Environmental Science & Technology

Article

pubs.acs.org/est

Simulation of Salinity Effects on Past, Present, and Future Soil Organic Carbon Stocks

Raj Setia,*[,†,⊥] Pete Smith,[‡] Petra Marschner,[†] Pia Gottschalk,[§] Jeff Baldock,[†,∥] Vipan Verma,[⊥] Deepika Setia,[†] and Jo Smith[‡]

[†]School of Agriculture, Food and Wine and The Waite Research Institute, The University of Adelaide, Adelaide SA5005, Australia

[‡]Institute of Biological and Environmental Sciences, 23 St. Machar Drive, University of Aberdeen, Aberdeen AB24 3UU, Scotland, U.K.

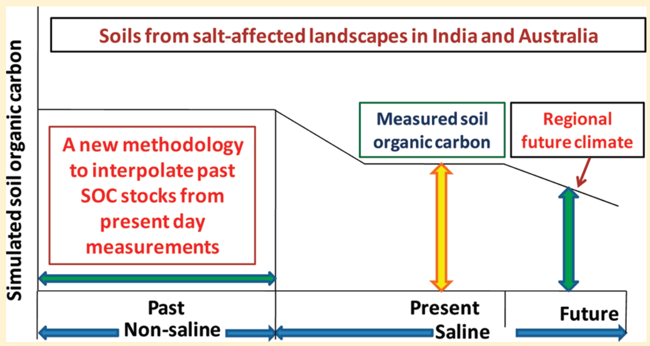
[§]Potsdam Institute for Climate Impact Research, Telegrafenberg, P.O. Box 601203, 14412 Potsdam, Germany

[∥]CSIRO Land and Water, Glen Osmond SA 5064, Australia

[⊥]Punjab Remote Sensing Centre, Ludhiana 141 004, Punjab, India

Supporting Information

ABSTRACT: Soil organic carbon (SOC) models are used to predict changes in SOC stocks and carbon dioxide (CO_2) emissions from soils, and have been successfully validated for non-saline soils. However, SOC models have not been developed to simulate SOC turnover in saline soils. Due to the large extent of salt-affected areas in the world, it is important to correctly predict SOC dynamics in salt-affected soils. To close this knowledge gap, we modified the Rothamsted Carbon Model (RothC) to simulate SOC turnover in salt-affected soils, using data from non-salt-affected and salt-affected soils in two agricultural regions in India (120 soils) and in Australia (160 soils). Recently we developed a decomposition rate modifier based on an incubation study of a subset of these soils. In the present study, we introduce a new method to estimate the past losses of SOC due to salinity and show how salinity affects future SOC stocks on a regional scale. Because salinity decreases decomposition rates, simulations using the decomposition rate modifier for salinity suggest an accumulation of SOC. However, if the plant inputs are also adjusted to reflect reduced plant growth under saline conditions, the simulations show a significant loss of soil carbon in the past due to salinization, with a higher average loss of SOC in Australian soils (55 t C ha^{-1}) than in Indian soils (31 t C ha^{-1}). There was a significant negative correlation ($p < 0.05$) between SOC loss and osmotic potential. Simulations of future SOC stocks with the decomposition rate modifier and the plant input modifier indicate a greater decrease in SOC in saline than in non-saline soils under future climate. The simulations of past losses of SOC due to salinity were repeated using either measured charcoal-C or the inert organic matter predicted by the Falloon et al. equation to determine how much deviation from the Falloon et al. equation affects the amount of plant inputs generated by the model for the soils used in this study. Both sets of results suggest that saline soils have lost carbon and will continue to lose carbon under future climate. This demonstrates the importance of both reduced decomposition and reduced plant input in simulations of future changes in SOC stocks in saline soils.



1. INTRODUCTION

World soils contain 1550 Pg of soil organic carbon (SOC) to 1 m depth, which is more than is found in the biotic (560 Pg C) and the atmospheric (760 Pg C) pools combined.[1] Thus, changes in SOC content could influence future atmospheric carbon dioxide (CO_2) concentrations.[2,3] Land use changes and soil degradation have played a significant role in increasing the atmospheric CO_2 concentration.[2]

Globally, 20% of cultivated land is salt-affected.[4] Salt-affected soils occur mainly in arid and semiarid regions. Among salt-affected soils, saline soils have a high concentration of soluble salts and an electrical conductivity (EC) of the saturation extract (EC_e) greater than 4 dS m^{-1}. Salinization is due to soluble salts originating from the weathering of primary minerals, aeolian recycling, cyclic accession, irrigation, or long-term changes in hydrology of the landscape due to land clearance.

Salinity reduces crop yield under greenhouse and field conditions, e.g., in barley,[5,6] wheat,[7−9] cotton,[10,11] sugar cane,[12] rice,[8] maize,[8] and sugar beet.[13] Crops and cultivars differ in their tolerance to salinity, which is further modulated by

Received: August 5, 2011
Revised: December 5, 2011
Accepted: December 20, 2011
Published: December 20, 2011

environmental and soil conditions. Moreover, increasing soil salinity causes ion imbalance and nutrient deficiency[14] which may impact plant productivity and nutrient cycling. Maas and Hoffman[15] concluded that yield of a certain crop as a function of salinity could be described reasonably well by a linear response function. Their comprehensive database includes threshold values for a wide range of crops, below which yields are not affected, and provides a function describing a linear reduction in yield with increasing salinity.

Microorganisms play a pivotal role in soil organic matter (SOM) decomposition; therefore salt-induced changes have implications for nutrient cycling and SOM dynamics.[14,16] High EC causes osmotic stress which alters the composition and activity of the microbial community and kills sensitive microorganisms,[17,18] and thus salinity decreases SOC mineralization.[16,19−23] Therefore, salinity will have an impact on SOC turnover, both by altering the amount of plant material entering the soil, and by influencing the rate of SOC decomposition, which will modify the role of soil as a source or sink of CO_2. Soil organic carbon stocks may be lower in saline soils due to poor plant growth and thus lower C inputs, but lower decomposition rates in these soils could counteract this effect, leading to similar or even higher SOC stocks than found in non-saline soils, despite lower inputs.[16]

Soil organic carbon models may help to predict and understand future changes in SOC in response to changing climate, altered land use, and land management practices.[24] Over the last 20 years, SOC models have been successfully used to predict changes in SOC in non-saline land using short-term or long-term plot and field scale data.[24−28] These simulations have been extended to regional[29] as well as country and continental scales.[30−32] However, these models do not take into account the potential effects of salt on SOC stocks and turnover. Given the global extent of salt-affected soils, this may result in substantial errors in estimation of greenhouse gas emissions, and may lead to incorrect predictions of SOC stocks.

