives can be created that account for the value of local co-benefits (Antle & Diagana, 2003).

6. Summary and conclusion

This study developed a generic assessment methodology for quantifying and comparing the economic feasibility of soil carbon sequestration strategies in agricultural systems from around the world. Carbon accumulation rates based on the IPCC methodology were combined with economic data to simulate the economic potential for agricultural soil carbon sequestration in sub-regions of five countries (Australia, India, Kazakhstan, Sweden and Uruguay). The analysis examined the economic potential for farmers to sequester additional carbon in the soil by changing land use and management practices in exchange for payments based on the number of tonnes of carbon they sequester.

Two types of changes in land use and management were generally considered, depending on what is feasible in each region: adoption of minimum tillage or no-till cultivation; and conversion of cropland to permanent grass or pasture. Rates of soil carbon sequestration were estimated in gross and net terms, where the latter adjusts for changes in carbon emissions associated with changes in management (e.g. fuel use, nitrogen fertilizer application, grazing by animals).

The analysis shows a substantial range of economic potential for soil carbon sequestration, both within and across regions. For a relatively low carbon price (i.e., less than $50 per tonne), all regions show a relatively low economic potential for soil carbon sequestration, with the economic potential falling substantially below the technical potential simulated by the IPCC carbon model. On average, only 17% of the technical potential was achieved. Farmers are willing to enter into carbon sequestration contracts on less than 34% of the available land. This latter value being the highest (predicted) participation rate at $50 per tonne C in the analysis (i.e. when converting from minimum tilled systems to pastures in Uruguay).

At $200 per tonne of carbon, 61% of the technical potential could be achieved, with farmers entering into contracts on less than 80% of the available land. This latter value represents the highest (predicted) participation rate at $200 per tonne C. Increased adoption of no-tillage in Kazakhstan and the Indo-Gangetic Plain were favoured at this price. A shift from conventional to minimum or no-tillage in South-Eastern Australia, were the least favoured strategies, but high rates of adoption already exist in this country.

At a carbon price of $50 per tonne of soil carbon sequestered, farmers in the regions where no-till cropping systems are being promoted (Australia, India, Kazakhstan and Uruguay) are willing to change land use and management practices on less than 20% of the available land and would sequester 18.9 million tonnes of carbon over 20 years. At a price of $200 per tonne of carbon, 87 million tonnes of carbon would be sequestered on conversion to no-tillage technologies, on less than 80% of the available land. At both $50 and $200 per tonne of C, the wheat-rice systems of the Indo-Gangetic Plain provided the maximum predicted participation (land conversion) rates.

The immaturity of the global carbon trading market makes it extremely difficult to adequately express the overall impact of institutional mechanisms involved in developing and coordinating carbon sequestration contracts. However, the study has identified a number of key region-specific technologies which now require more detailed assessment before investment. Detailed case studies, incorporating both on-farm and institutional surveys, are now needed to assess the economic feasibility of soil carbon sequestration in these target regions, as well as permanence of the technologies. The accurate quantification of transaction costs, as well as the development of techniques for the accurate and consistent assessment of co-benefits needs to be considered a priority in future studies.

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9. Appendix 1: Instructions for completing the production system data spreadsheet

The purpose of the spreadsheet is to collect information for computation of net returns for each major production system in the region being evaluated. As noted in the *Methodology* section (2), the ultimate goal is to estimate the opportunity cost of adopting practices that sequester carbon.

The research team will evaluate the types of practices that are being used in a region and reach an agreement on the distinct production systems that can be modelled for both carbon potential and economic potential.

One spreadsheet is needed for each production system that is identified for the analysis. Please name each separate spreadsheet using the format REGION.xls, using the region name specified in the spreadsheet.

General Information

Name of Respondent = the name of the person providing the data.

Region = the place represented by the data (e.g., State of Punjab, India).

Spatial Unit = if multiple sites or pixels are represented in the data, define the unit (e.g., farm field, farm, agro-ecological zone (explain how defined), county, province, state).

Production System = the name used to designate the production system represented by the data (e.g., rainfed rice-wheat rotation with conventional tillage; irrigated rice wheat rotation with conservation tillage).

Other factors affecting adoption: note any factors that might affect adoption, including lack of private property rights to land; any issues associated with making cash payments to farmers (e.g., social organization, caste, etc.); lack of financing for conservation investments; or any other factor deemed relevant.

Variable Definitions

ID = unique identifier for the region (1, 2, …)

Long, Lat = spatial coordinates for the site if point data is used; coordinates of the centroid if pixels are used; leave blank if not applicable (e.g., if only one representative data point for the region is available).

Oquant* = output quantity, where * = 1,2,3, etc. (insert more columns if needed). Typically this is a crop yield. Note that important by-products can be included as outputs, e.g., amount of crop residue harvested for use as animal feed.

Oprice* = output price per unit corresponding to Oquant*. In the case of survey data, this should be the price the farm-gate price reported by the farmer. In the case of data for a political unit (e.g., province) reported by a government entity, use the price reported for the period the crop was harvested if possible.

Area = number of hectares in production in the spatial unit.

Iquant* = input quantity, where * = 1,2,3,etc. (insert more columns if needed). These are variable input quantities, i.e., human labor (measured in days), animal labor, mechanical labor, rates of fertilizer or pesticide applications, seeding rates, etc. See discussion of units of measurement below.

Iprice* = input price per unit, where * = 1,2,3,etc.

