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Soil carbon sequestration and associated economic costs for farming systems of the Indo-Gangetic Plain: A meta-analysis

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ABSTRACT

Soil organic carbon sequestration rates over 20 years based on the Intergovernmental Panel for Climate Change (IPCC) methodology were combined with local economic data to determine the potential for soil C sequestration in wheat-based production systems on the Indo-Gangetic Plain (IGP). The C sequestration potential of rice–wheat systems of India on conversion to no-tillage is estimated to be 44.1 Mt C over 20 years. Implementing no-tillage practices in maize–wheat and cotton–wheat production systems would yield an additional 6.6 Mt C. This offset is equivalent to 9.6% of India's annual greenhouse gas emissions (519 Mt C) from all sectors (excluding land use change and forestry), or less than one percent per annum. The economic analysis was summarized as carbon supply curves expressing the total additional C accumulated over 20 year for a price per tonne of carbon sequestered ranging from zero to USD 200. At a carbon price of USD 25 Mg C^{-1}, 3 Mt C (7% of the soil C sequestration potential) could be sequestered over 20 years through the implementation of no-till cropping practices in rice–wheat systems of the Indian States of the IGP, increasing to 7.3 Mt C (17% of the soil C sequestration potential) at USD 50 Mg C^{-1}. Maximum levels of sequestration could be attained with carbon prices approaching USD 200 Mg C^{-1} for the States of Bihar and Punjab. At this carbon price, a total of 34.7 Mt C (79% of the estimated C sequestration potential) could be sequestered over 20 years across the rice–wheat region of India, with Uttar Pradesh contributing 13.9 Mt C.

1. Introduction

Soil organic carbon (SOC) is essential for maintaining fertility, water retention, and plant production in terrestrial ecosystems. 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). Globally, the amount of carbon stored in soils is over three times that found in the atmosphere (Schlesinger, 1999). The amount of SOC stored within an ecosystem, is dependent on the quantity and quality of organic matter returned to the soil matrix, the soils ability to retain organic carbon (a function of texture and cation exchange capacity), and abiotic influences of both temperature and precipitation (Grace et al., 2006).

The global decline in SOC as a result of land use changes, including deforestation, shifting cultivation and arable cropping have made significant contributions to increased levels of atmospheric CO_2. Because of this past depletion of SOC levels, soils have the capacity to store more carbon than they do at present (Paustian et al., 1997; Lal et al., 1998). Soil organic carbon can be increased by adopting practices that reduce soil disturbance and/or by increasing the amount of biomass produced and retained.

There are many well-defined land use and management practices that can be adopted to increase soil carbon (IPCC, 2000). For example, a switch from conventional to conservation tillage reduces carbon oxidation and thus emissions of CO_2 (Reicosky, 1997); increasing crop or pasture biomass through increased mineral or organic fertilizer additions or the introduction of pasture legumes increases carbon inputs to soils (Conant et al., 2001). The potential for these practices to sequester carbon varies in that it is influenced by both the textural composition of soils and climatic conditions (i.e. temperature and moisture regime) (Grace et al., 2006).

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Changes in management strategies must be economically feasible for the agricultural producer. Regional differences in biogeochemical, climatic and socio-economic conditions imply that a single management practice will not be equally efficient at sequestering C. Reduced or no-tillage is preferred in the croplands of the US Midwest and South America (Lal et al., 2007) and Canadian prairies (VandenBygaart et al., 2003). On the IGP, increased use of fertilizers and farmyard manures has been shown to promote soil C accumulation (Duxbury et al., 2000; Gami et al., 2001, 2009), and whilst minimal data exists on the C sequestration benefits of no-tillage in this region, there are significant savings in both water and fuel usage (Mehla et al., 2000; Gupta et al., 2002; Hobbs and Gupta, 2003; Erenstein and Laxmi, 2008). In examining 78 published studies worldwide (with a minimum soil depth of 30 cm), Govaerts et al. (2009) reported that in the majority of cases, soil C was found to significantly increase under no-tillage when compared to conventional tillage.

Carbon markets offer the potential of additional income for farmers including landholders in developing countries (Govaerts et al., 2009). Studies examining both the technical and economic feasibility of soil C sequestration have only been carried out in a limited number of regions of the world (e.g. Antle and Diagana, 2003; Tschakert, 2004; Paustian et al., 2006; Antle et al., 2007; Diagana et al., 2007; Grace et al., 2010).

This study aims to assess both the technical (i.e. biogeochemical) and economic potential of sequestering SOC in response to the introduction of no-tillage practices in the IGP of India. This region is one of the largest cereal producing regions in the world, with relatively low SOC stores (Pal et al., 2009) and diverse fertilization management including organic manures (Bhandari et al., 2002; Yadvinder-Singh et al., 2004). Rice and wheat contribute more than 80% of total cereal production in this region (Timsina and Connor, 2001), with the intensively cultivated rice–wheat system fundamental to employment, income and livelihoods (Paroda et al., 1994). No-tillage agriculture is being successfully promoted across the region with soil carbon storage and fuel savings as major benefactors (Hobbs et al., 1997; Gupta and Seth, 2006). The focus of this case study is the northern Indian States (Punjab, Haryana, Uttar Pradesh, Bihar and West Bengal) which occupy over 75% of the irrigated rice–wheat area of the IGP (Hobbs and Morris, 1996).