Recently, we developed a decomposition rate modifier for salinity[33]and modified the Rothamsted Carbon Model (RothC[34,35]) to be able to simulate SOC decomposition in saline soils. Simulations using the modified version of RothC were run using data from a field in South Australia, and showed that previous predictions underestimated the future decrease SOC stocks from these soils.[33] In the present study, the modified version of RothC was used for two agricultural regions of India and Australia varying in climate and soil characteristics to estimate (i) past losses of SOC due to salinity and (ii) future SOC stocks in saline soils. This work describes a new method that is used to estimate the steady state SOC content in soils before salinization, and demonstrates the ability of the model to be used in simulations of past and future regional SOC dynamics in saline soils.

2. MATERIALS AND METHODS

2.1. Soils. Two regions were used for collection of soil samples: Kadina, South Australia (area 159 km^2, between latitudes 33° 52′ S and 34° 0′ S, between longitudes 137° 36′ E and 137° 44′ E) where dry saline land (salinity not associated with the groundwater table) and dry land salinity (salinity associated with the groundwater table) are widespread; and Muktsar, Punjab, India (area 2631 km^2, between latitudes 29° 54′ and 30° 40′ N, between longitudes 74° 14′ and 74° 49′ E) where irrigation-induced salinity is dominant.

The Australian site (hereafter referred to as Australia) has a dry Mediterranean climate; the average winter and summer temperatures are 15.4 and 30.5 °C, respectively. The average annual rainfall is 270 mm. The soils in this study area are predominantly characterized by a marked texture contrast with loam over clay and belong to the order Calcarosols and Sodosols.[36] The climate at the Indian site (hereafter referred to as India) is subtropical; the average winter and summer temperatures are 15.7 and 33.8 °C, respectively. The average annual rainfall is 280 mm. The area is mainly irrigated by groundwater and canal water. Most soils of this region are coarse to fine loamy and belong to the order Aridisols and Inceptisols.[37] Exceptions are the sand dunes, which are highly permeable with very low water and nutrient holding capacity, and belong to the order Entisols.[37]

Using Quick Bird data (spatial resolution 0.6 m) for the Australian site and IRS P-6 satellite data (spatial resolution 23.5 m) for the Indian site, various land use classes were delineated to select representative sampling sites.[38] On the basis of land use and soil types, composite soil samples were collected to a depth of 0.3 m: 120 from India [61 non-saline (EC_e < 4.0 dS m^{-1}), 27 low salinity (EC_e 4.0−8.0 dS m^{-1}), 14 medium salinity (EC_e 8.0−16.0 dS m^{-1}), and 18 high salinity (EC_e > 16.0 dS m^{-1})] and 160 from Australia [90 non-saline, 23 low salinity, 21 medium salinity, and 26 high salinity]. For each sampling site, four subsamples from within an area of 1 m^2 were collected and combined in order to minimize the influence of fine-scale spatial variability. Sampling sites were located in the field with a Global Positioning System (Garmin eTrex model); the location of the sampling sites is shown in Figure S1 (Supporting Information). The soils were air-dried, passed through a 2-mm sieve, and stored air-dry.

2.2. Soil Characterization. Soil pH and EC were measured in a 1:5 soil/water suspension after 1 h end-over-end shaking at 25 °C. The spatial distribution maps of $EC_{1:5}$ of soils from both regions were generated using ArcGIS 9.3 (Figure S1 in Supporting Information). An alternative and more biologically meaningful measure of the effect of salt in soils with different texture is the osmotic potential, which takes into account the water content. Due to differences in water holding capacity of soils, at a given $EC_{1:5}$, the osmotic potential of the soil solution is lower in the coarse-textured soils than fine-textured soil.[39] Therefore, the osmotic potential provides a better measure of the effect of salt on plant growth[40] and microbial activity[39] than the EC of a soil extract. The osmotic potential (O_s) of each soil was calculated as using an equation developed by Richards:[41]

$$O_s = -0.036EC_{1:5}(\theta_{ref}/\theta_{act}) \tag{1}$$

where O_s is the osmotic potential (MPa) of soil solution at the actual soil moisture content (θ_{act}, g g^{-1}) and $EC_{1:5}$ is the electrical conductivity (dS m^{-1}) of 1:5 soil/water extract at the reference water content (θ_{ref}, g g^{-1}) of the 1:5 soil/water mixture. The actual soil moisture content (θ_{act}, g g^{-1}) was calculated dynamically in the model for each time step from field capacity minus soil moisture deficit. The water content at field capacity was calculated from a pedo-transfer function based on silt, clay, and organic C[42] and soil moisture deficit is calculated in RothC from precipitation, open-pan evaporation, and clay content.[36] The EC_e was calculated from $EC_{1:5}$ and clay content using an equation proposed by Shaw et al.[43]

$$EC_e = EC_{1:5}(-2.21 \times \%Clay^{0.5} + 23.78) \tag{2}$$

dx.doi.org/10.1021/es2027345 | Environ. Sci. Technol. 2012, 46, 1624−1631

where %Clay is the percentage clay of the soil.

Bulk density was measured by the clod method before sieving the soil.[44] Particle size distribution, total SOC, and charcoal-C (char-C) were estimated by mid infrared (MIR) spectroscopy on tungsten-milled subsample of the air-dried soil.[45,46] The MIR was calibrated for these soils and the details of calibration are reported in Setia et al.[39]

2.3. Rothamsted Carbon Model. The effect of salinity on SOC stocks in soils of India and Australia was modelled using RothC, which includes five pools of SOM: decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), humified OM (HUM), and inert OM (IOM).[35] Setia et al.[33] introduced an additional decomposition rate modifier (d) for the impact of salinity on the rate of decomposition (eq 3) for these pools (except IOM):

$$y = y_0(1 - e^{-abcdkt}) \tag{3}$$

where y_0 is the initial amount of C in a particular pool (t C ha^{-1}); a, b, c, and d are rate-modifying factors for temperature, moisture, plant retainment factor (if the soil is vegetated or not), and salinity, respectively; k is the rate constant for the given pool ($month^{-1}$), and t is $^1/_{12}$ to convert k to a monthly time step.