Kquant* = capital quantity, where * = 1,2,3,etc. (insert more columns as needed). The number of specified types of capital, e.g., tools, tractors, etc.

Kprice* = capital price, where * = 1,2,3,etc.

Z* = other variables (as needed). When survey data are available, a number of other relevant variables may be available, e.g., number of years of schooling of the farm head of household; farm size; etc.

Irate = interest rate on agricultural loans to purchase land or capital equipment. Specify source of loan in units spreadsheet.

Carbon = equilibrium stock of soil carbon (Mg C ha^{-1})

Duration = number of years required to reach equilibrium after adoption of this system.

Units of Measurement

A separate page is used to define units of measurement. In this sheet the respondent should provide as much information as possible about units of measurement used. Particular care must be taken with input quantities, as noted below.

Output quantities (Oquant*): use kg ha^{-1}

Output prices (Oprice*): use local currency per kg. **Note local currency used and current exchange rate with US dollars.**

Area: hectares.

Iquant*:

- Human labor: man-day equivalents (if male, female, or children's labor is aggregated, specify any weighting scheme used, e.g., 1 female day = 0.75 male day). If labor from two different operations is reported, treat them as two different inputs (e.g., Iquant1 = labor for land preparation and planting, Iquant2 = labor for cultivation, Iquant3= labor for harvest).
- Animal labor: animal days, specify type of animal. As with human labor, specify different inputs for different operations such as planting, cultivation, harvest.
- Mechanical labor: tractor days, specify type of tractor (e.g. horsepower). As with human labor, specify different inputs for different operations such as planting, cultivation, harvest.
- Fertilizer: kg/ha. Specify type (e.g., manure, commercial formulation). Use a different variable for each distinct type, e.g., Iquant5 = manure, Iquant6 = 20-20-20 formulation of NPK.
- Pesticides: kg/ha. Identify each major commercial formulation as a separate input.

Iprice*: specify prices corresponding to the Iquant units, use local currency per unit.

Kquant*: specify type of tool or machine.

Kprice*: price in local currency.

Z*: define units as appropriate.

Irate: annual percentage rate, specify source of loan (personal, private bank, public agricultural bank, NGO, etc.)

10. Appendix 2: Instructions for completing the transaction cost data spreadsheet

The transaction cost spreadsheet is used to record data about likely costs of implementing carbon programs or contracts. In most cases, actual programs or contracts will not have been implemented, so these data will have to be based on the best available data and the judgment of the respondent and any local experts that can be consulted.

Brokerage fee: if the coordinating organization charges a one-time fee for its services, record this fee here, as a percent of the value of the contract or in money terms.

Measurement/Monitoring Method: specify how compliance with the contract will be measured or monitored. E.g., use of extension workers or remote sensing to monitor adoption of practices, soil sampling at specified sites.

Annual Costs of Administration: estimate administrative costs of operating the program or managing compliance with the contract. For example, if this is a program managed by a government agency, estimate the number of personnel required to manage the program, their salary and benefit costs, and any operational costs.

Annual Costs of Technical Support: estimate costs of technical support, as for administrative costs.

Annual Costs of Risk Management: If the program or contract requires insurance against contract default, estimate the cost of this insurance.

11. Appendix 3: Economic model summary outputs

Appendix 3.1
Carbon sequestration (Mg C) in response to technological change for all countries.

Carbon Price	AUSTRALIA		IGP			KAZAKHSTAN		URUGUAY		SWEDEN
$/MgC	Conv-Min	Conv-NT	Wheat-Rice	Wheat-Cotton	Wheat-Maize	Conv-Min	Conv-NT	Red-NT	Red-NMP	Cer-Gley
0	0	0	0	0	0	0	0	0	0	0
10	87938	389614	1101778	39295	45076	274656	1003140	49769	1662087	81946
20	219044	833217	2463714	86945	86395	608752	2578923	110542	3582930	247682
30	331770	1323711	3723616	133806	169034	1021440	4651432	180407	5559468	393801
40	438029	1790765	5526690	173062	251672	1508426	6465221	263685	7346688	504040
50	563205	2180338	7290548	250485	356849	2111183	8437585	336274	9111511	609541
60	656714	2598483	9528537	327493	480806	2658086	10739141	425432	10776161	693616
70	782498	3089795	11699748	419141	570958	3233415	13046031	531010	12175577	760627
80	910269	3449810	13922438	502472	702428	3881800	15479670	637559	13351610	826237
90	990998	3770368	16266301	600599	811361	4475436	17924163	745126	14384978	879800
100	1114129	4258268	18548484	707457	920294	4973187	20462657	869409	15159778	925237
110	1203016	4620921	20645120	816569	1070546	5561979	23189135	1011786	15820004	984755
120	1310502	4988015	22896000	946839	1243335	6226802	25746425	1169326	16407397	1037985
130	1433900	5296606	24958576	1038111	1363537	6865850	27689498	1308433	16859904	1093876
140	1537815	5624997	26635579	1130252	1479982	7508717	30159137	1446140	17212043	1146283
150	1644583	5909354	28018353	1242267	1581402	8224101	32285855	1589864	17530410	1201684
160	1801943	6335331	29631780	1346379	1742923	8952490	34039671	1749328	17791540	1234710
170	1894561	6566858	31044751	1466336	1848100	9709008	35225012	1910485	17972718	1278725
180	1981334	6979441	32287683	1571614	1923226	10380068	36702101	2065310	18119414	1306391
190	2085546	7278192	33626430	1663832	1975814	10961238	37940997	2220344	18255712	1341116
200	2168403	7500649	34699671	1748822	2047184	11901588	39072691	2396767	18331700	1365582

Appendix 3.2
Participation rates in relation to technological changes for sequestering carbon as a function of the price of soil carbon. Adjusted carbon data, all countries.