Pathak et al. (2011) recently examined the potential and economics of soil C in Indian agriculture using data from existing long-term fertility experiments. Our study differs considerably from Pathak et al. (2011) in that we have specifically targeted reduced tillage systems, of which virtually no published data exists for the IGP. Secondly, a comprehensive cost assessment of carbon sequestration must also take into account all greenhouse gas emissions when comparing farming systems and strategies. Compared to CO_2, emissions of nitrous oxide (N_2O) and methane (CH_4) are of greater significance in terms of their contribution to the enhanced greenhouse effect (Robertson et al., 2000). These latter emissions are also influenced by land use and agronomic management. In our study, we used the full cost (or net) greenhouse gas (GHG) accounting approach as outlined in the 2006 IPCC Guidelines for Greenhouse Gas Inventories (IPCC, 2006) for estimating changes in SOC (and associated emissions of CO_2, CH_4 and N_2O). Briefly, increases in SOC over a 20 year time frame are estimated as a direct result of shifting from conventional to no-tillage. The net carbon (equivalent) change of the cropping system is then determined by including associated CO_2 non-CO_2 greenhouse gas emissions (e.g. from fuel, fertilizer) associated with the tillage practices. Our economic analysis examines the cost of making the change to no-tillage agriculture as a function of net carbon change assuming a monetary value is also placed on carbon.

2. Materials and methods

2.1. Regional characteristics

The IGP is historically characterized by fertile soils, favourable climate and abundant surface and groundwater and is the backbone of food security in India. Rice and wheat, the major cereal crops of this region are grown in rotation on nearly 10 million hectares (Gupta et al., 2003). These crops are the principal source of food, nutrition and livelihood security for several hundred million people. With 21% of India's rice grown after wheat, and 35% of the wheat after rice (Kataki et al., 2001), it is estimated that 171 Mt of grain was produced by this rotation across the IGP in 2007 (FAOSTAT). Yields range from 1 to 4.3 Mg ha^{-1} for wheat, and 2.1–5.6 Mg ha^{-1} for rice (Ladha et al., 2003). However long-term experiments in the IGP confirm an overall decline in productivity since the mid 1980s (Duxbury et al., 2000).

Soils are mainly alluvial, based on deposits of the Indus and Ganges river systems. Texture ranges from sandy loams to silty clay loam. Many soils are alkaline, although acid soils are also present in the piedmont and some floodplain (Bijay-Singh et al., 2002). Benchmark soils across the IGP include Vertic Haplustalfs and Typic Ustipsamments in the west (Punjab) to Chromic Vertic Hapludalfs in the east (West Bengal) (Bhattacharyya et al., 2007a). The northwest part of the IGP is endowed with extensive canal irrigation systems using water storage reservoirs in the Himalayan mid-hills.

It is also clear that the rice–wheat rotation over time has been removing more nutrients than the amount externally added through nitrogen fertilizers (Regmi et al., 2002). The fact that the soils are now low (0.2–0.8%) in organic carbon (Duxbury et al., 2000) but are in an environment that can sustain high levels of net primary production makes them well suited to practices (such as reduced or zero-tillage) that can promote soil carbon sequestration. The increased adoption and productivity of wheat and rice in rotation during the last three decades has resulted in the heavy usage of irrigation, fertilizer, electricity and diesel fuel (Ladha et al., 2003). These have a direct impact on the emissions of all greenhouse gases (GHGs). It has been estimated that on an annual basis, the rice–wheat system in IGP emits GHGs which has a global warming potential of 13–26 Mg CO_2 ha^{-1} depending upon the management practices used (Grace et al., 2003).

The opportunities for soil carbon sequestration in agro-ecosystems of the IGP whilst meeting 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 (e.g. reduced or no-tillage) and diversification from rice–wheat are required to sequester more carbon (Bhattacharyya et al., 2007b) thus improving soil fertility and ensuring agricultural sustainability. For example, surface seeding and 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., 2008). 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 reduce the loss of soil carbon thus mitigating the increase of CO_2 in the atmosphere.

On the IGP of India, multiple cropping is commonplace, with two crops per annum. The rice–wheat rotation dominates, whilst cotton–wheat and maize–wheat are also common. Wheat and rice yields are in excess of 4 Mg ha^{-1} in the western extents of the IGP (Punjab and Haryana States) tend to decrease heading east to W. Bengal (Ladha et al., 2003). Maize and cotton are commonly found in Punjab and Uttar Pradesh with yields of 1–2 Mg 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 to 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 Mg ha^{-1} applied to both wheat and rice crops.

2.2. Estimating carbon sequestration

To estimate net C sequestration rates for wheat based cropping systems in the IGP we used the full cost GHG accounting approach described in the 2006 IPCC Guidelines for Greenhouse Gas Inventories (IPCC, 2006). 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 using peer-reviewed literature; 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. This approach includes an empirically based methodology for determination of SOC change as well as discounting for emissions of N_2O and CH_4 from a wide variety of agricultural sources. The empirical IPCC approach to estimating SOC change in agricultural soils in response to management on the IGP has been successfully employed by Bhattacharyya et al. (2007b).