The method for calculating the decomposition rate modifier for salinity (d) is described in full in Setia et al.[33] Briefly, the CO_2 emission from a subset of soils, covering the whole range of ECs and sodium adsorption ratios (SAR) from the study sites, was measured in laboratory incubations over a 120 day period. Modelled CO_2 emissions (based on field data) were higher than measured CO_2 due to disturbance of the soil and incubation of the soils in the laboratory. Soil disturbance and laboratory incubation were necessary to determine CO_2 emissions from a large number of soils. To separate these laboratory effects from the effect on decomposition of salinity, the modelled and measured CO_2 emissions were matched for a subset of the non-salt-affected soils, using a decomposition rate modifier. Equilibrium and short-term simulations of RothC were run, adjusting the additional decomposition rate modifier to achieve an agreement between modelled and measured CO_2 emissions. An equation was developed from these non-salt-affected soils to account for the laboratory effect in soils of different textures. Having removed the laboratory effect from the results, an additional decomposition modifier could then be derived from the laboratory incubations of the salt-affected soils to account for the impacts of salinity on decomposition. The following exponential relationship was obtained between osmotic potential and the decomposition rate modifier d:

$$d = e^{0.073O_s}\ (R^2 = 0.65) \tag{[4]}$$

where d is the decomposition rate modifier for salinity and O_s is the osmotic potential. In non-saline soils (ECe < 4.0 dS m^{-1}), d = 1.

2.4. Calculation of the Plant Input Modifier. Plant growth is reduced by salinity, resulting in a lower C input, which should be included in simulations of the impact of salinity on changes in SOC stocks. The calculation of plant input modifier is described in full in Setia et al.[33] Assuming that the impact of salinity on yield is similar to the impact on plant inputs,[30] the following equation for the change in plant inputs into the soil with salinization was developed from a modified Maas and Hoffman[15] equation on a 0−1 scale:

$$p_{PI} = (100 - B(EC_e - A))/100 \tag{5}$$

where p_{PI} is the plant input returned to the soil with a given soil salinity (EC_e), expressed as a proportion of the plant inputs in a non-saline soil. The values of the slope (B = 6.1% yield decrease per unit salinity increase) and threshold (A = 6.9 dS m^{-1}) were calculated from the average of these values for barley, wheat, legumes, and cotton,[15] the major crops grown in the two study areas. The slope and threshold values were the same in both regions since the average slope and threshold of cotton and wheat grown at Indian site were similar to that of barley, wheat, and cowpea grown at the Australian site. The plant input modifier was used only for saline soils. The p_{PI} modifier for soils with an $EC_{1:5}$ > 1.5 dS m^{-1} was assumed to be equal to the p_{PI} modifier at $EC_{1:5}$ 1.5 dS m^{-1} because a linear decrease in plant input beyond $EC_{1:5}$ is unlikely since salinity increases slowly over time,[47] and thus plant adaptation may be expected to result in higher plant inputs than predicted by eq 5 at very high values of EC_e.

2.5. Calculation of Plant Inputs. The past plant inputs that have resulted in the SOC measured at the sampling sites are unknown and therefore were derived following the approach used by Smith et al.[30] The RothC model was run in inverse mode to calculate the plant inputs from total SOC measured at the sampling in 2008, using the percent clay and weather data measured at the given site and the estimated size of the IOM pool. The model was then run using these calculated plant inputs adjusted according to the plant input modifier (eq 5).

The IOM pool has a significant effect on the plant inputs generated by the model because the higher the IOM, the lower the proportion of SOC available for C cycling in the soil. The amount of IOM in the soil can be estimated using the equation derived by Falloon et al.:[48]

$$IOM = 0.049^*\text{total SOC}^{1.139} \tag{6}$$

where IOM is the amount of C in the IOM pool (t C ha^{-1}), and total SOC is the total measured SOC (t C ha^{-1}).

To verify the applicability of the Falloon et al. equation for Australian and Indian soils, IOM was assumed to be equivalent to measured char-c, following the approach used by Skjemstad et al.[28] The model was run using IOM obtained from the measured char-C, or IOM calculated by the Falloon et al. equation. Comparison of the results allowed the significance of any error introduced by using the Falloon et al. equation in place of measured values to be quantified.

2.6. Modelling Past SOC Content When the Presently Saline Soils Were Non-saline. The present day SOC content, measured under saline conditions (SOC_1), was taken as an initial estimate of the steady state C content of the non-saline soil prior to the onset of salinization. Clearly, in a saline soil, this is unlikely to be a good estimate, but it provided a starting point that allowed an improved estimate of the C content of the non-saline soil to be obtained by iteration. As described in the previous section, the model was run to equilibrium, giving the steady state SOC pools after 10 000 years, which was used to determine the plant inputs (PI_1) needed to achieve the assumed SOC content (SOC_1) under non-saline conditions. The equilibrium run was then repeated assuming the measured soil salinity to determine the decomposition rate modifier (d) and the plant input modifier (p_{PI}). The plant inputs (PI_2) used in the equilibrium run were calculated from the plant inputs for the non-saline conditions

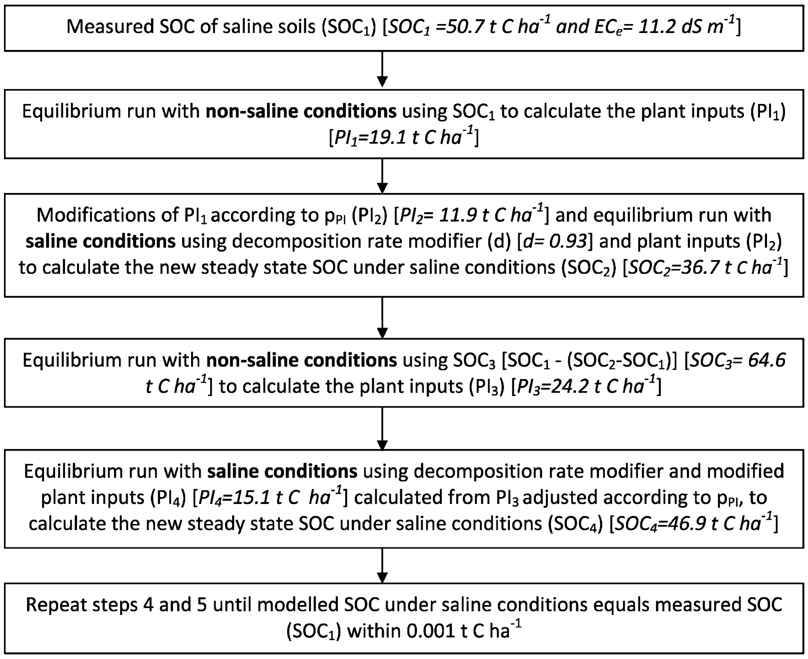


Figure 1. Schematic diagram of the approach for modelling of the past SOC content when the presently saline soils were non-saline (values in italics are an example of the first steps of this iterative approach).