Carbon Price	AUSTRALIA			IGP		KAZAKHSTAN		URUGUAY		SWEDEN
$/MgC	Conv-Min	Conv-NT	Wheat-Rice	Wheat-Cotton	Wheat-Maize	Conv-Min	Conv-NT	Red-NT	Red-NMP	Cer-Gley
0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10	0.5%	1.1%	2.8%	1.3%	1.7%	1.1%	2.3%	0.8%	6.0%	2.7%
20	1.3%	2.3%	6.3%	2.8%	3.3%	2.3%	5.4%	1.7%	13.1%	8.4%
30	2.0%	3.5%	9.7%	4.3%	6.4%	4.0%	9.7%	2.8%	20.5%	13.2%
40	2.7%	4.9%	14.3%	5.6%	9.6%	6.0%	13.5%	4.1%	27.1%	16.8%
50	3.5%	5.9%	19.2%	8.1%	13.6%	8.3%	17.9%	5.4%	33.9%	19.9%
60	4.1%	7.0%	25.0%	10.6%	18.3%	10.4%	23.0%	6.8%	40.2%	22.2%
70	4.8%	8.3%	30.9%	13.7%	21.7%	12.7%	28.3%	8.4%	45.7%	24.1%
80	5.6%	9.3%	37.1%	16.5%	26.7%	15.5%	33.5%	10.1%	50.5%	25.7%
90	6.2%	10.2%	42.9%	19.5%	30.9%	17.9%	38.7%	11.9%	54.4%	26.9%
100	7.0%	11.5%	48.9%	22.7%	35.0%	20.0%	43.8%	13.9%	57.5%	28.0%
110	7.5%	12.5%	53.9%	26.4%	40.7%	22.8%	49.1%	16.0%	60.0%	29.3%
120	8.1%	13.5%	58.8%	30.4%	47.3%	25.7%	54.9%	18.4%	62.3%	30.4%
130	8.9%	14.4%	63.2%	33.5%	51.9%	28.2%	58.5%	20.6%	64.0%	31.7%
140	9.5%	15.2%	66.4%	36.3%	56.3%	30.9%	63.7%	23.0%	65.4%	32.6%
150	10.2%	15.9%	69.0%	39.8%	60.1%	33.7%	67.5%	25.3%	66.5%	33.6%
160	11.0%	16.8%	71.8%	42.8%	66.3%	36.8%	70.8%	27.7%	67.5%	34.3%
170	11.5%	17.4%	73.8%	46.5%	70.3%	39.5%	73.1%	30.1%	68.1%	35.1%
180	12.0%	18.2%	75.6%	49.7%	73.1%	42.1%	75.9%	32.6%	68.7%	35.6%
190	12.7%	19.1%	77.3%	52.3%	75.1%	44.5%	78.2%	35.1%	69.2%	36.3%
200	13.3%	19.6%	78.6%	55.0%	77.9%	48.2%	80.3%	37.8%	69.5%	36.8%

Appendix 3.3
Participation rates, annual sequestration rates and total sequestration over 20 years for Uruguay, converting minimum tillage to no-tillage cropping.

	Unadjusted Carbon			**Adjusted Carbon**		
Carbon Price $/MgC	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**
0	0.0%	0	0	0.0%	0	0
10	0.7%	2179	43571	0.8%	2488	49769
20	1.6%	4914	98276	1.7%	5527	110542
30	2.7%	8067	161333	2.8%	9020	180407
40	3.9%	11736	234711	4.1%	13184	263685
50	5.0%	14872	297439	5.4%	16814	336274
60	6.4%	18813	376265	6.8%	21272	425432
70	7.8%	23241	464814	8.4%	26550	531010
80	9.4%	28052	561035	10.1%	31878	637559
90	11.0%	32717	654340	11.9%	37256	745126
100	12.7%	37614	752279	13.9%	43470	869409
110	14.6%	43243	864858	16.0%	50589	1011786
120	16.9%	50140	1002807	18.4%	58466	1169326
130	19.0%	56675	1133498	20.6%	65422	1308433
140	21.2%	63192	1263846	23.0%	72307	1446140
150	23.4%	69348	1386963	25.3%	79493	1589864
160	25.6%	75685	1513703	27.7%	87466	1749328
170	27.9%	82841	1656825	30.1%	95524	1910485
180	30.3%	90351	1807017	32.6%	103266	2065310
190	32.4%	96412	1928235	35.1%	111017	2220344
200	34.7%	103609	2072181	37.8%	119838	2396767

Appendix 3.4
Participation rates, annual sequestration rates and total sequestration over 20 years for Uruguay, converting minimum tillage to nominally managed pastures