The IPCC model has advantages in that it is easy to apply and requires a minimum of data requirements, specifically land use history and agronomic management information. Furthermore the parameters in the model are based on an extensive survey and statistical analysis of published studies. It therefore provides a consistent framework for comparing SOC sequestration potentials in international studies. Long-term agronomic trials have provided the best quantitative evidence of the influence of management strategies to either promote or degrade soil carbon stocks (Rasmussen et al., 1998) thus the parameters in the model are based on extensive surveys and statistical analysis of published studies.

Specifically, the IPCC method first estimates the changes in SOC stocks for mineral soils based on relative stock changes over a defined time interval (in this case 20 years). The SOC stock change value is subsequently combined with other greenhouse gases (N_2O, CH_4) emitted by each these systems to get a net value expressed in carbon equivalents. There are three main kinds of information required for calculating changes in SOC: stock change factors which relate to specific land use and management practices; reference SOC stocks, on which the stock change factors are applied and; activity data that records the changes in land use and management that occur over time.

These are combined in the following way:

$$\Delta C_i = \left[\frac{C_{it} - C_{i(t-20)}}{20}\right] * \mathrm{LA}_i \quad (1)$$

$$C_{it} = C_{\mathrm{R}} * F_{\mathrm{LU}} * F_{\mathrm{MG}} * F_{\mathrm{I}} \quad (2)$$

where C_i is SOC stock for the ith parcel of land at time t and t−20 years, $\mathrm{LA_i}$ 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 SOC storage (IPCC, 1997, 2004).

Table 1
Default reference organic carbon stocks (SC_R) (0–30 cm) used in the IPCC methodology for estimating soil organic carbon change in wheat based rotations of the Indo-Gangetic Plains.

IPCC climate[a]	hac soils (Mg C ha^{-1})[b]	lac soils (Mg C ha^{-1})[c]	san soils (Mg C ha^{-1})[d]
Tropical, dry (trd)	38	35	31
Tropical, moist (trm)	65	47	39

[a] For more detail refer to IPCC (2006).
[b] Soils with high activity clay minerals are lightly to moderately weathered soils.
[c] Soils with low activity clay minerals are highly weathered soils.
[d] san includes all soils having >70% sand and <8% clay.

Cropland categories are based on the carbon input to the soil pools, and include low, medium, high and high w/amendment input categories (Ogle et al., 2005). Managed pastures are classified according to productivity and carbon input, similar to cropland, and include degraded, nominal, improved, and improved with high input categories (Ogle et al., 2004). Values for reference carbon stocks (Table 1) and management factors, including the base, tillage, and cropland input factors (Table 2), were based on estimates provided in IPCC (2006). These included estimates of uncertainty associated with the individual management factors, which ranged from 5 to 17% in all cases, except for long-term cultivated systems of the tropics and paddy rice (50%). Additional information on the management factors and how they were derived is provided in Ogle et al. (2004, 2005).

To generate the reference SOC stocks and change estimates for the economic analysis, we superimposed the IPCC's generalized climate and soil characterizations (IPCC, 2006) over the Indian States of the IGP. Soils data were 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. The spatial databases, together with information on representative current and potential management practices within the IGP were then used to generate a matrix of average annual SOC changes (0–30 cm) over 20 years for both current (conventionally tilled) crop sequences and potential changes in land use and management with each State. These changes included an increased adoption of no-tillage practices.

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., 2004, 2005). 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).

The change in SOC storage was estimated 50,000 times (using a Monte Carlo approach) for each management scenario by randomly selecting management factors and reference carbon stocks from the PDFs in an iterative process whilst accounting for dependencies among these inputs. A SOC sequestration rate was estimated for each scenario and then adjusted to account for fuel-based CO_2 and ancillary non-CO_2 emissions over the defined time interval of 20 years. The latter were converted to CO_2 using Global Warming Potentials of 23 and 296 for CH_4 and N_2O respectively. The IPCC Tier 1 default emission factors (IPCC, 2006) were used for calculating all

Table 2
Relative stock change factors (F_{LU}, F_{MG}, F_I) for different management activities on cropland for estimating soil organic carbon change as used in the 2006 IPCC Guidelines for Greenhouse Gas Inventories (IPCC, 2006).

Factor value type	Level	Temperature regime	Moisture regime	Factor value	Description
Land use (F_{LU})	Long-term cultivated	Temperate	Dry	0.80	Continuously managed for >20 years, to predominantly annual crops. Input and tillage factors are applied to estimate carbon stock changes
			Wet	0.69	
		Tropical	Dry	0.58	
			Wet	0.48	
Land use (F_{LU})	Paddy rice	Temperate and Tropical	Dry & Wet	1.1	Annual cropping for >20 year. Tillage and input factors not used
Tillage (F_{MG})	Full	Temperate and Tropical	Dry and Wet	1.0	Soil disturbance with full inversion and/or frequent tillage operations. At planting time, <30% of the surface is covered by residues.
Tillage (F_{MG})	Reduced/Minimum	Temperate	Dry	1.02	Reduced soil disturbance. Normally leaves surface with >30% coverage by residues at planting
			Wet	1.08	
		Tropical	Dry	1.09	
			Wet	1.15	
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	1.15	
		Tropical	Dry	1.17	
			Wet	1.22	
Input (F_I)	Low	Temperate	Dry	0.95	Low residue return due to removal of residues, frequent bare-fallowing or production of crops yielding low residues (e.g. vegetables, tobacco, cotton)
			Wet	0.92	
		Tropical	Dry	0.95	
			Wet	0.92	
Input (F_I)	Medium	Temperate and tropical	Dry and wet	1.0	Annual cropping with all crop residues returned to the field. If residues removed organic matter (e.g. manure) is added
Input (F_I)	High–without manure	Temperate and tropical	Dry	1.04	Significant inputs due to production of high residue crops, green manures, cover crops
			Wet	1.11	
Input (F_I)	High–with manure	Temperate and tropical	Dry	1.37	Represents high input of crop residues together with regular addition of animal manure
			Wet	1.44	

emissions (except for CH_4 emissions from rice cultivation) based on the estimated inputs supplied for each region.