Table 1. Descriptive Statistics of Soil Properties (0−0.30 m) of the Two Regions: Australia (n = 160) and India (n = 120)[a]

parameter	pH	$EC_{1:5}$ (dS m^{-1})	EC_e (dS m^{-1})	osmotic potential (Mpa)	clay (%)	bulk density (Mg m^{-3})	total SOC (t ha^{-1})	char-C (t ha^{-1})
				Australia				
minimum	7.9	0.1	1.56	−0.05	13.0	1.1	56.3	2.8
maximum	9.6	8.2	102	−3.68	49.3	1.3	198	26.7
mean	8.8	0.9	8.90	−0.29	33.5	1.2	130	11.2
median	8.8	0.3	3.64	−0.11	34.0	1.2	131	10.9
standard deviation	0.3	1.3	12.7	0.46	6.7	0.04	25.0	4.1
				India				
minimum	8.1	0.1	1.41	−0.05	4.6	1.2	13.2	0.006
maximum	10.2	6.9	88.7	−3.87	34.8	1.7	102	6.59
mean	8.9	0.8	12.0	−0.47	16.0	1.5	54.2	1.50
median	8.8	0.3	3.91	−0.16	15.3	1.5	52.8	1.26
standard deviation	0.4	1.4	19.3	0.79	6.2	0.1	16.9	1.38

[a]pH and $EC_{1:5}$ were measured in 1:5 soil/water ratio; EC_e = electrical conductivity of saturated paste; SOC = soil organic carbon; Char-C = charcoal-C.

(PI_1), modified according to p_{PI},

$$PI_2 = p_{PI} \times PI_1 \tag{7}$$

The steady-state SOC content, calculated under saline conditions (SOC_2) was used to revise the initial estimate of SOC content under non-saline conditions (SOC_3) using the following equation:

$$SOC_3 = SOC_1 - (SOC_2 - SOC_1) \tag{8}$$

The equilibrium run under non-saline conditions was then repeated, this time using SOC_3 as the estimate of the steady-state SOC content of the non-saline soil. As before, the plant inputs (PI_3) needed to achieve this SOC content (SOC_3) in a non-saline soil were calculated by running the model to equilibrium, and adjusting the plant inputs according to the ratio of simulated and measured SOC.

The equilibrium run using the decomposition rate and plant input modifiers calculated by eqs 3 and 5 and modifying plant inputs as ($p_{PI} \times PI_3$) was again used to obtain a new estimate of steady-state SOC achieved under saline conditions. This provided a new estimate for the SOC content of the non-saline soil. This process was continued iteratively until the SOC content calculated under saline conditions matched the measured values to within 0.001 t C ha^{-1}. The resulting estimate for the SOC content provided by eq 8 was then taken to be the C content of the soil when the currently saline soils were non-saline. A schematic diagram of the approach is shown in Figure 1.

To assess the impact of uncertainty in the plant input modifier, the revised plant input modifier equations were used that equated to the mean value ± the 95% confidence interval of the data used to derive the equation.

2.7. Modelling Future SOC Content of Soils. Soil properties and climatic conditions differ between the Australian site (dry Mediterranean climate) and the Indian site (subtropical climate). Therefore, the future SOC stocks from the year 2009 to 2100 were estimated separately for the two regions using climate data derived by the HadCM3 model forced using the IPCC B2 emissions scenario.[49] For each sampling point, the model was run to equilibrium in 2008 under constant environmental conditions using the decomposition rate modifier and the plant input modifier in order to obtain the initial SOC content and the annual plant inputs. The climatic conditions were obtained from average climate data from 1945 to 2008 for the Australian site and 1998 to 2008 for the Indian site (best available data). The plant input modifier and the decomposition rate modifier were set to one (no change) for non-saline soils (EC_e < 4.0 dS m^{-1}). The median values of SOC in each year for four salinity classes (non-saline, low salinity, medium salinity, and high salinity) were calculated.

3. RESULTS

3.1. Soil Properties. *3.1.1. Australia.* The Australian soils were characterized by pH values >7 and were non-saline to highly saline (EC_e from 1.6 to 102 dS m^{-1}). The osmotic potential of these soils ranged between −0.05 and −3.68 MPa (Table 1). The clay content varied from 13 to 49.3% with a median value of 34%. The median value of total SOC was 131 t ha^{-1}, ranging from 56.3 to 198 t ha^{-1}. The char-C content varied from 2.8 to 26.7 t ha^{-1} with a median value of 10.9 t ha^{-1}. The distribution of saline soils in the region was patchy (Figure S1 in Supporting Information).

3.1.2. India. The pH of the Indian soils was >7; soils were non-saline to highly saline (EC_e from 1.4 to 89 dS m^{-1}). The osmotic potential of these soils varied between −0.05 and −3.87 MPa (Table 1). The Indian soils had a coarser texture than the Australian soils. The clay content varied between 4.6 and 34.8%. Compared to the Australian soils, the Indian soils had a lower total SOC and char-C content which varied from 13.2 to 102 t C ha^{-1} and from traces to 6.59 t ha^{-1}, respectively. Salinity was unevenly distributed in the region being highest in the southern part (Figure S1 in Supporting Information).

3.2. Relationship between SOC Simulated Using IOM Obtained from Measured Char-C and IOM Predicted by the Falloon et al. Equation. At both sites, similar values of past SOC content of presently saline soils were simulated using IOM estimated from measured char-C, and IOM calculated by the Falloon et al. equation (Figure S2 in Supporting Information). The relationship between simulated SOC contents obtained using the different estimates of IOM did not differ (R^2 = 1.0, p < 0.05) for both Indian and Australian soils.