	Unadjusted Carbon			**Adjusted Carbon**		
Carbon Price $/MgC	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**
0	0.0%	0	0	0.0%	0	0
10	4.7%	53719	1074383	6.0%	83104	1662087
20	10.4%	115330	2306598	13.1%	179147	3582930
30	16.7%	186366	3727315	20.5%	277973	5559468
40	22.2%	245418	4908352	27.1%	367334	7346688
50	27.7%	305176	6103527	33.9%	455576	9111511
60	33.0%	360969	7219375	40.2%	538808	10776161
70	38.0%	415595	8311901	45.7%	608779	12175577
80	42.6%	464954	9299078	50.5%	667580	13351610
90	46.5%	505195	10103891	54.4%	719249	14384978
100	50.2%	543067	10861330	57.5%	757989	15159778
110	53.1%	571857	11437138	60.0%	791000	15820004
120	55.5%	596663	11933259	62.3%	820370	16407397
130	57.6%	618661	12373226	64.0%	842995	16859904
140	59.3%	636770	12735403	65.4%	860602	17212043
150	60.9%	653591	13071826	66.5%	876520	17530410
160	62.2%	667803	13356065	67.5%	889577	17791540
170	63.5%	681441	13628810	68.1%	898636	17972718
180	64.5%	692796	13855917	68.7%	905971	18119414
190	65.3%	701940	14038795	69.2%	912786	18255712
200	66.1%	709148	14182956	69.5%	916585	18331700

Appendix 3.5
Adjusted carbon sequestration after 20 years for regions of Uruguay, converting minimum tillage to no-tillage cropping.

Carbon Price $/MgC	Total Uruguay	Basprof	Crstcent	Lechsur MgC	Litnort	Litsur	Llaneste	Noreste
0	0	0	0	0	0	0	0	0
10	49769	660	11112	8605	16341	6703	2538	3810
20	110542	3018	28573	20974	35525	11172	4060	7219
30	180407	5659	42066	36033	50445	26813	7359	12031
40	263685	7734	62703	47865	71760	45246	10532	17847
50	336274	10186	74608	57545	93075	62004	14592	24263
60	425432	13298	96832	74755	115101	76527	17637	31282
70	531010	15845	119055	96805	142100	96078	21824	39303
80	637559	18957	150010	113477	169809	113395	26392	45519
90	745126	22541	172233	135527	191124	136856	32102	54743
100	869409	26879	202394	159728	221675	158082	37685	62964
110	1011786	30369	243667	183392	252227	188246	43903	69983
120	1169326	35745	299226	205980	286331	212824	49612	79608
130	1308433	39423	339705	232332	321145	229582	56211	90035
140	1446140	44893	362722	259760	357381	257512	62809	101064
150	1589864	50552	398439	283424	392905	284883	68772	110889
160	1749328	54796	440505	314616	429851	314489	74355	120715
170	1910485	58758	489714	341507	463245	346328	80192	130741
180	2065310	63945	526225	373237	497349	375934	85648	142973
190	2220344	68849	571466	404968	525058	405539	91865	152598
200	2396767	74319	622263	433471	564136	441289	98464	162825

Appendix 3.6
Adjusted carbon sequestration after 20 years for regions of Uruguay, converting minimum tillage to nominally managed pastures.

Carbon Price $/MgC	**Total Uruguay**	**Basprof**	**Crstcent**	**Lechsur MgC**	**Litnort**	**Litsur**	**Llaneste**	**Noreste**
0	0	0	0	0	0	0	0	0
10	1662087	48840	587016	253156	310425	282143	57670	122837
20	3582930	98798	1178024	617614	697770	585500	133689	271535
30	5559468	161059	1753060	927512	1151045	935528	209184	422080
40	7346688	209526	2260209	1252687	1535643	1253735	282582	552306
50	9111511	266195	2715446	1577862	1922987	1597398	360174	671449
60	10776161	321745	3190649	1865936	2299343	1879541	424659	794286
70	12175577	370212	3510113	2125640	2620757	2174413	493339	881103
80	13351610	411223	3781658	2356972	2903711	2367458	563591	966997
90	14384978	441049	4025249	2546839	3178423	2554140	607630	1031648
100	15159778	469383	4169008	2688694	3395446	2709000	641183	1087063
110	15820004	489515	4304780	2815272	3576756	2829919	674212	1129548
120	16407397	509275	4424580	2926574	3755319	2923260	697280	1171110
130	16859904	522324	4528405	3016051	3851469	3025086	714057	1202512
140	17212043	537237	4608271	3074976	3953112	3088727	728736	1220984
150	17530410	548794	4688138	3127353	4041020	3150247	738173	1236685
160	17791540	556623	4768004	3166636	4117940	3186310	749183	1246844
170	17972718	561097	4807937	3188460	4178377	3226617	755998	1254233
180	18119414	566690	4831896	3203736	4236066	3258437	762814	1259774
190	18255712	570418	4859850	3225560	4282767	3279651	767532	1269934
200	18331700	574519	4871829	3238654	4304744	3294501	773824	1273628

Appendix 3.7
Participation rates, annual sequestration rates and total sequestration after 20 years for wheat-rice in the Indo-Gangetic Plain, converting conventional tillage to no-tillage cropping.