Specifically, CO_2 from fuel used in farm machinery used in tillage, harvest or pumping operations, at 2.6 kg CO_2 per liter 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 for N_2O of 1.25% from nitrogen applied as fertilizer to wheat, cotton or maize or crop residue decomposition and 2.0% from nitrogen applied as animal manure. This emission factor is slightly higher than the recommended Tier 1 emission factor of 1% to accommodate the fact that all rotations we assessed included flooded rice and the N_2O emissions associated with flooded rice, whilst small, still need to be considered. The IPCC accounting methodology also requires the inclusion of N_2O emissions from mineral nitrogen sources that are lost from the soil, specifically the volatilization of ammonia (NH_3) and the leaching of the nitrate ion (NO_3^-). The IPCC Tier 1 Tier 1 default 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 to account for these indirect N_2O emissions. The burning of crop residues releases CH_4 and N_2O, however any CO_2 released on burning is assumed (by the IPCC methodology) to be assimilated by surrounding plants. The annual emission factor of 100 kg CH_4 ha^{-1} rice is the weighted average of CH_4 emissions associated with continuous flooded, intermittently flooded (single and multiple aeration) and deep flooded rice as reported in Gupta et al. (2009) using the respective areas for irrigated rice for the period 1996–2006.

Off-site emissions applicable to nitrogen fertilizer production were not included as they were considered not applicable to site-specific carbon projects, and their inclusion at a project level is still a topic of contention in the international community. Rotation sequences and the relevant IPCC climate, soil, and management classifications for each region within the IGP, including the additional GHG sources used in the simulation of SOC change are detailed in Table 3.

2.3. Economic analysis

The economic feasibility of SOC sequestration was assessed by constructing marginal cost curves, or supply curves, for the quantity of carbon that can be permanently stored in agricultural soils in each region for each rotation x tillage scenario, using the “minimum-data” (MD) model of ecosystem services supply proposed by Antle and Valdivia (2006). The MD model generalizes

Table 3
Rotation sequences and nominated carbon sequestering technologies for the Indo-Gangetic Plain, including IPCC classifications and associated greenhouse gas emission sources.

Region	Rotation[a]	Technology[b]	IPCC climate[c]	IPCC soil[d]	IPCC input system[e]	Other GHG sources[f]					
						Burn	N inputs	N loss	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
Uttar 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
West 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
	WR	CONV	trm	san	Medium	X	X	X	X		X
	WR	NOT	trm	san	Medium	X	X	X	X		X

[a] W = wheat, C = cotton, R = rice. Two crops in rotation every year.
[b] CONV = conventional tillage, NOT = no tillage.
[c] trd = tropical region dry, trm = tropical region moist. For more detail refer to IPCC (2006).
[d] lac = low activity soils, hac = high activity soils, san = sandy soils. For more detail refer to IPCC (2006).
[e] Relative carbon input into cropping or pasture system (e.g. low = crop + fallow; medium = crop + residues removed + organic manures; high = crop + pasture).
[f] 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.
X = emissions included from this source.

the concept of a "representative farm" that is often used by agricultural economists, by utilizing population-level data to describe a "representative population" of heterogeneous farms. The MD model is designed for use with typically available data to determine the marginal cost associated with crop production across a region i.e. crop area and average crop yield and costs of production, and respective measures of variability (such as the coefficient of variation) in yield and production costs. The model is publicly available on the world-wide web, and has been validated against more complex, site-specific simulation models (Antle and Valdivia, 2006; Antle et al., 2009).

For the analysis presented here, the carbon supply curve (i.e. amount of carbon that can be potentially sequestered as a function of the tradeable cost of the carbon in a financial market) was derived after estimating two key components. First, the mass of additional carbon supplied by landholders to a financial market as a direct consequence of the carbon sequestering practice (in this case, the introduction of a no-tillage system). Second, the additional financial cost to the farmer to undertake the carbon sequestering practice (including any costs of equipment, chemicals, fertilizers and transaction costs to verify any changes in soil carbon). The economic logic has been presented in detail in Antle et al. (2003), and is similar to the economic approaches used to assess forestry sequestration (e.g. Stavins, 1999).

Because of the spatial and temporal variation in bio-physical (soils, climate, management) and socio-economic conditions (prices, production technology, farm decision maker characteristics, financial constraints), both the opportunity costs and the C sequestration rates in each State are spatially heterogeneous. In our analysis, it is assumed that contracts with farmers are based on an expected (mean) C sequestration rate for each region that is subsequently verified over the life of the contract. The opportunity cost of switching from conventional tillage to no-till varies spatially because the returns to each practices varies across the IGP. The MD model is designed to approximate the spatial variation in opportunity costs, based on statistics for the mean crop yields, mean cost of production, and yield variation associated with each tillage practice. In addition, an estimate of the correlation between the returns to each practice is needed and area of the tillage practice within the region. This data were provided by regional agronomists within the IGP. An estimate of production costs was based on the national procedures to determine the cost of cultivation of principal crops in India, e.g. the cost of specialist equipment in converting to no-till agriculture; the cost of labour, fuel, herbicides, insecticides, seed, organic and mineral fertilizers; and grain prices.