3.3. Simulation of the Change in SOC Content with Salinization. The past SOC content simulated for presently saline soils using modification of both the plant inputs and decomposition rate modifier in response to salinity was higher than the current SOC content measured under saline conditions for both Australia and India. The SOC loss due to salinity, calculated as the difference between the past SOC content simulated for the non-saline soils and the SOC content measured in the saline soils, increased with decreasing (more negative) osmotic potential. For example, the historic loss of SOC in an Indian soil with an osmotic potential of −0.36 MPa was 13.2%, whereas the loss increased to 57% for a soil with an osmotic potential of −3.5 MPa. A similar loss of C due to both reduced plant input modifier and rate of decomposition was also observed in the Australian soils. The projected historic loss of SOC due to salinity varied from 2.4 to 62% for Indian soils and 1.2 to 61% for Australian soils (Figure 2).

There was a significant negative correlation between osmotic potential and the loss of SOC due to salinization (r = −0.59, p < 0.05 for India and r = −0.52, p < 0.05 for Australia). The average loss of SOC due to salinity was 31 t C ha^{-1} for the Indian site, and 55 t C ha^{-1} for the Australian site.

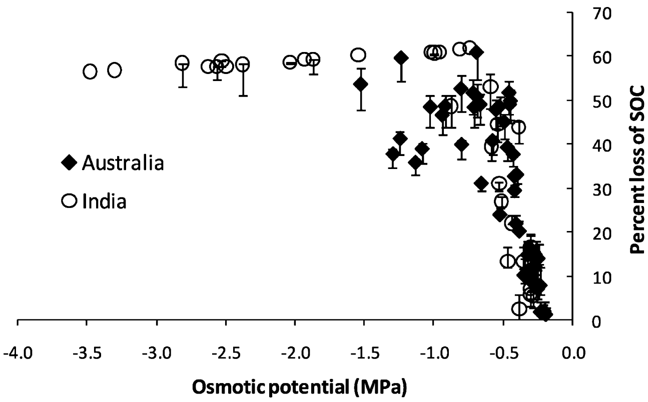


Figure 2. Simulated precent loss of SOC from soils of Australia and India. Modelling included plant input modifier and decomposition rate modifier. Vertical bars indicate standard deviation for plant inputs at ±95% confidence interval.

When the simulations were done accounting for the impact of salinity on the rate of decomposition only, without taking into account reduced plant input, the past SOC content simulated for the non-saline soils was lower than SOC content measured in the saline soils for both Australia and India. The accumulation of SOC calculated using the salinity decomposition rate modifier increased linearly with decreasing osmotic potential (Figure S3 in Supporting Information).

3.5. Modelling Future SOC of Non-saline and Saline Soils. The modelled future SOC of non-saline and saline soils decreased under the projected future climate, but the magnitude of decrease was greater in saline soils (Figure 3). On average, the projected decrease in SOC by the year 2100 of saline soils is 40% of the present SOC content for the Indian site, and 28% for the Australian site. Without accounting for the decomposition rate modifier and plant input modifier due to salinization, the projected decrease in SOC by the year 2100 of the currently saline soils is 15% of the present SOC content for the Indian site, and 12% for the Australian site.

4. DISCUSSION

The simulation with Roth C modified for saline soils showed that SOC stocks are reduced in saline soils. The average loss of SOC due to salinity was 31 t ha^{-1} for the Indian site, and 55 t ha^{-1} for the Australian site. The projected future SOC stocks decrease in all soils, but the decrease is greater in saline soils. Whereas the non-saline soils are projected to lose only about 10% of their current SOC by 2100, the medium and highly saline soils are projected to lose more than 30%. Without accounting for salinity in the saline soils, projected SOC decrease in these soils by the year 2100 is 12% of the present SOC content for the Australian site and 15% for the Indian site.

4.1. Indian and Australian soils. The differences in SOC contents of Indian and Australian soils (Table 1) are due to differences in cropping history, soil texture, and climate. The lower SOC content at the Indian site can be explained by (i) higher average temperature combined with irrigation which is conducive to SOC decomposition, and (ii) the coarser texture of the Indian soils which would reduce binding of SOC to soil particles and thus increase decomposition rate of the organic matter. The distribution of salinity in both regions was related

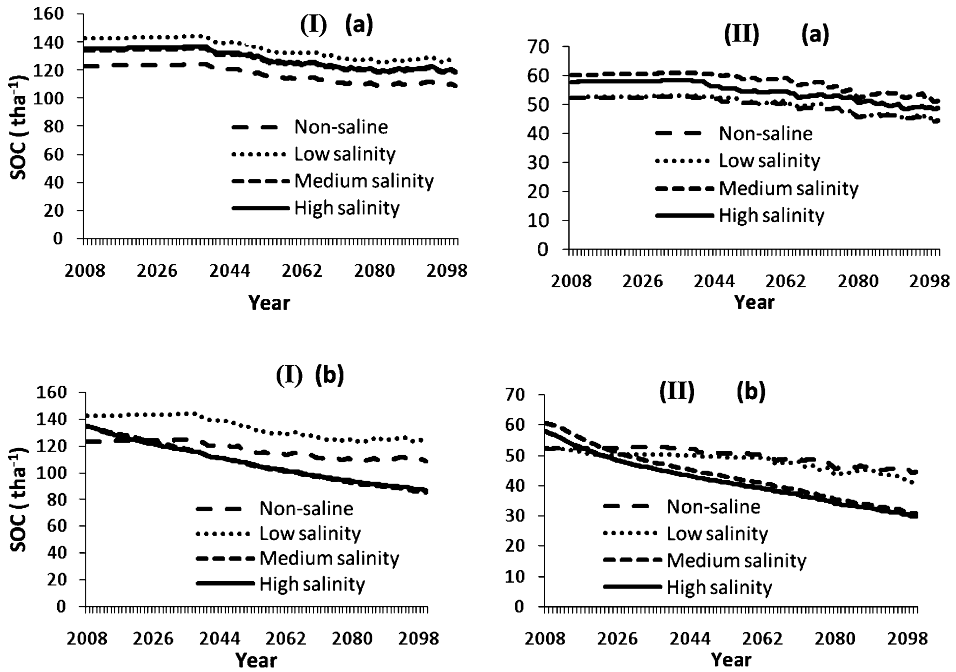


Figure 3. Projected SOC content of (I) Australia and (II) India (a) *without* plant input modifier and decomposition rate modifier and (b) *with* plant input modifier and decomposition rate modifier in non-saline soils (EC_e < 4.0 dS m^{-1}), and soils with low salinity (EC_e 4.0–8.0 dS m^{-1}), medium salinity (EC_e 8.0–16.0 dS m^{-1}), and high salinity (EC_e > 16.0 dS m^{-1}).

to topography, with low lying regions having higher salinity. The potential threat of salinity to agriculture was first reported in Punjab (India) in 1855[50] and in Australia in 1924.[51] Since then, the area affected by salinity has increased as a result of inappropriate land management. This is exacerbated by climate change which will, in many agricultural regions, reduce rainfall. Given the importance of SOC for atmospheric CO_2 concentrations, it is important to understand the impact of salt on SOC contents.