	Unadjusted Carbon			Adjusted Carbon		
Carbon Price $/MgC	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**
0	0.0%	0	0	0.0%	0	0
10	2.3%	37115	742304	2.8%	55089	1101778
20	5.2%	80364	1607284	6.3%	123186	2463714
30	8.0%	127531	2550618	9.7%	186181	3723616
40	11.2%	177381	3547623	14.3%	276334	5526690
50	15.4%	243928	4878566	19.2%	364527	7290548
60	20.2%	319982	6399649	25.0%	476427	9528537
70	24.9%	389233	7784660	30.9%	584987	11699748
80	30.0%	469979	9399585	37.1%	696122	13922438
90	35.7%	558708	11174169	42.9%	813315	16266301
100	41.0%	647149	12942979	48.9%	927424	18548484
110	46.0%	728684	14573671	53.9%	1032256	20645120
120	50.7%	809024	16180479	58.8%	1144800	22896000
130	54.7%	878331	17566621	63.2%	1247929	24958576
140	58.2%	942923	18858451	66.4%	1331779	26635579
150	61.6%	1006388	20127754	69.0%	1400918	28018353
160	64.5%	1068208	21364157	71.8%	1481589	29631780
170	67.0%	1117885	22357700	73.8%	1552238	31044751
180	69.1%	1164495	23289910	75.6%	1614384	32287683
190	70.8%	1201829	24036585	77.3%	1681322	33626430
200	72.2%	1237216	24744315	78.6%	1734984	34699671

Appendix 3.8
Adjusted carbon sequestration after 20 years for regions of the Indo-Gangetic Plain in wheat-rice, converting conventional tillage to no-tillage cropping.

Carbon Price $/MgC	**Total IGP**	**Bihar**	**Haryana Mg C**	**Punjab**	**UP**	**W. Bengal**
0	0	0	0	0	0	0
10	1101778	268828	238688	340853	232273	21135
20	2463714	564540	569669	677280	597273	54952
30	3723616	806485	833817	1066827	912501	103986
40	5526690	1209728	1088418	1615733	1426819	185991
50	7290548	1760827	1323924	2107093	1791820	306885
60	9528537	2406015	1546700	2607307	2505229	463286
70	11699748	2997438	1759928	3098667	3202048	641668
80	13922438	3615743	1941331	3634293	3882276	848795
90	16266301	4422229	2094091	4050400	4695231	1004351
100	18548484	5295921	2230939	4550613	5292504	1178506
110	20645120	5927668	2332779	5010987	6055687	1317999
120	22896000	6586298	2431437	5497920	6951597	1428748
130	24958576	7231486	2504635	5936160	7764552	1521743
140	26635579	7634729	2565102	6241600	8610689	1583459
150	28018353	7984206	2590563	6555893	9257735	1629956
160	29631780	8387449	2619205	6839200	10120463	1665464
170	31044751	8615953	2635118	7038400	11066145	1689135
180	32287683	8763809	2644665	7224320	11945464	1709425
190	33626430	8898223	2663760	7348267	12990692	1725488
200	34699671	8978871	2663760	7472213	13853420	1731406

Appendix 3.9

Participation rates, annual sequestration rates and total sequestration after 20 years for wheat-maize in the Indo-Gangetic Plain, converting conventional tillage to no-tillage cropping. No regional data as one state only in wheat-maize.

	Unadjusted Carbon			Adjusted Carbon		
Carbon Price $/MgC	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**
0	0.0%	0	0	0.0%	0	0
10	1.3%	1506	30120	1.7%	2254	45076
20	2.6%	3012	60241	3.3%	4320	86395
30	5.3%	6191	123828	6.4%	8452	169034
40	7.4%	8701	174029	9.6%	12584	251672
50	12.1%	14224	284471	13.6%	17842	356849
60	15.7%	18407	368139	18.3%	24040	480806
70	19.4%	22758	455153	21.7%	28548	570958
80	22.4%	26272	525434	26.7%	35121	702428
90	27.0%	31626	632529	30.9%	40568	811361
100	30.9%	36145	722890	35.0%	46015	920294
110	34.3%	40161	803211	40.7%	53527	1070546
120	39.0%	45683	913653	47.3%	62167	1243335
130	45.7%	53547	1070949	51.9%	68177	1363537
140	49.7%	58233	1164657	56.3%	73999	1479982
150	53.4%	62584	1251671	60.1%	79070	1581402
160	57.4%	67269	1345379	66.3%	87146	1742923
170	60.9%	71285	1425700	70.3%	92405	1848100
180	66.6%	77978	1559569	73.1%	96161	1923226
190	69.7%	81660	1633197	75.1%	98791	1975814
200	72.7%	85174	1703478	77.9%	102359	2047184

Appendix 3.10

Participation rates, annual sequestration rates and total sequestration after 20 years for wheat-cotton in the Indo-Gangetic Plain, converting conventional tillage to no-tillage cropping.

	Unadjusted Carbon			Adjusted Carbon		
Carbon Price $/MgC	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**
0	0.0%	0	0	0.0%	0	0
10	1.1%	1465	29302	1.3%	1965	39295
20	2.3%	3131	62626	2.8%	4347	86945
30	3.5%	4847	96937	4.3%	6690	133806
40	5.0%	6611	132217	5.6%	8653	173062
50	6.2%	7958	159166	8.1%	12524	250485
60	8.2%	10656	213119	10.6%	16375	327493
70	10.3%	13286	265726	13.7%	20957	419141
80	12.9%	16666	333324	16.5%	25124	502472
90	15.1%	19279	385571	19.5%	30030	600599
100	17.8%	22825	456510	22.7%	35373	707457
110	20.0%	25807	516137	26.4%	40828	816569
120	22.9%	29871	597417	30.4%	47342	946839
130	26.2%	33982	679648	33.5%	51906	1038111
140	29.6%	38462	769241	36.3%	56513	1130252
150	32.0%	41676	833518	39.8%	62113	1242267
160	34.8%	45456	909125	42.8%	67319	1346379
170	37.4%	48820	976400	46.5%	73317	1466336
180	40.2%	52734	1054682	49.7%	78581	1571614
190	42.6%	56099	1121976	52.3%	83192	1663832
200	46.0%	60596	1211910	55.0%	87441	1748822

Appendix 3.11
Adjusted carbon sequestration after 20 years for regions of the Indo-Gangetic Plain in wheat-cotton, converting conventional tillage to no-tillage cropping.