One piece of information that is difficult to estimate is the fixed cost of changing from conventional tillage to conservation tillage. For example, the type (and cost) of specialist machinery used for introducing no-tillage practices can vary between regions and little data on machinery type is available in the literature. Likewise, socio-economic factors, such as risk aversion, may affect a landholder's decision to change practices. The MD modeling methodology can address these issues by assuming that differences between observed and simulated land allocation in the base case (i.e. with no payment for carbon sequestration) is due to these fixed costs as well as other unobserved factors affecting farmers' willingness to adopt conservation tillage. Thus, the distribution in net returns for each alternative practice in each State were calibrated by adjusting the mean net returns for the alternative (sequestering) practice so that the model produced the observed allocation of land between the conventional and alternative practice in the base case. This adjustment was interpreted as the fixed cost of adoption of the carbon sequestering practice, which would generally include the costs of physical capital as well as any other costs of adjustment associated with changing practices, including farmers' perceptions of risk. These annual fixed costs of adoption differed between each State and production system, ranging from USD 5-40 and USD 30-50 for rice–wheat and cotton–wheat systems respectively, and USD 20 ha^{-1} $annum^{-1}$ for maize–wheat (because it was only determined for one State–Uttar Pradesh). These fixed costs were then assumed to increase over a 20-year period at 10% per annum.

Until the actual implementation of carbon contracts occur, it is difficult to estimate transaction costs associated with sequestration projects. Brokerage fees for similar kinds of financial transactions were considered to be reasonable first-order approximations to the costs of designing and negotiating contracts. Costs of verifying compliance with contracts also depend on the type of practices involved, the type of soil carbon measurement method used (e.g. field sampling versus remote sensing) and the frequency and number of observations required (Mooney et al., 2002). We assumed that the transaction costs were dependent on the size of the contract in terms of mass of carbon offset and were a relatively small percentage of the price of carbon. In reality, actual farm size plays a rather minor role, as it will be an aggregation of fields from a number of farms that will determine the marketable contract.

Measuring and monitoring costs are estimated to be USD 2 per hectare of land under contract; brokerage and administrative costs are calculated as 2% of the value of the contract. In addition, we have assumed that there is a minimum brokerage and administrative cost of USD 5 per hectare. However, regardless of these assumptions, the estimated transaction costs are low (less than 10% of the price except for prices below USD 25 Mg C^{-1}) relative to the total cost of the contract so our results are not sensitive to these assumptions. 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. We therefore included 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. To estimate the additionality discounts (which ranged from 13 to 55% and 35 to 51% for adopting no-tillage in rice–wheat and cotton–wheat systems respectively across the IGP, and 34% for maize–wheat, we used our 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. These should be considered upper-bound estimates of additionality discounts because we assumed that eventually all farmers who could potentially benefit from adopting the conservation practice would in fact adopt.

To implement the economic simulations, the model samples the spatial distributions of net returns within each State, and calculates the opportunity cost of changing from conventional to no-tillage systems in the State. Next, the opportunity cost of changing practices (net of fixed and transaction costs) is compared to the payment the farmer would receive, assuming a specified price of carbon. This process is repeated over a range of carbon prices, and the model determines the proportion of area in the unit that would participate in carbon contracts at each price. Finally, the model uses the technology specific C sequestration rate for each State to compute the total quantity of C sequestered in each State at each price.

In interpreting the economic results, the aggregate carbon supply curve for each production system within each State is derived from five pieces of information. Specifically, the average C change rate estimated for that State based on the application of the IPCC method; the number of hectares in that State on which the carbon-sequestering practice could be adopted, which is equivalent to the total number of hectares still under conventional tillage; the number of hectares within the State on which farmers would adopt carbon sequestering practices (the rate of participation in carbon contracts) based on the estimated net returns for each practice in each State; the estimated transactions costs; and the estimated fixed adoption costs. 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 State enters into contracts because the benefit exceeds the cost on all land units.

3. Results and discussion

3.1. Carbon change

The gross SOC stock values in Table 4 refer to the final SOC content (0–30 cm) after 20 years in each region in response to management, without discounting for associated field emissions of GHGs. The simulations suggest a change to no-tillage across the rice–wheat region of India would increase SOC levels by an average of 5 Mg C ha^{-1} (or 19% when compared to the conventionally tilled wheat–rice systems) after 20 years. The largest change in SOC after 20 years was found in the high activity soils i.e. those with relatively higher clay contents in rice–wheat systems of West Bengal, where the IPCC model estimated that an additional 8.7 Mg C ha^{-1} was stored over 20 years when shifting from conventional tillage to no-tillage farming practices. The smallest gain in SOC over 20 years in response to changing tillage practices, 3.6 Mg C ha^{-1}, was found in the coarser-textured soils of Punjab and Haryana States under both rice–wheat and cotton–wheat systems. Simulated annual C sequestration rates when converting from conventional to no-tillage practices in rice–wheat across the IGP ranged from 182 to 433 kg C ha^{-1} which is consistent with field data reported by Malik et al. (2004) of average annual increases in C of 62–585 kg ha^{-1} concentrated in the top 15 cm (and assuming a bulk density of 1.3 g cm^{-3}). 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

Table 4
Impact of tillage on SOC (0–30 cm) and associated field based greenhouse gas emissions in Indian States of the Indo-Gangetic Plain.