4.2. Inert Organic Matter. The equation presented by Falloon et al.[48] has been widely used for estimating IOM where radiocarbon data are not available to allow IOM to be estimated directly; this equation estimates that ~10% of the total SOC is IOM. Our results show that there was no significant difference between values of SOC simulated in non-saline soils using measured char-C and those using IOM predicted by the equation. Therefore, this equation can be used to calculate IOM in the study areas, where average char-C is 8.5% of total SOC for the Australian site and 2.8% for the Indian site. However, this equation may not be appropriate for soils with higher amounts of IOM, such as found in some Australian soils which contain up to 40% of SOC as IOM in the form of char-C.[52] Further comparisons between modelled and measured SOC using soils with higher char/IOM content are needed to test the general applicability of the Falloon et al. equation.

4.3. Modelled Past SOC Content When the Presently Saline Soils Were Non-saline. Modelling of past SOC using the decomposition rate modifier and the plant input modifier suggests that, before the saline conditions developed, the SOC content was higher than is measured today. This difference occurs due to the reduced plant inputs under saline conditions; reduced decomposition rates alone would have increased SOC content. This finding implies that as these soils became saline they lost a significant amount of SOC (Figure 2). The average historic loss of SOC due to salinization was greater in the Australian soils than the Indian soils. Although the coarser textured soils at the Indian site are conducive to losses of C via decomposition; the smaller loss of SOC in India is due to the greater area at the Indian site with low salinity than at the Australian site (Figure S1 in Supporting Information).

The difference between the past SOC content simulated for non-saline conditions and SOC content measured in the saline soils increased with decreasing osmotic potential. This is explained by the negative impact of low osmotic potential on plant inputs. Therefore, to accurately model SOC content in saline soils, both reduced decomposition and reduced plant input must be considered.

4.4. Modelled Future SOC Stocks. Given no limitation of soil moisture, increasing temperatures are predicted to accelerate the rate of decomposition, increasing future losses of SOC. These increased losses could, however, be offset by increased plant inputs from higher plant production in temperate regions.[30] On the other hand, increasing temperatures will also increase salinity, particularly if coupled with reduced rainfall.[53] In otherwise optimal conditions, higher atmospheric CO_2 concentration will increase plant growth and thus C inputs into soils.[54] However, due to the poor physical, chemical, and biological properties of saline soils, it is unlikely that plant growth will increase on saline soils. In agreement with Jenkinson et al.,[55] our simulations suggest that SOC stocks will decrease in the future in these regions, where low temperatures are not limiting plant growth. Our data show that the decrease in SOC stocks in these two areas, where salinity is widespread, may be greater than predicted when salinity is neglected. The projected decrease of SOC by the year 2100 in soils with high salinity (EC_e > 16 dS m^{-1}) is 36% of the present SOC content for the Australian site and 49% for the Indian site (Figure 3). Hence, the projected loss of SOC is higher in the Indian soils than the Australian soils, which can be explained by the higher projected rainfall in India than in Australia. In Australia, decomposition would be limited by lack of water, while the higher water content combined with high temperatures in India would result in high decomposition rates.

4.5. Sources of Uncertainty. The modelled data are based on a number of assumptions, each of which may introduce a degree of uncertainty. The plant inputs were calculated using a generalized equation based on Maas and Hoffman.[15] This approach does not take into account differences in salt sensitivity between crop species and cultivars. We quantified the uncertainty introduced by this approach by simulating the SOC content using the Maas and Hoffman equation recalculated to fit the 95% confidence interval of the crop data provided. This was used to estimate the loss of C due to salinity assuming the maximum and minimum likely plant inputs at the 95% confidence interval. The magnitude of the simulated loss due to salinization differs substantially, for example at an osmotic potential of −0.5 MPa the loss of C due to salinization ranges from 13 to 52%. This discrepancy highlights the importance of plant inputs for maintaining SOC stocks in saline soils. It also emphasizes the potential to substantially increase SOC stocks in saline soils by development of salt-tolerant plant species, which produce greater biomass under saline conditions.

Note that the salinity of soils in future simulations was assumed to remain unchanged. Future calculations should include a link to a salinity model to quantify the change in salinity level and extent with climate change. Including changes in salinity associated with changes in the future climate is likely to further increase the simulated impacts of salinity on changes in SOC.

5. IMPLICATIONS

Most models currently used to estimate regional and global changes in SOC stocks do not account for the impact of salinity. The inclusion of a decomposition rate modifier for salinity and salt modified plant inputs into RothC has demonstrated that salinity can result in a greater decrease in SOC stocks than was previously estimated. The importance of plant inputs for determining SOC stocks in saline soils suggests that development of salt-tolerant crops could potentially be an important mitigation measure for sustainable land use, not only in ensuring income for land users, but also in reducing losses of SOC from saline soils.

■ ASSOCIATED CONTENT

Supporting Information

Figures for the spatial distribution maps of electrical conductivity ($EC_{1:5}$) of soil and sampling locations in Australia and India, the relationship between modelled past soil organic carbon (SOC) content of presently saline soils using measured inert organic matter (IOM) and modelled past SOC content of presently saline soils using predicted IOM by the Falloon et al. equation in soils of Australia, and the simulated percent gain of SOC from soils of Australia and India (modelling included decomposition rate modifier only). This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*Phone: +61 8 8313 7306; fax: +61 8 8303 6511; e-mail: raj.setia@adelaide.edu.au; current address: School of Agriculture, Food and Wine, Waite Campus, The University of Adelaide, Australia 5005.

■ ACKNOWLEDGMENTS

We acknowledge Mr. Sean Forrester for MIR analyses and predictions, Northern and Yorke Natural Resources Management Board, Department of Climate Change and The Future Farm Industries CRC for funding. R.S. also acknowledges the scholarship from The University of Adelaide. P.S. is a Royal Society-Wolfson Research Merit Award holder.