Carbon Price $/MgC	**Total IGP**	**Haryana**	**Punjab**
0	0	0	0
10	39295	17957	21338
20	86945	41899	45046
30	133806	65842	67965
40	173062	79808	93254
50	250485	117717	132768
60	327493	153630	173863
70	419141	191539	227602
80	502472	227453	275019
90	600599	281323	319275
100	707457	339184	368273
110	816569	385073	431496
120	946839	452910	493929
130	1038111	492814	545297
140	1130252	540699	589553
150	1242267	600555	641712
160	1346379	660411	685968
170	1466336	724257	742078
180	1571614	782118	789495
190	1663832	837984	825849
200	1748822	881878	866943

Appendix 3.12
Participation rates and annual sequestration rates and total sequestration after 20 years for South-Eastern Australia, converting conventional tillage crop-pasture systems to minimum-tillage.

	Unadjusted Carbon			Adjusted Carbon		
Carbon Price $/MgC	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**
0	0.0%	0	0	0.0%	0	0
10	0.3%	1328	26559	0.5%	4397	87938
20	0.8%	3822	76440	1.3%	10952	219044
30	1.5%	6961	139222	2.0%	16589	331770
40	2.1%	10097	201939	2.7%	21901	438029
50	2.5%	11778	235563	3.5%	28160	563205
60	3.1%	14459	289182	4.1%	32836	656714
70	3.6%	17313	346254	4.8%	39125	782498
80	4.1%	19578	391565	5.6%	45513	910269
90	4.7%	22526	450523	6.2%	49550	990998
100	5.3%	25168	503354	7.0%	55706	1114129
110	5.6%	26656	533123	7.5%	60151	1203016
120	6.1%	29463	589264	8.1%	65525	1310502
130	6.5%	31338	626752	8.9%	71695	1433900
140	7.0%	34182	683647	9.5%	76891	1537815
150	7.7%	37081	741612	10.2%	82229	1644583
160	8.1%	39642	792830	11.0%	90097	1801943
170	8.5%	40984	819683	11.5%	94728	1894561
180	8.9%	42957	859133	12.0%	99067	1981334
190	9.6%	46404	928077	12.7%	104277	2085546
200	10.0%	48383	967670	13.3%	108420	2168403

Appendix 3.13

Adjusted carbon sequestration after 20 years for regions of South-Eastern Australia, converting conventional tillage crop-pasture systems to minimum tillage.

Carbon Price $/MgC	Total Australia	Mallee	Wimmera	High Rainfall MgC	Mid-North	Central West	Slopes
0	0	0	0	0	0	0	0
10	87938	0	40776	12149	21960	8662	4391
20	219044	3265	81552	36447	58560	21655	17565
30	331770	6530	101940	64216	102480	34648	21957
40	438029	6530	142717	81571	124440	47641	35131
50	563205	6530	173299	107604	153721	64965	57087
60	656714	9794	214075	126695	153721	90950	61479
70	782498	13059	249754	140580	204961	108274	65870
80	910269	16324	305821	159671	219601	138591	70261
90	990998	16324	321112	185704	241561	147253	79044
100	1114129	16324	382277	208267	263521	155915	87827
110	1203016	16324	423053	218680	270841	181901	92218
120	1310502	16324	438344	239507	307441	207887	101001
130	1433900	19589	474023	256862	344041	225211	114174
140	1537815	19589	519896	274218	358681	246865	118566
150	1644583	22853	555575	296780	395281	255527	118566
160	1801943	29383	575963	317606	483122	268520	127348
170	1894561	35913	591254	331491	527042	281513	127348
180	1981334	45707	616740	343640	549002	294506	131740
190	2085546	48972	657516	364466	570962	307499	136131
200	2168403	55501	683001	381822	578282	320492	149305

Appendix 3.14
Participation rates, annual sequestration rates and total sequestration after 20 years for South-Eastern Australia, converting conventional tillage crop-pasture systems to no-tillage.

	Unadjusted Carbon			Adjusted Carbon		
Carbon Price $/MgC	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**
0	0.0%	0	0	0.0%	0	0
10	0.7%	8283	165663	1.1%	19481	389614
20	1.6%	17727	354538	2.3%	41661	833217
30	2.4%	27621	552419	3.5%	66186	1323711
40	3.4%	39074	781477	4.9%	89538	1790765
50	4.2%	49552	991040	5.9%	109017	2180338
60	5.0%	59051	1181014	7.0%	129924	2598483
70	5.8%	66903	1338063	8.3%	154490	3089795
80	6.5%	75743	1514860	9.3%	172490	3449810
90	7.3%	84434	1688685	10.2%	188518	3770368
100	7.9%	91057	1821144	11.5%	212913	4258268
110	8.9%	104088	2081763	12.5%	231046	4620921
120	9.8%	114811	2296212	13.5%	249401	4988015
130	10.3%	121476	2429525	14.4%	264830	5296606
140	11.0%	128314	2566275	15.2%	281250	5624997
150	11.6%	135891	2717822	15.9%	295468	5909354
160	12.1%	141038	2820759	16.8%	316767	6335331
170	12.7%	148526	2970515	17.4%	328343	6566858
180	13.1%	155026	3100518	18.2%	348972	6979441
190	13.6%	160974	3219488	19.1%	363910	7278192
200	14.1%	165609	3312171	19.6%	375032	7500649

Appendix 3.15

Adjusted carbon sequestration after 20 years for regions of South-Eastern Australia, converting conventional tillage crop-pasture systems to no-tillage.