Region/state	Soil type[a]	Gross SOC stock[b] ($Mg\,C\,ha^{-1}$)		Associated GHGs[c] ($Mg\,C\,ha^{-1}$)		Net SOC stock[d] ($Mg\,C\,ha^{-1}$)		SOC change[e] ($Mg\,C\,ha^{-1}$)		SOC change[f] ($kg\,C\,ha^{-1}\,year^{-1}$)	
		Conv. till	No-till	Conv. till	No-till	Conv. till	No-till	Gross	Net	Gross	Net
Wheat–rice											
Bihar	lac	27.25	33.52	23.29	23.33	3.96	10.19	6.27	6.23	314	312
Haryana	lac	24.14	28.25	32.10	30.84	−7.96	−2.59	4.11	5.37	206	269
Haryana	san	21.39	25.03	32.10	30.84	−10.71	−5.81	3.64	4.9	182	245
Punjab	hac	26.22	30.68	34.76	33.52	−8.54	−2.84	4.46	5.7	223	285
Punjab	lac	24.15	28.25	34.76	33.52	−10.61	−5.26	4.1	5.35	205	268
Punjab	san	21.39	25.03	34.76	33.52	−13.37	−8.49	3.64	4.88	182	244
U. Pradesh	hac	26.22	30.68	26.52	25.17	−0.30	5.51	4.46	5.81	223	291
U. Pradesh	lac	24.15	28.25	26.52	25.17	−2.37	3.09	4.1	5.46	205	273
W. Bengal	hac	37.69	46.35	25.67	24.76	12.02	21.59	8.66	9.57	433	479
W. Bengal	lac	27.25	33.52	25.67	24.76	1.58	8.75	6.27	7.17	314	359
W. Bengal	san	22.61	27.81	25.67	24.76	−3.06	3.05	5.2	6.11	260	306
Wheat–maize											
U. Pradesh	lac	24.14	28.25	8.65	8.14	15.49	20.11	4.11	4.62	206	231
Wheat–cotton											
Haryana	lac	24.14	28.25	11.62	10.87	12.52	17.38	4.11	4.86	206	243
Haryana	san	21.39	25.03	11.62	10.87	9.77	14.16	3.64	4.39	182	220
Punjab	lac	24.14	28.25	13.16	12.42	10.98	15.83	4.11	4.85	206	243
Punjab	san	21.39	25.03	13.16	12.42	8.23	12.61	3.64	4.38	182	219

[a] lac = low activity soils, hac = high activity soils, san = sandy soils. For more detail refer to IPCC (2006).
[b] Simulated SOC change (0–30 cm) after 20 years.
[c] Associated on-field greenhouse gas emissions over 20 years (expressed as carbon equivalents) as outlined in Table 3.
[d] Simulated SOC change (0–30 cm) after 20 years and adjusted for associated greenhouse gas emissions.
[e] Net SOC change (0–30 cm) under the new technology relative to conservation tillage after 20 years.
[f] Average net SOC change (0–30 cm) per annum under the new technology relative to conservation tillage.

and this contributes to both CH_4 and N_2O emissions. The burning of residues is not an accountable CO_2 source.

For maize–wheat, only one State (Uttar Pradesh) was analysed, with an annual SOC sequestration rate under no-tillage of 206 kg C ha^{-1}. The sequestration rate in the cotton–wheat systems of Haryana and Uttar Pradesh ranged from 182 to 206 C ha^{-1} $annum^{-1}$. The relative magnitude of these changes are at the low end of the sequestration rates reported from the limited data that exists in northern India on the long-term impact of conservation tillage on SOC levels (Bhattacharyya et al., 2009).

The associated GHGs emitted over 20 years from conventionally tilled rice–wheat systems across the IGP are (on average) 29.3 Mg C ha^{-1}, with no-till systems emitting, 3% less than those systems under conventional tillage (Table 4). Methane from rice cropping contribute one-third of all emissions. Nitrous oxide is also a major source, with N 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 Mg ha^{-1} in West Bengal also contribute to N_2O emissions but these manures are generally considered poor sources of nitrogen. Rice–wheat systems in Haryana and Punjab produced some of the largest amounts of associated GHGs, averaging 1.6 Mg C (equivalents) ha^{-1} $annum^{-1}$, 28% higher than the associated GHG emissions from rice–wheat systems of Uttar Pradesh and West Bengal. Greenhouse gases from conventionally tilled wheat–maize and wheat–cotton were (on average) only 11.6 Mg C ha^{-1}, with no-tillage systems saving an additional 0.7 Mg C ha^{-1}.