■ REFERENCES

(1) Lal, R. Carbon sequestration. *Philos. Trans. R. Soc., B* **2008**, *363*, 815−830.

(2) Lal, R. Challenges and opportunities in soil organic matter research. *Eur. J. Soil Sci.* **2009**, *60*, 158−169.

(3) Smith, P. Soils as carbon sinks: The global context. *Soil Use Manage.* **2004**, *20*, 212−218.

(4) Flowers, T.; Yeo, A. Breeding for salinity resistance in crop plants: Where next? *Funct. Plant Biol.* **1995**, *22*, 875−884.

(5) Pal, B.; Singh, C.; Singh, H. Barley yield under saline water cultivation. *Plant Soil* **1984**, *81*, 221−228.

(6) Richards, R.; Dennett, C.; Qualset, C.; Epstein, E.; Norlyn, J.; Winslow, M. Variation in yield of grain and biomass in wheat, barley, and triticale in a salt-affected field. *Field Crops Res.* **1987**, *15*, 277−287.

(7) Richards, R. Should selection for yield in saline regions be made on saline or non-saline soils? *Euphytica* **1983**, *32*, 431−438.

(8) Bajwa, M.; Josan, A.; Hira, G.; Singh, N. Effect of sustained saline irrigation on soil salinity and crop yields. *Irrig. Sci.* **1986**, *7*, 27−35.

(9) Panahi, M.; Feizi, M.; Khayambashi, B.; Hajiakhondi, H., Saline condition and its effect on yield of nine durum wheat cultivars. In *Tenth International Water Technology Conference, IWTC10 2006, Alexandria, Egypt*, 2006.

(10) Meloni, D.; Oliva, M.; Ruiz, H.; Martinez, C. Contribution of proline and inorganic solutes to osmotic adjustment in cotton under salt stress. *J. Plant Nutr.* **2001**, *24*, 599−612.

(11) Soomro, A.; Mirjat, M.; Oad, F.; Soomro, H.; Samo, M.; Oad, N. Effect of irrigation intervals on soil salinity and cotton yield. *OnLine J. Biol. Sci.* **2001**, *1*, 472−474.

(12) Choudhary, O.; Josan, A.; Bajwa, M.; Kapur, M. Effect of sustained sodic and saline-sodic irrigation and application of gypsum and farmyard manure on yield and quality of sugarcane under semi-arid conditions. *Field Crops Res.* **2004**, *87*, 103−116.

(13) Ghoulam, C.; Foursy, A.; Fares, K. Effects of salt stress on growth, inorganic ions and proline accumulation in relation to osmotic adjustment in five sugar beet cultivars. *Environ. Exp. Bot.* **2002**, *47*, 39−50.

(14) Marschner, H. *Mineral Nutrition of Higher Plants*; Academic Press: London, 1995.

(15) Maas, E.; Hoffman, G. Crop salt tolerance current assessment. *J. Irrig. Drain. Div., Am. Soc. Civ. Eng.* **1977**, *103*, 115−134.

(16) Setia, R.; Marschner, P.; Baldock, J.; Chittleborough, D. Is CO_2 evolution in saline soils affected by an osmotic effect and calcium carbonate? *Biol. Fertil. Soils* **2010**, *46*, 781−792.

(17) Gros, R.; Poly, F.; Jocteur Monrozier, L.; Faivre, P. Plant and soil microbial community responses to solid waste leachates diffusion on grassland. *Plant Soil* **2003**, *255*, 445−455.

(18) Wichern, J.; Wichern, F.; Joergensen, R. Impact of salinity on soil microbial communities and the decomposition of maize in acidic soils. *Geoderma* **2006**, *137*, 100−108.

(19) McCormick, R.; Wolf, D. Effect of sodium chloride on CO_2 evolution, ammonification, and nitrification in a sassafras sandy loam. *Soil Biol. Biochem.* **1980**, *12*, 153−157.

(20) Sarig, S.; Roberson, E.; Firestone, M. Microbial activity-soil structure: Response to saline water irrigation. *Soil Biol. Biochem.* **1993**, *25*, 693−697.

(21) Tripathi, S.; Chakraborty, A.; Chakrabarti, K.; Bandyopadhyay, B. Enzyme activities and microbial biomass in coastal soils of India. *Soil Biol. Biochem.* **2007**, *39*, 2840−2848.

(22) Ghollarata, M.; Raiesi, F. The adverse effects of soil salinization on the growth of *Trifolium alexandrinum* L. and associated microbial