Carbon Price $/MgC	Total Australia	Mallee	Wimmera	High Rainfall MgC	Mid-North	Central West	Slopes
0	0	0	0	0	0	0	0
10	389614	5748	80304	101890	38429	14307	148935
20	833217	28741	160609	179521	69172	78687	316488
30	1323711	45985	230875	295967	92229	100147	558508
40	1790765	68978	361370	402709	122972	164527	670209
50	2180338	68978	491865	475488	146029	178834	819145
60	2598483	80474	542055	567674	199829	221754	986697
70	3089795	91970	692626	645305	215200	271827	1172866
80	3449810	114963	782969	718084	245943	321900	1265951
90	3770368	126459	863273	781159	261315	379127	1359036
100	4258268	143704	973692	873345	307429	414894	1545205
110	4620921	183941	1053996	926716	345858	472121	1638290
120	4988015	195437	1104187	970383	384286	565114	1768608
130	5296606	212681	1194529	994643	415029	636648	1843076
140	5624997	229926	1284872	1033458	438086	665261	1973394
150	5909354	229926	1335062	1067422	476515	715334	2085096
160	6335331	247170	1405328	1086829	514944	772561	2308499
170	6566858	258666	1455519	1101385	545686	822634	2382967
180	6979441	281659	1505709	1120793	576429	851248	2643604
190	7278192	298903	1575975	1154756	614858	915628	2718071
200	7500649	310400	1646242	1169312	637915	944241	2792539

Appendix 3.16

Participation rates, annual sequestration rates and total sequestration after 20 years for Sweden, converting cereal cropping to pastures.

	Unadjusted Carbon			Adjusted Carbon		
Carbon Price $/MgC	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**
0	0.0%	0	0	0.0%	0	0
10	9.6%	29314	586280	2.7%	4097	81946
20	17.7%	55252	1105039	8.4%	12384	247682
30	21.8%	68683	1373667	13.2%	19690	393801
40	24.8%	79072	1581444	16.8%	25202	504040
50	26.6%	85877	1717539	19.9%	30477	609541
60	28.4%	92967	1859336	22.2%	34681	693616
70	29.9%	98644	1972888	24.1%	38031	760627
80	31.1%	104044	2080887	25.7%	41312	826237
90	32.6%	110563	2211253	26.9%	43990	879800
100	34.0%	116564	2331279	28.0%	46262	925237
110	35.0%	120710	2414194	29.3%	49238	984755
120	35.8%	124275	2485500	30.4%	51899	1037985
130	36.5%	127257	2545130	31.7%	54694	1093876
140	37.3%	130511	2610218	32.6%	57314	1146283
150	37.8%	132524	2650477	33.6%	60084	1201684
160	38.6%	136005	2720099	34.3%	61736	1234710
170	39.2%	138468	2769354	35.1%	63936	1278725
180	39.8%	140978	2819564	35.6%	65320	1306391
190	40.3%	143060	2861208	36.3%	67056	1341116
200	40.7%	144716	2894312	36.8%	68279	1365582

Appendix 3.17
Adjusted carbon sequestration after 20 years for regions of Sweden, converting cereal cropping to pastures.

Carbon Price $/MgC	**Total Sweden**	**Gss**	**Gmb**	**Gsk**	**Gns MgC**	**Ss**	**Ssk**	**Nn**	**No**
0	0	0	0	0	0	0	0	0	0
10	81946	6212	4860	17497	10796	19787	5531	5275	11989
20	247682	15186	13499	67487	26991	56317	23969	16527	27707
30	393801	24159	22678	109145	45884	86758	39640	26373	39163
40	504040	33823	30237	139139	62079	105023	51164	36218	46357
50	609541	41416	38876	162884	82322	129376	61765	42548	50353
60	693616	48319	42656	174132	99866	153729	70984	49581	54349
70	760627	55221	49675	179964	110662	170472	82507	55910	56214
80	826237	62814	56155	182464	125507	187215	94492	59778	57813
90	879800	68337	60474	184130	143051	202435	99562	63998	57813
100	925237	79381	63714	184547	159246	208524	105554	66459	57813
110	984755	92496	69113	184547	175440	222222	113851	69272	57813
120	1037985	102850	76133	184547	187586	240487	117538	71030	57813
130	1093876	118036	83692	184547	202431	252664	122609	72085	57813
140	1146283	124939	88012	184547	218626	272451	126757	73140	57813
150	1201684	133912	90171	184547	245617	286149	129984	73492	57813
160	1234710	142886	94491	184547	260462	289193	131827	73492	57813
170	1278725	151859	99351	184547	278006	301370	132288	73492	57813
180	1306391	157381	102050	184547	291501	305936	133671	73492	57813
190	1341116	167735	106370	184547	307696	308980	134132	73843	57813
200	1365582	173948	110150	184547	317142	313547	134593	73843	57813

Appendix 3.18
Participation rates, annual sequestration rates and total sequestration after 20 years for Kazakhstan, converting conventionally tilled cropping to minimum tillage.