Net changes in SOC changes are reported after subtracting associated GHG emissions from the gross SOC stocks (Table 4). 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 no-tillage technologies that determine the actual sequestration potential. In all cases, the net change in SOC when shifting from conventional to no-tillage was higher than the gross changes in SOC between tillage systems. This is mainly due to the reduction in fuel use in the conservation tillage systems. In the rice–wheat rotations, many of the simulated increases in SOC in both conventional and no-tillage systems are heavily discount due to the large quantities of ancillary GHGs generated in these relatively high inputs systems.

The average net SOC sequestration rate after 20 years for the rice–wheat system is estimated to be 6.1 Mg C ha^{-1} under no-tillage, equivalent to a per annum SOC sequestration rates of 302 kg C ha^{-1} $annum^{-1}$. The conversion to no-till from conventional tillage in rice–wheat systems in West Bengal is the most productive in terms of potential carbon gains on an area basis. Whilst there is an average increase (across all soil types) of 7.6 Mg C after 20 years, the actual area under rice–wheat is small compared to the other States (Table 5).

In terms of the total returns in C (i.e. accumulation rate of carbon by areal extent), the implementation of no-tillage practices in rice–wheat systems across the IGP of India would sequester 44.1 Mt C over 20 years (Table 5), with half of this in the State of Uttar Pradesh. India has more than 7.7 million hectares of conventionally tilled soils under rice–wheat with a potential net C sequestration rate of 5.7 Mg C ha^{-1}. Implementation of no-tillage in maize–wheat and cotton–wheat systems would yield an additional 6.6 Mt C, with the total yield being in excess of 50 Mt C over 20 years across all wheat based systems in the five States of India. This offset is equivalent to 9.6% of India's annual greenhouse gas emissions (519 Mt C) from all sectors (excluding land use change and forestry) (Ministry of Environment and Forests, 2010), or less than one percent per annum.

3.2. Economic analysis

The economic results are outlined for all regions and practices with respect to net C sequestration rates (i.e. adjusted for associated GHGs). Note that in the economic analysis, Fig. 1, 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. The vertical axis represents the price (USD) per Mg

Table 5
Distribution of tillage management and total net SOC sequestration potential (after 20 years) in agro-ecosystems of the Indo-Ganetic Plain.

Region/State	Land area in system[a] (ha × 1000)			Proportion of area (%)		Seq. rate[b] (Mg C ha^{-1})	Total C Seq.[c] (Mt C)
	Conv.	No-till	Total[d]	Conv.	No-till	No-till	No-till
Wheat–rice							
Bihar	1493	18	1511	99	1	6.23	9.30
Haryana	517	350	867	60	40	5.14	2.66
Punjab	1535	215	1750	88	12	5.31	8.15
Uttar Pradesh	3948	175	4123	96	4	5.64	22.27
W. Bengal	233	0	233	100	0	7.62	1.78
Total W–R	7726	758	8484	89	11	–	44.15
Wheat–maize							
Uttar Pradesh	570	0	570	100	0	4.62	2.63
Wheat–cotton							
Haryana	603	0	603	100	0	4.62	2.79
Punjab	240	0	240	100	0	4.63	1.11
Total W–C	843	0	843	100	0	–	3.99

[a] Estimate supplied by regional agronomists.
[b] SOC sequestration per hectare after 20 years in response to management and derived from the net SOC change data in Table 4.
[c] Total additional SOC potentially sequestered after 20 years without economic constraints with all cropping area currently under conventional tillage converted to no-till.
[d] Total area = conventional + no-tillage.

C sequestered based on costings for the 2005 year. All of the outputs incorporate transaction costs.

At a carbon price of USD 25 Mg C^{-1}, 3 Mt C (7% of the soil C sequestration potential) could be sequestered over 20 years through the implementation of no-till cropping practices in rice–wheat systems of the Indian States of the IGP, increasing to 7.3 Mt C (17% of the soil C sequestration potential) at USD 50 Mg C^{-1}. The States of Uttar Pradesh, Haryana, Bihar and Punjab all offer similar gains in C over 20 years for all carbon prices less than USD 25 Mg C^{-1}. Between USD 25 and USD 100 Mg C^{-1}, the States of Uttar Pradesh, Bihar and Punjab all offer similar returns in carbon. For example, a carbon price of USD 100 Mg C^{-1} would realize, on average, 5 Mt C per State over 20 years, approximately 56% of the estimated C sequestration potential of rice–wheat under no-tillage for both Bihar and Punjab, and 24% of sequestration potential for Uttar Pradesh (Table 6).

Maximum levels of sequestration (with nearly 100% conversion from conventional to no-tillage technologies in rice–wheat systems) could be attained in Bihar and Punjab with carbon prices approaching USD 200 Mg C^{-1}. At this carbon price, a total of 34.7 Mt C (79% of the estimated C sequestration potential) could be sequestered over 20 years in rice–wheat systems of the IGP, with Uttar Pradesh contributing 13.9 Mt C. For the States of West Bengal and Haryana, where rice–wheat cropping only covers 750,000 ha (compared to nearly 4 Mha in Uttar Pradesh) there is little increase in the total amount of C sequestered across these States under no-tillage over 20 years once the carbon price exceeds USD 100 Mg C^{-1}.