and biochemical properties in a soil from Iran. *Soil Biol. Biochem.* **2007**, *39*, 1699−1702.
(23) Setia, R.; Marschner, P.; Baldock, J.; Chittleborough, D.; Verma, V. Relationships between carbon dioxide emission and soil properties in salt-affected landscapes. *Soil Biol. Biochem.* **2011**, *43*, 667−674.
(24) Smith, P.; Smith, J.; Powlson, D.; McGill, W.; Arah, J.; Chertov, O.; Coleman, K.; Franko, U.; Frolking, S.; Jenkinson, D. A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. *Geoderma* **1997**, *81*, 153−225.
(25) Jenkinson, D.; Andrew, S.; Lynch, J.; Goss, M.; Tinker, P. The Turnover of Organic Carbon and Nitrogen in Soil [and Discussion]. *Philos. Trans.: Biol. Sci.* **1990**, *329*, 361−368.
(26) Parton, W. The CENTURY model. *NATO ASI Series I* **1996**, *38*, 283−294.
(27) Coleman, K.; Jenkinson, D.; Crocker, G.; Grace, P.; Klir, J.; Körschens, M.; Poulton, P.; Richter, D. Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. *Geoderma* **1997**, *81*, 29−44.
(28) Skjemstad, J.; Spouncer, L.; Cowie, B.; Swift, R. Calibration of the Rothamsted organic carbon turnover model (RothC ver. 26.3), using measurable soil organic carbon pools. *Aust. J. Soil Res.* **2004**, *42*, 79−88.
(29) Ardo, J.; Olsson, L. Assessment of soil organic carbon in semi-arid Sudan using GIS and the CENTURY model. *J. Arid Environ.* **2003**, *54*, 633−651.
(30) Smith, J.; Smith, P.; Wattenbach, M.; Zaehle, S.; Hiederer, R.; Jones, R.; Montanarella, L.; Rounsevell, M.; Reginster, I.; Ewert, F. Projected changes in mineral soil carbon of European croplands and grasslands, 1990−2080. *Global Change Biol.* **2005**, *11*, 2141−2152.
(31) Smith, J.; Smith, P.; Wattenbach, M.; Gottschalk, P.; Romanenkov, V.; Shevtsova, L.; Sirotenko, O.; Rukhovich, D.; Koroleva, P.; Romanenko, I.; Lisovoi, N. Projected changes in the organic carbon stocks of cropland mineral soils of European Russia and the Ukraine, 1990−2070. *Global Change Biol.* **2007**, *13*, 342−356.
(32) Smith, J.; Gottschalk, P.; Bellarby, J.; Chapman, S.; Lilly, A.; Towers, W.; Bell, J.; Coleman, K.; Nayak, D.; Richards, M.; Hillier, J.; Flynn, H. C.; Wattenbach, M.; Aitkenhead, M.; Yeluripurti, J. B.; Farmer, J.; Milne, R.; Thomson, A.; Evans, C.; Whitmore, A. P.; Falloon, P.; Smith, P. Estimating changes in Scottish soil carbon stocks using ECOSSE. I. Model description and uncertainties. *Clim. Res.* **2010**, *45*, 179−192.
(33) Setia, R.; Smith, P.; Marschner, P.; Baldock, J.; Chittleborough, D. J.; Smith, J. Introducing a decomposition rate modifier in the Rothamsted carbon model to predict soil organic carbon stocks in saline soils. *Environ. Sci. Technol.* **2011**, *45*, 6396−6403.
(34) Jenkinson, D.; Hart, P.; Rayner, J.; Parry, L. Modelling the turnover of organic matter in long-term experiments at Rothamsted. *Intecol. Bull.* **1987**, *15*, 1−8.
(35) Coleman, K.; Jenkinson, D. RothC-26.3-A Model for the turnover of carbon in soil. *NATO ASI Series* **1996**, *38*, 237−246.
(36) Isbell, R. F. *The Australian Soil Classification*; CSIRO Publishing: Collingwood, Australia, 2002.
(37) Soil Survey Staff. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*, 2nd ed.; US Department of Agriculture Soil Conservation Service: Washington, DC, 1999.
(38) Setia, R. Modelling organic carbon turnover in salt-affected soils, Ph D Thesis. The University of Adelaide, Australia, 2011.
(39) Setia, R.; Marschner, P.; Baldock, J.; Chittleborough, D.; Smith, P.; Smith, J. Salinity effects on carbon mineralization in soils of varying texture. *Soil Biol. Biochem.* **2011**, *43*, 1908−1916.
(40) Ben-Gal, A.; Borochov-Neori, H.; Yermiyahu, U.; Shani, U. Is osmotic potential a more appropriate property than electrical conductivity for evaluating whole-plant response to salinity? *Environ. Exp. Bot.* **2009**, *65*, 232−237.
(41) Richards, L., *Diagnosis and Improvement of Saline and Alkali Soils*; Agricultural Handbook No. 60; U.S. Department of Agriculture: Washington, DC, 1954.
(42) Batjes, N. Development of a world data set of soil water retention properties using pedotransfer rules. *Geoderma* **1996**, *71*, 31−52.
(43) Shaw, R.; Hughes, K.; Thorburn, P.; Dowling, A. Principles of landscape, soil and water salinity − processes and management options. Part A. In *Landscape, soil and water salinity; Proceedings of the Brisbane regional salinity workshop*; Brisbane, 1987.
(44) Blake, G., Bulk density. In *Methods of Soil Analysis. Part 1. Physical and Mineralogical Properties*; Black, C., Evans, D., Ensminger, L., White, J., Clark, F., Eds.; American Society of Agronomy: Madison, WI, 1965; pp 374−390.
(45) Janik, L. J.; Skjemstad, J. O.; Shepherd, K. D.; Spouncer, L. R. The prediction of soil carbon fractions using mid-infrared-partial least square analysis. *Aust. J. Soil Res.* **2007**, *45*, 73−81.
(46) Janik, L. J.; Merry, R. H.; Skjemstad, J. O. Can mid infrared diffuse reflectance analysis replace soil extractions? *Aust. J. Exp. Agric.* **1998**, *38*, 681−696.
(47) Askri, B.; Bouhlila, R.; Job, J. Development and application of a conceptual hydrologic model to predict soil salinity within modern Tunisian oases. *J. Hydrol.* **2010**, *380*, 45−61.
(48) Falloon, P.; Smith, P.; Coleman, K.; Marshall, S. Estimating the size of the inert organic matter pool from total soil organic carbon content for use in the Rothamsted carbon model. *Soil Biol. Biochem.* **1998**, *30*, 1207−1211.
(49) Mitchell, T.; Carter, T.; Jones, P.; Hulme, M.; New, M. *A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901−2000) and 16 scenarios (2001−2100). Working Paper 55*; Tyndall Centre for Climate Change Research, University of East Anglia: Norwich, 2004.
(50) Sharma, P.; Singh, C.; Verma, V.; Chopra, R.; Minakshi. *Mapping and Monitoring of Salt Affected Soils in Punjab using Remote Sensing Technology*; PRSC-TR/98; Punjab Remote Sensing Centre: Ludhiana, India, 1998.
(51) Wood, W. E. Increase of salt in soil and streams following the destruction of native vegetation. *J. Proc. R. Soc. Western Aust.* **1924**, *10*, 35−48.
(52) Lehmann, J.; Skjemstad, J.; Sohi, S.; Carter, J.; Barson, M.; Falloon, P.; Coleman, K.; Woodbury, P.; Krull, E. Australian climate−carbon cycle feedback reduced by soil black carbon. *Nat. Geosci.* **2008**, *1*, 832−835.
(53) Rengasamy, P. Salinity in the landscape: A growing problem in Australia. *Geotimes* **2008**, *53*, 34−39.
(54) Polglase, P.; Wang, Y. Potential CO_2-enhanced carbon storage by the terrestrial biosphere. *Aust. J. Bot.* **1992**, *40*, 641−656.
(55) Jenkinson, D.; Adams, D.; Wild, A. Model estimates of CO_2 emissions from soil in response to global warming. *Nature* **1991**, 304−306.