	Unadjusted Carbon			Adjusted Carbon		
Carbon Price $/MgC	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**
0	0.0%	0	0	0.0%	0	0
10	2.0%	43257	865137	1.1%	13733	274656
20	4.1%	85062	1701242	2.3%	30438	608752
30	7.8%	163882	3277648	4.0%	51072	1021440
40	11.0%	232397	4647932	6.0%	75421	1508426
50	15.2%	318184	6363689	8.3%	105559	2111183
60	18.8%	388586	7771713	10.4%	132904	2658086
70	22.7%	458697	9173931	12.7%	161671	3233415
80	27.6%	556387	11127747	15.5%	194090	3881800
90	31.4%	634046	12680928	17.9%	223772	4475436
100	35.8%	724770	14495392	20.0%	248659	4973187
110	40.7%	824057	16481142	22.8%	278099	5561979
120	44.9%	918700	18373991	25.7%	311340	6226802
130	49.0%	1001584	20031686	28.2%	343292	6865850
140	54.1%	1105372	22107433	30.9%	375436	7508717
150	58.0%	1191595	23831900	33.7%	411205	8224101
160	61.2%	1258512	25170249	36.8%	447624	8952490
170	65.6%	1356784	27135676	39.5%	485450	9709008
180	68.6%	1420798	28415962	42.1%	519003	10380068
190	70.6%	1467394	29347871	44.5%	548062	10961238
200	73.1%	1525311	30506225	48.2%	595079	11901588

Appendix 3.19
Adjusted carbon sequestration after 20 years for regions of Kazakstan, converting conventionally tilled cropping to minimum tillage.

Carbon Price $/MgC	Total Kazakhstan	Common Chernozem	Southern Chernozem MgC	Chestnut
0	0	0	0	0
10	274656	134690	75708	64258
20	608752	346344	151416	110991
30	1021440	577241	239742	204458
40	1508426	750413	454248	303765
50	2111183	1115999	580428	414757
60	2658086	1423860	731844	502381
70	3233415	1712481	895878	625056
80	3881800	1981860	1123002	776939
90	4475436	2289722	1274418	911296
100	4973187	2578342	1337508	1057337
110	5561979	2789997	1539396	1232587
120	6226802	3078617	1728666	1419519
130	6865850	3405720	1917936	1542194
140	7508717	3752065	2056734	1699918
150	8224101	4117650	2283858	1822593
160	8952490	4463995	2473128	2015367
170	9709008	4887305	2712870	2108833
180	10380068	5214408	2939994	2225666
190	10961238	5503028	3104028	2354182
200	11901588	6022545	3343770	2535273

Appendix 3.20
Participation rates, annual sequestration rates and total sequestration after 20 years for Kazakhstan, converting conventionally tilled cropping to no tillage.

	Unadjusted Carbon			Adjusted Carbon		
Carbon Price $/MgC	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**	**Participation rate**	**Carbon MgC/yr**	**Total Carbon MgC**
0	0.0%	0	0	0.0%	0	0
10	3.5%	117501	2350013	2.3%	50157	1003140
20	8.4%	284613	5692253	5.4%	128946	2578923
30	14.1%	481159	9623183	9.7%	232572	4651432
40	20.7%	695271	13905428	13.5%	323261	6465221
50	28.0%	916030	18320603	17.9%	421879	8437585
60	35.5%	1167648	23352953	23.0%	536957	10739141
70	42.8%	1411432	28228635	28.3%	652302	13046031
80	50.0%	1671357	33427148	33.5%	773984	15479670
90	56.9%	1898288	37965758	38.7%	896208	17924163
100	63.5%	2127592	42551843	43.8%	1023133	20462657
110	68.9%	2323901	46478025	49.1%	1159457	23189135
120	72.5%	2463240	49264807	54.9%	1287321	25746425
130	76.2%	2600443	52008862	58.5%	1384475	27689498
140	79.4%	2716757	54335137	63.7%	1507957	30159137
150	82.1%	2820727	56414542	67.5%	1614293	32285855
160	84.3%	2904995	58099905	70.8%	1701984	34039671
170	85.2%	2942263	58845262	73.1%	1761251	35225012
180	86.1%	2979531	59590620	75.9%	1835105	36702101
190	87.0%	3018461	60369210	78.2%	1897050	37940997
200	87.6%	3041486	60829717	80.3%	1953635	39072691

Appendix 3.21
Adjusted carbon sequestration after 20 years for regions of Kazakhstan, converting conventionally tilled cropping to no tillage.

Carbon Price $/MgC	**Total Kazakhstan**	**Common Chernozem**	**Southern Chernozem MgC**	**Chestnut**
0	0	0	0	0
10	1003140	404019	380664	218457
20	2578923	1285515	856494	436914
30	4651432	2277198	1594031	780204
40	6465221	3268881	2093652	1102688
50	8437585	4297293	2569482	1570810
60	10739141	5399163	3259436	2080543
70	13046031	6427575	3996972	2621484
80	15479670	7676361	4734509	3068801
90	17924163	8888418	5519628	3516117
100	20462657	10320849	6209582	3932226
110	23189135	11826738	7066076	4296321
120	25746425	12928608	7970153	4847665
130	27689498	14177394	8445983	5066122
140	30159137	15279264	9397643	5482230
150	32285855	16711695	9873473	5700687
160	34039671	17629920	10563426	5846325
170	35225012	18217584	11015465	5991963
180	36702101	19025622	11538878	6137601
190	37940997	19613286	12086082	6241629
200	39072691	20090763	12657078	6324850