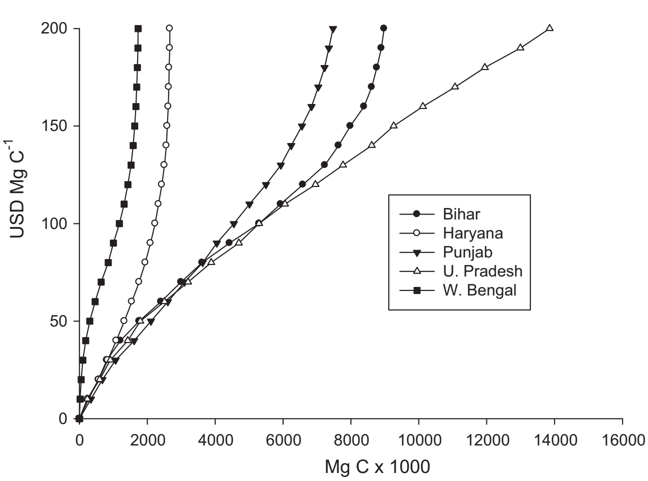

Fig. 1. Carbon supply curves (based on 20 year accumulation rates) for the Indo-Gangetic Plain of India when converting from conventional to no-tillage practices in rice–wheat cropping systems.

Table 6
Proportion (%) of potential net C sequestration achieved after 20 years over a range of carbon prices (USD) when implementing no-tillage practices in wheat based cropping systems of the Indo-Gangetic Plain.

State	Rotation	Carbon price (USD Mg C^{-1})			
		25	50	100	200
Bihar	Rice–wheat	7.4	18.9	56.9	96.5
Haryana	Rice–wheat	26.4	49.8	84	100
Punjab	Rice–wheat	10.7	25.9	55.8	91.7
Uttar Pradesh	Rice–wheat	3.4	8	23.8	62.2
West Bengal	Rice–wheat	4.5	17.3	66.4	97.5
Total	Rice–wheat	7	16.5	42	78.6
Uttar Pradesh	Maize–wheat	4.9	13.6	35	77.8
Haryana	Cotton–wheat	1.9	4.2	12.2	31.6
Punjab	Cotton–wheat	5.1	11.9	33.1	78
Total	Cotton–wheat	2.8	6.3	17.7	43.8

Collectively, maize–wheat and cotton-maize rotation systems are only found on 1.2 Mha of the IGP of India. In maize–wheat systems under no-till, a carbon price of USD 50 Mg C^{-1} would realize 252,000 Mg C, approximately 14% of the sequestration potential, increasing to 811,000 Mg C (or 35% of potential) at a carbon price of USD 100 Mg C^{-1}. For cotton–wheat, a carbon price of USD 50 Mg C^{-1} would return 173,000 Mg C over 20 years, 6% of the simulated C sequestration potential, increasing to 18% at a carbon price of USD 100 Mg C^{-1}. If we were to run the carbon price to a high enough level, the supply curves would eventually all become vertical when the economic potential for C sequestration approaches the technical potential.

4. Conclusions

This study examined the economic potential of adopting no-till practices on soil C sequestration in wheat-based cropping systems of the IGP using an empirical simulation methodology, taking into account all GHGs. Net C sequestration rates (i.e. after discounting for associated GHG emissions) ranged from 244 to 359 kg C ha^{-1} annum^{-1} when converting from conventional tillage to no-till in rice–wheat systems, and 219–231 kg C ha^{-1} annum^{-1} when converting from conventional tillage to no-till in maize–wheat and cotton–wheat systems. West Bengal provides the largest net gains in C (per hectare) at 6.6 Mg C ha^{-1} over 20 years when converting to no-tillage, however the total potential supply is low considering the area under cultivation is small compared to the rest of the IGP. Without considering economic constraints, the greatest potential gain in soil carbon (on an areal basis) is in Uttar Pradesh. With nearly 4 Mha of conventionally tilled wheat–rice cropping available, this area could technically sequester more than 22 Mt C over 20 years, half of the total C sequestration potential of rice–wheat in the Indian States of the IGP. Uttar Pradesh also offers the best return in soil carbon over 20 years for all carbon prices, whilst cotton–wheat systems in Haryana and Punjab offer the least return. But, even at a carbon price of USD 200 Mg C^{-1}, the transition from conventional tillage to no-tillage practices will still only realize 79% of the total sequestration potential of rice–wheat systems of Indian States of IGP over a 20 year time period.

Efforts to adapt and promote no-tillage technologies in the IGP have been underway for nearly three decades, but it is only since the turn of the century that the technologies are finding acceptance by the local farmers. The adoption of no-till is also taking place moreso in the irrigated region but is yet to be rooted in the rainfed agro-ecoregions (Hobbs et al., 2008). Adoption in the IGP may also likely be limited by market imperfections and the lack of access to specialized planting equipment. In our study, transaction costs are also estimated to be relatively low 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. The study is the first attempt to couple both biogeochemical and economic analyses with respect to the feasibility of reduced tillage for SOC sequestration across one of the major agricultural production areas of the developing world, the IGP. The study identifies target areas and strategies for maximizing SOC sequestration in the IGP and provides the basis for a more comprehensive assessment, incorporating both on-farm and institutional surveys, to fully assess the economic feasibility of SOC sequestration. The immaturity of the global carbon trading market also makes it extremely difficult to adequately express the overall impact of institutional mechanisms required to develop and coordinate carbon sequestration contracts. The accurate quantification of fixed costs of changing management practices, as well as transaction costs, including the real cost of verification and compliance, also need to be considered priorities in future studies.

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